

# **3D SIMULATION ON THE SEVER LOCAL SCOUR INDUCED BY TSUNAMIS**

## **三維模擬海嘯所引致之局部沖刷**

**Tso-Ren Wu, Yu-Ming Ko, Mei-Hui Chuang, Chung-Yue Wang,  
and Chia-Ren Chu**

吳祚任、柯昱明、莊美惠、王仲宇、朱佳仁

*Graduate Institute of Hydrological and Oceanic Sciences, National Central University, Taiwan  
Dept. of Civil Engineering, National Central University, Taiwan*

*Sponsored by CECI*

[tsoren@ncu.edu.tw](mailto:tsoren@ncu.edu.tw)



# Tsunami Inland Intrusion

- 由原本波浪的傳能不傳質，變成傳能也傳質。





(陳慧慈，2011)

## Turned over two-story RC building



( Ando, 2011)<sup>4</sup>

# Load effects of tsunami

- Inundation height
- Seawater intrusion through unanticipated paths
- Hydrodynamic forces
- **Scouring**
- Uplift
- Sea sand immixed in seawater

Adopted from TAKAMATSU, 2012

# Scouring



- Many coastal seawalls were destroyed due to scouring by huge flows once tsunami overflows them.
- New sea wall constructions are planned or underway at many Japanese NPP sites.
- They should be constructed with strong wall structures and strong foundations to withstand impulsive tsunami pressure, etc. to prohibit excessive scouring.

Adopted form TAKAMATSU, 2012

# Tsunami Scour in 2004

## South Asia Tsunami Event

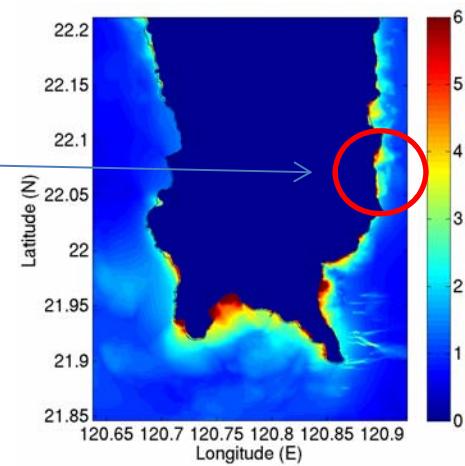
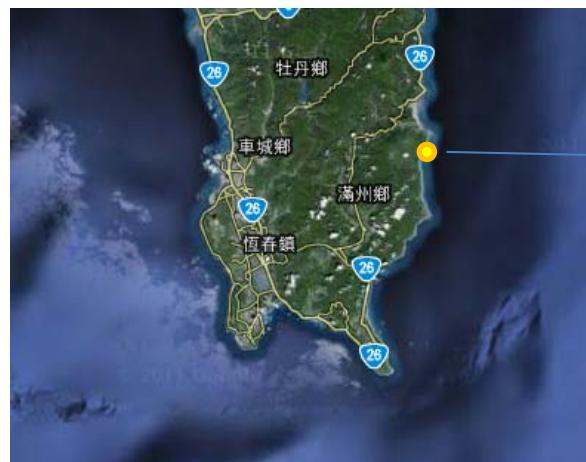
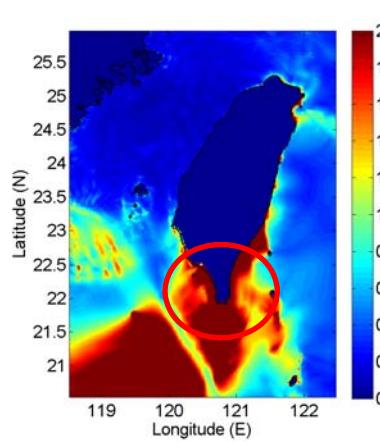
- Sri Lanka Tsunami Scour
  - Photos by Prof. Patrick Lynett



<https://ceprofs.civil.tamu.edu/plynett/Sri%20Lanka%20Tsunami%20Damage/index.html>

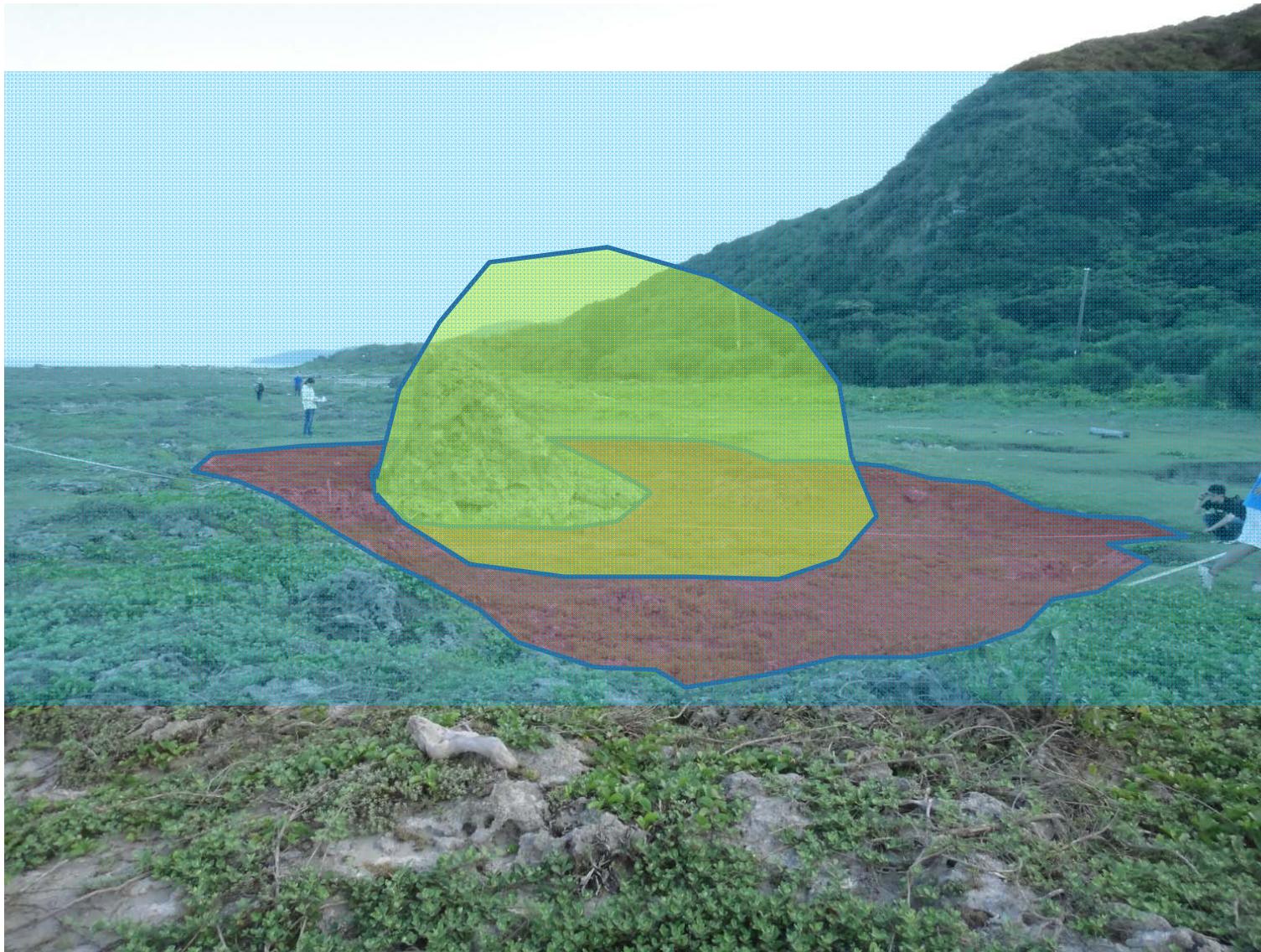
# Motivation

## Tsunami Boulders were found in Southern Taiwan



## Motivation-2

One of them presents a huge scour hole



Similar scour holes were found around  
the neighboring boulders



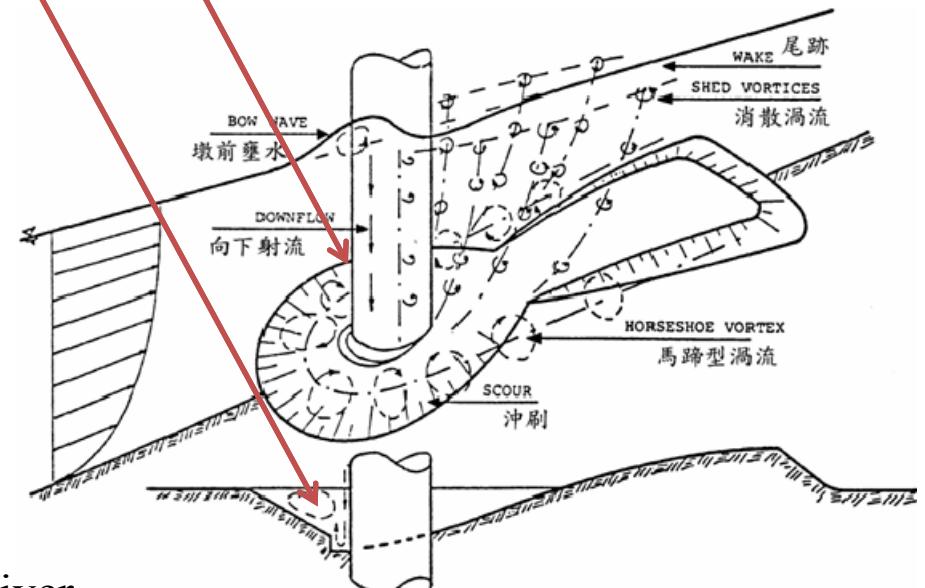
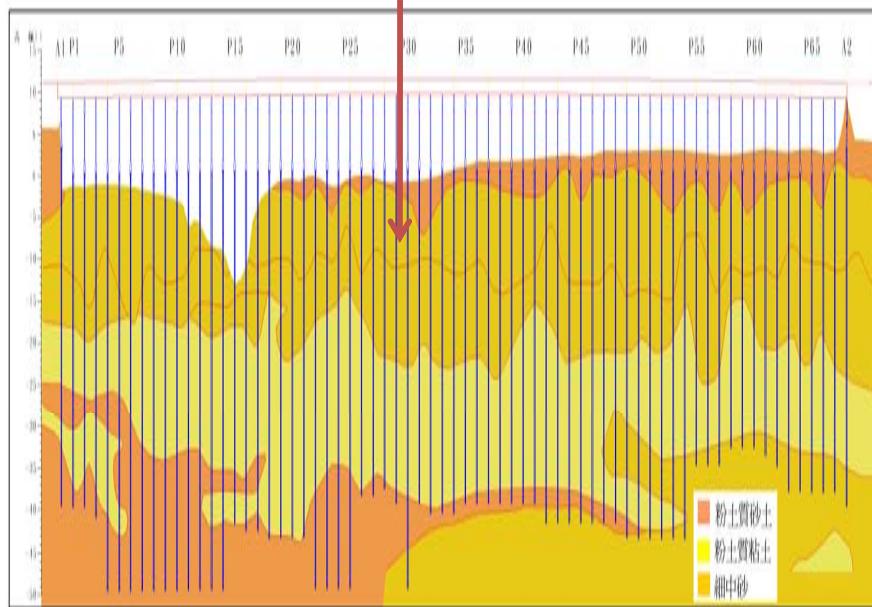
# Flood-Structure interaction has been widely studied in the bridge scouring problem

1. Downward scouring during the ordinary days.
2. Plus, sever local scour during the typhoon event.



# Features of Local Scour in Severe Floods

- The free-surface effect cannot be ignored.
- The 3D effect of the flow has to be taken into account.
- Fast-developed scouring riverbed.  
(Movable bed)
- Stratified bed material



Field survey on the bed material at Gaoping river.

We need a **3D hydrodynamic model**  
for simulating tsunami bore

### 3D NS-VOF Model

This model solves NS equations directly. VOF  
method is adopted to construct the water  
surface. LES turbulence is included.

# Feature of boulder transportation

1. Because both Reynolds number and Froude number are involved, only 1:1 scale can be used. In other words, only numerical model is feasible.
2. Challenges:
  1. Breaking wave
  2. Turbulence
  3. Moving Solid
  4. Scouring
  5. Large scale tsunami modeling
3. Each one is a big topic in numerical modeling

## Breaking wave modeling

We adopted the Splash3D numerical model to solve for the breaking wave problems (Wu, 2004; Liu et al., 2005). This model solves 3-dimensional incompressible flow with Navier-Stokes equations. The free-surface is tracked by Volume-of-Fluid (VOF) method. The domain is discretized by finite volume method (FVM). The turbulent effect is closed by large eddy simulation (LES) with Smagorinsky model.

Incompressible continuity equation:

$$\nabla \cdot \mathbf{u} = 0$$

Navier-Stokes Equation

$$\frac{\partial(\mathbf{u})}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = -\frac{1}{\rho} \nabla P + \frac{1}{\rho} \nabla \cdot \tilde{\tau} + \mathbf{g} + \mathbf{F}_0$$

# Volume of Fluid (VOF) method

The fluid density is presented in fluid fraction, and the transport equation is used to describe the fluid movement.

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}) = \frac{\partial \rho_m}{\partial t} + \mathbf{u} \frac{\partial \rho_m}{\partial x} + \mathbf{v} \frac{\partial \rho_m}{\partial y} + \mathbf{w} \frac{\partial \rho_m}{\partial z} = 0$$

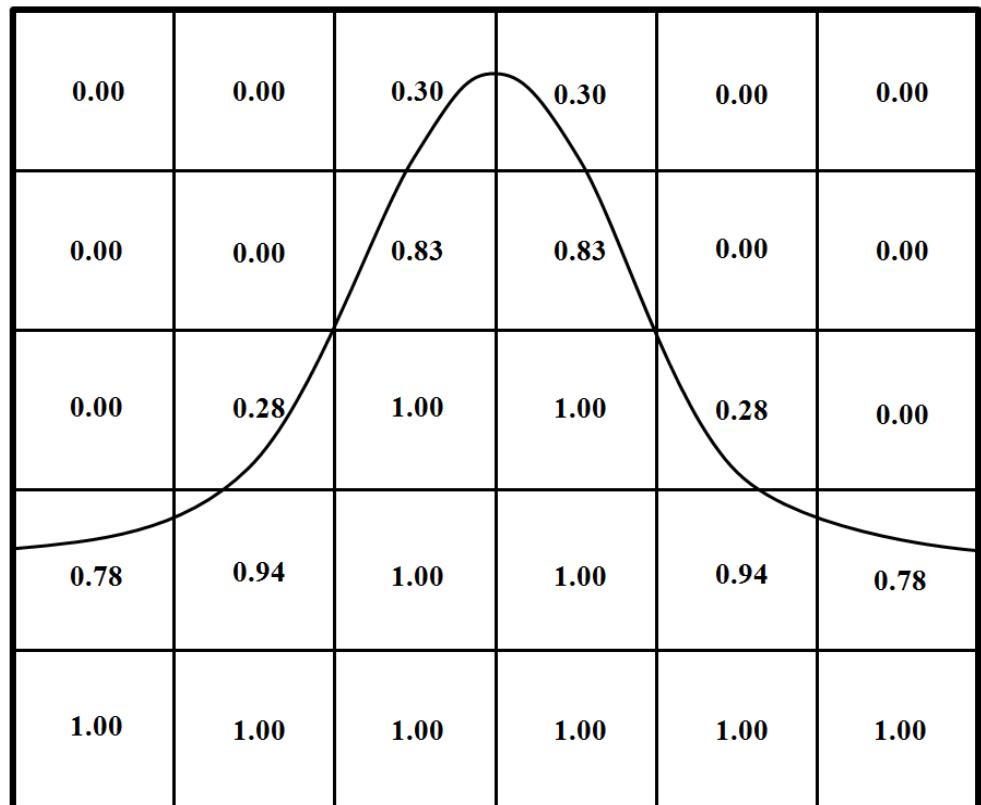
$$\rho = \sum_m f_m \rho_m^0$$

$$\frac{\partial f_m}{\partial t} + \nabla \cdot (\mathbf{u}_i f_m) = 0$$

Piecewise linear interface calculation (PLIC)

$$\vec{N} \cdot \vec{x}_p - C_p = 0$$

$$F(C_p) = V_{tr}(C_p) - f_m * \forall \approx 0$$



## Partial-Cell treatment

$$\nabla_{eff} = (1 - f_{solid}) \nabla = \theta \nabla$$

$$\partial \frac{(\theta f_m)}{\partial t} + \nabla \cdot (\theta f_m V) = 0$$

$$\theta \frac{\partial (V)}{\partial t} + \nabla \cdot (\theta V V) = -\frac{\theta}{\rho} \nabla p + \frac{\theta}{\rho} \nabla \cdot \tilde{\tau} + \theta g + \theta F_0$$

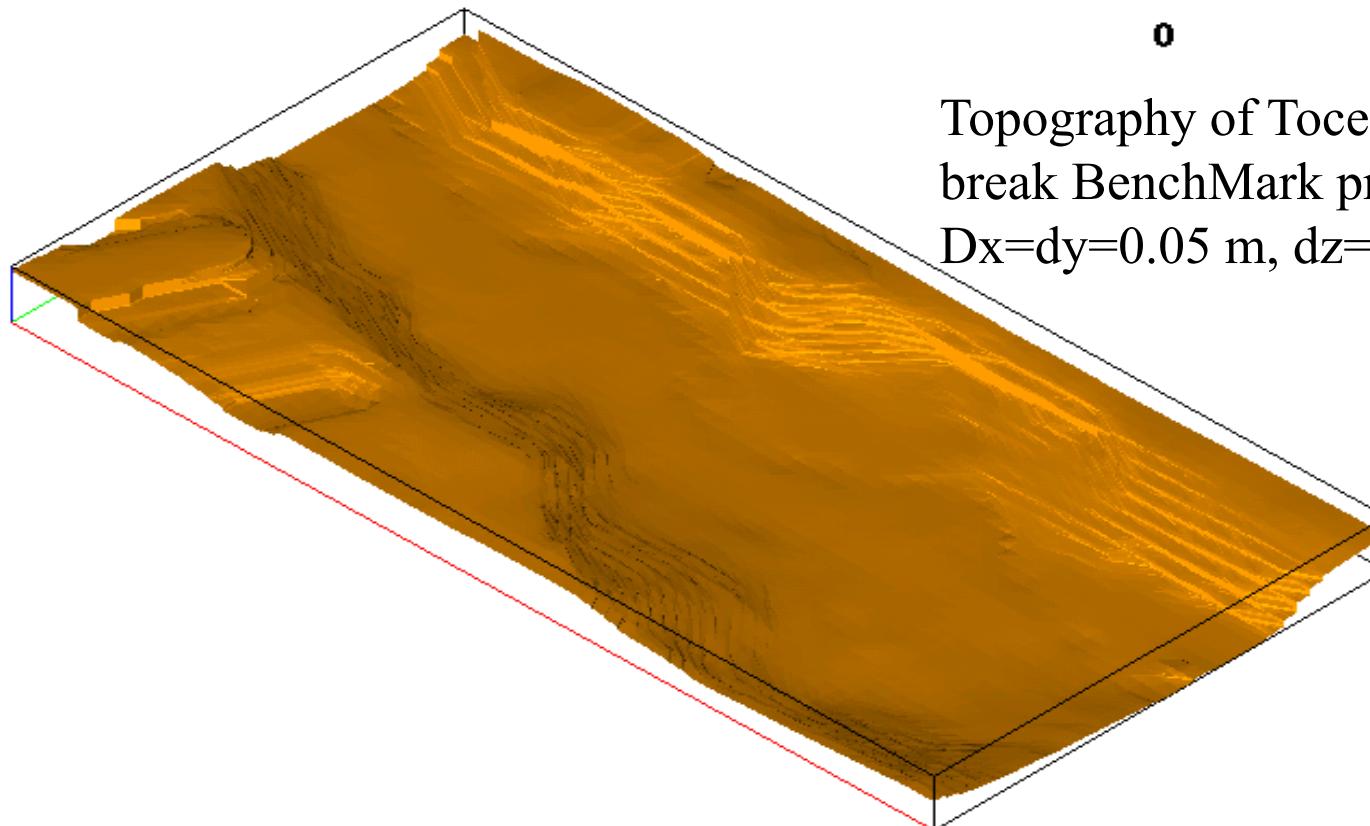
If a cell contains partial volume of solid material, the flow solver has to deal with it. Cell faces are defined either to be entirely closed, or not. Cell faces are “closed” only if at least one of the two immediately neighboring cells is entirely occupied by solid material. If the cell faces are “closed”, the face velocity of the cell is set to zero, and the face pressure is no longer calculated in the pressure solution. On the other hand, if any face between two cells, containing at least a partial cell volume of fluid, is “open”, the code solves the velocities and pressure gradients.

DEM topography module and COMCOT boundary coupling module

## DEM topography module

The real topography can be easily constructed in the Splash3D by using PCT.

Example of DEM topography module



Topography of Toce River Valley Dam-break BenchMark problem.  
 $Dx=Dy=0.05\text{ m}$ ,  $Dz=0.01\text{ m}$ .

# LES (Large Eddy Simulation) Filtering

A low-pass filtering operation is performed so that the resulting filtered velocity can be adequately resolved on a relatively coarse grid.

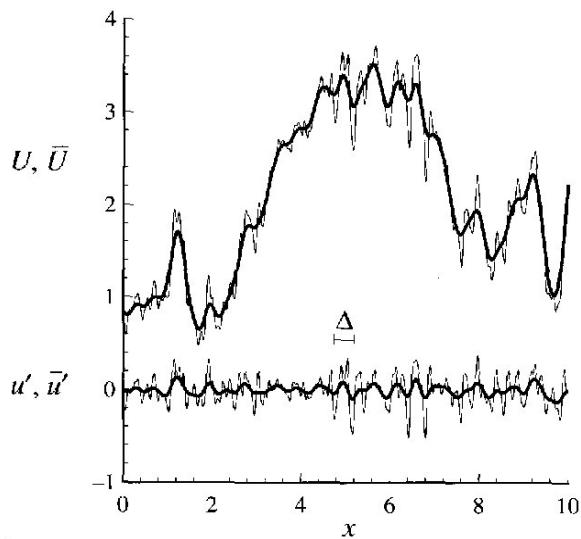


Fig. 13.2. Upper curves: a sample of the velocity field  $U(x)$  and the corresponding filtered field  $\bar{U}(x)$  (bold line), using the Gaussian filter with  $\Delta \approx 0.35$ . Lower curves: the residual field  $u'(x)$  and the filtered residual field  $\bar{u}'(x)$  (bold line).

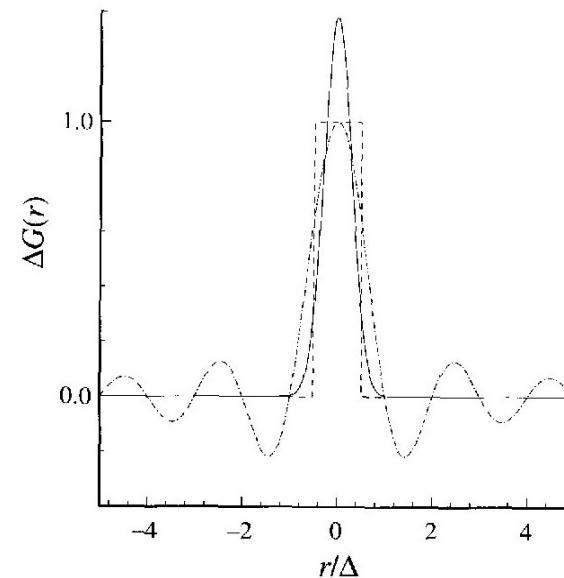


Fig. 13.1. Filters  $G(r)$ : box filter, dashed line; Gaussian filter, solid line; sharp spectral filter, dot dashed line.

$\Delta$  : the filter width

$\eta$  : the radius

# Filtered Conservation Equations

- Continuity equation:

$$\overline{\left( \frac{\partial U_i}{\partial x_i} \right)} = \frac{\partial \bar{U}_i}{\partial x_i} = 0$$

$$\frac{\partial u'_i}{\partial x_i} = \frac{\partial}{\partial x_i} (U_i - \bar{U}_i) = 0$$

- Conservation of Momentum:

$$k_r \equiv \frac{1}{2} \tau_{ii}^R$$

$$\tau_{ij}^r \equiv \tau_{ij}^R - \frac{2}{3} k_r \delta_{ij}$$

the anisotropic residual-stress tensor is:

$$\tau_{ij}^r \equiv \tau_{ij}^R - \frac{2}{3} k_r \delta_{ij}$$

$$\bar{p} \equiv \bar{P} + \frac{2}{3} k_r$$

$$\frac{\partial \bar{U}_j}{\partial t} + \frac{\partial \bar{U}_i U_j}{\partial x_i} = \nu \frac{\partial^2 \bar{U}_j}{\partial x_i \partial x_i} - \frac{1}{\rho} \frac{\partial \bar{P}}{\partial x_j}$$

$$\because \bar{U}_i \bar{U}_j \neq \bar{U}_i U_j$$

$$\text{Let } \tau_{ij}^R \equiv \bar{U}_i \bar{U}_j - \bar{U}_i U_j$$

$$\frac{D \bar{U}_j}{Dt} = \nu \frac{\partial^2 \bar{U}_j}{\partial x_i \partial x_i} - \frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_j} - \frac{\partial \tau_{ij}^r}{\partial x_i}$$

$$\text{where } \frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \bar{\mathbf{U}} \cdot \nabla$$

# Smagorinsky Model

$$\tau_{ij}^r = -\nu_t \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) = -2\nu_t \bar{S}_{ij}$$

$$\nu_t = \ell_s^2 \bar{\mathbf{S}} = (C_s \Delta)^2 \bar{\mathbf{S}}$$

$\ell_s$  : Smagorinsky length scale

$C_s$  : Smagorinsky coefficient

$\Delta$  : filter width

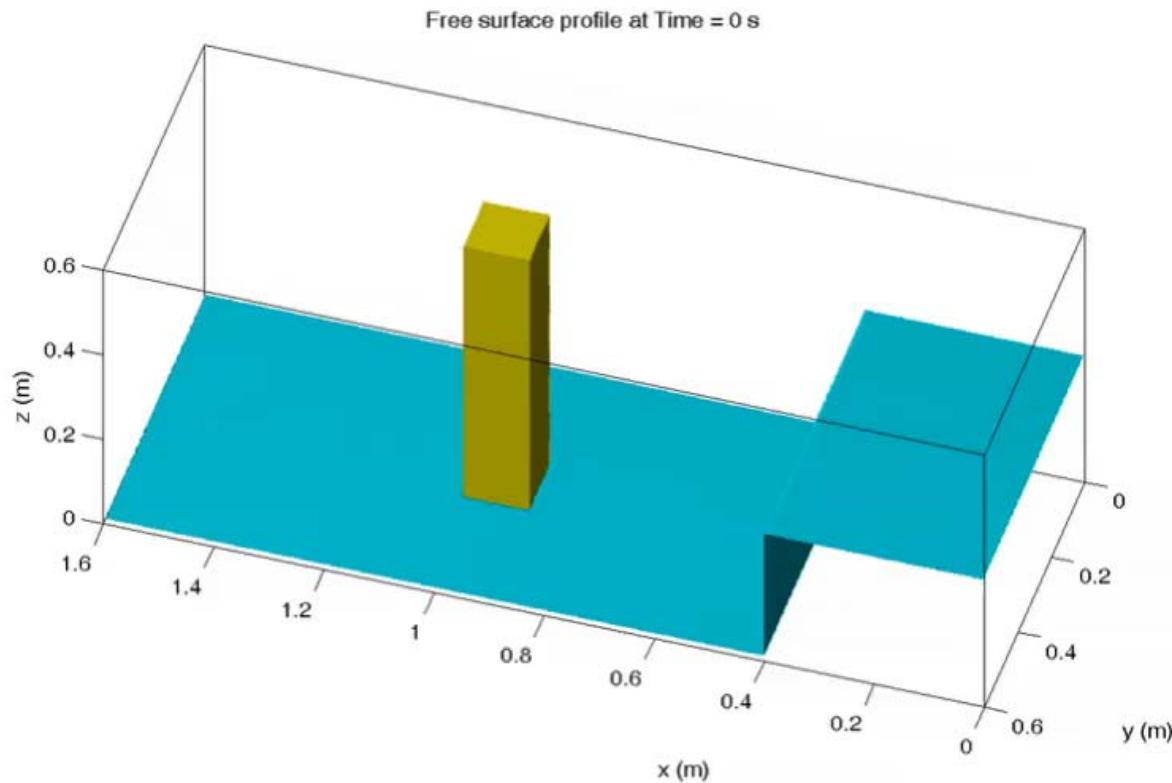
$$\bar{\mathbf{S}} \equiv \left( 2 \bar{S}_{ij} \bar{S}_{ij} \right)^{1/2} : \text{the characteristic filtered rate of strain}$$

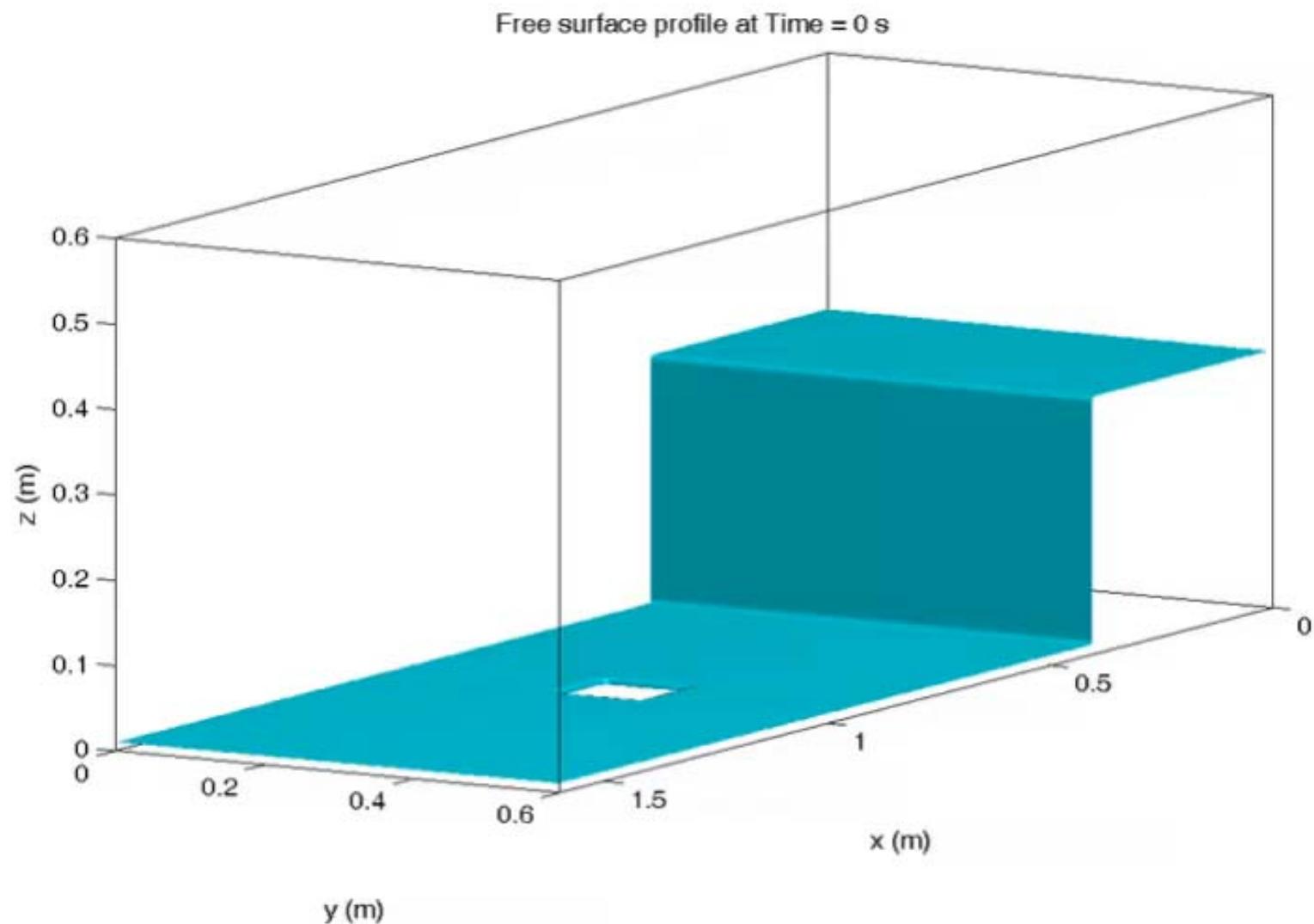
$$\Delta = (\Delta x_1 \times \Delta x_2 \times \Delta x_3)^{1/3}$$

## 淚望大海「無處去」

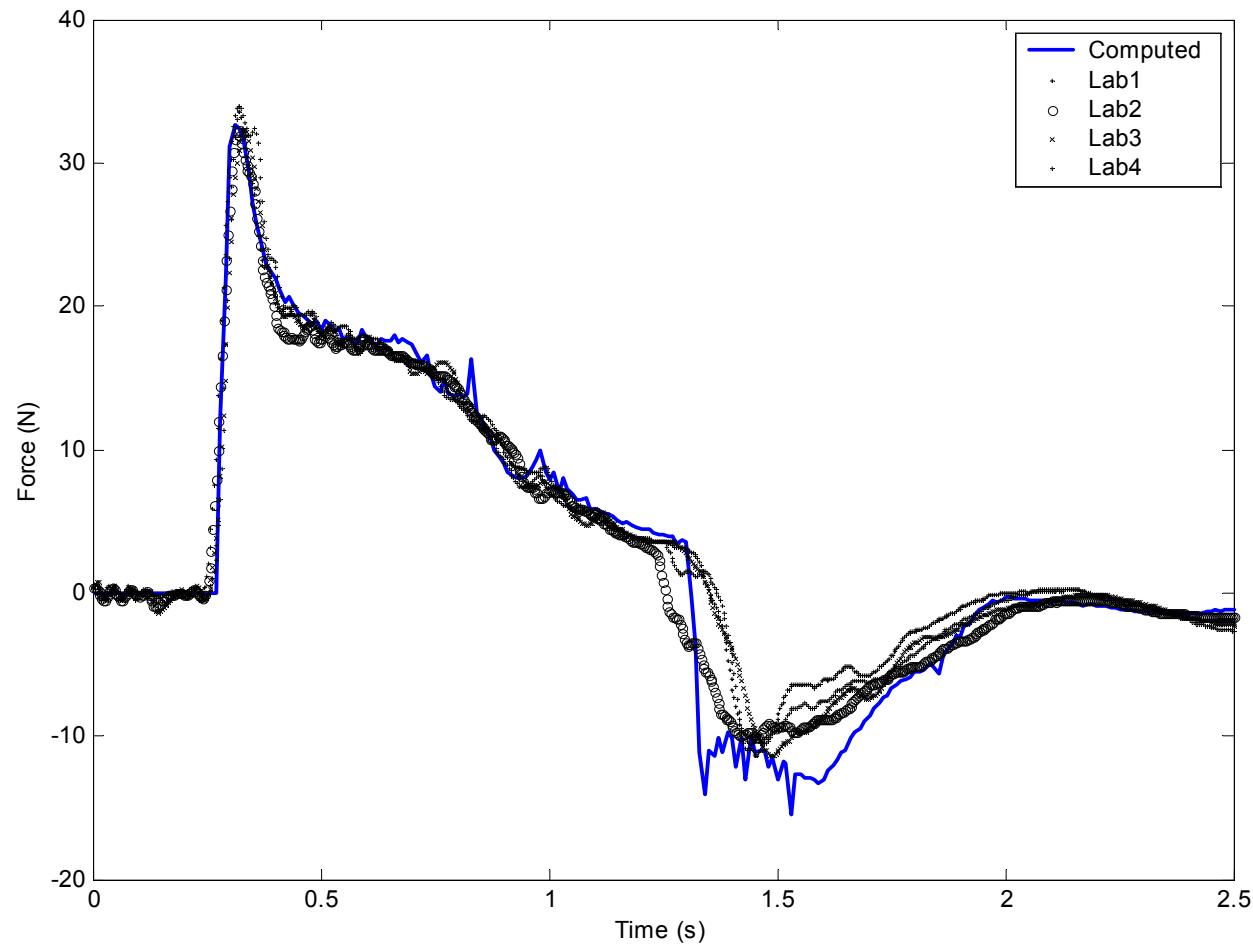
葛西先生說，當天強震後，海嘯警報響起，他趕緊與老婆爬到高處避難，起初第一、二波海嘯襲來時，就與漲潮無異，「只是第三波後越來越強，海水激烈衝撞，有一股無形力量將海水都吸到遠方去，幾乎能看到海底，第四波海嘯累積能量後，衝過來打向岸邊發出『砰』的聲音，威力就像一顆炸彈。」

他們親眼目睹岸邊房子瞬間被「炸」毀，2、300人罹難

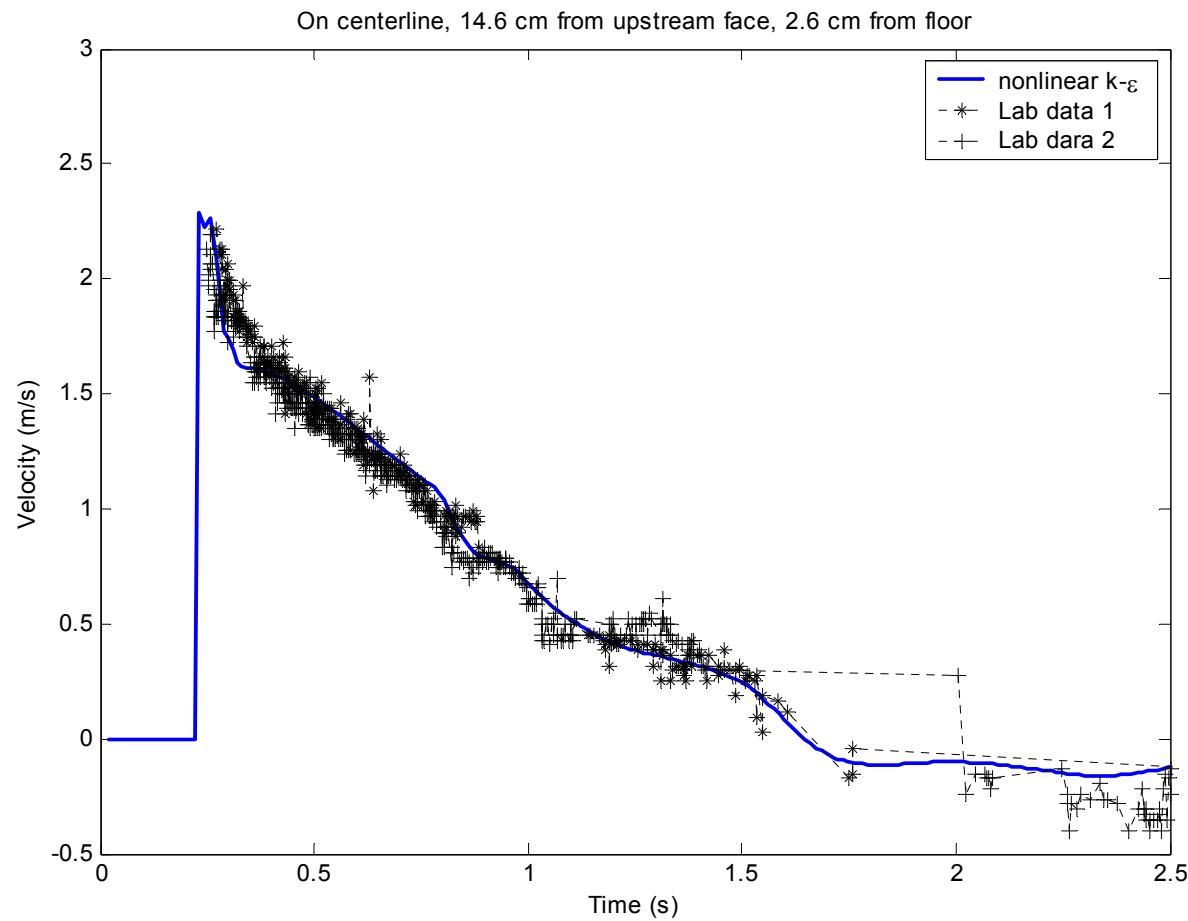




## Total force acting on the square cylinder

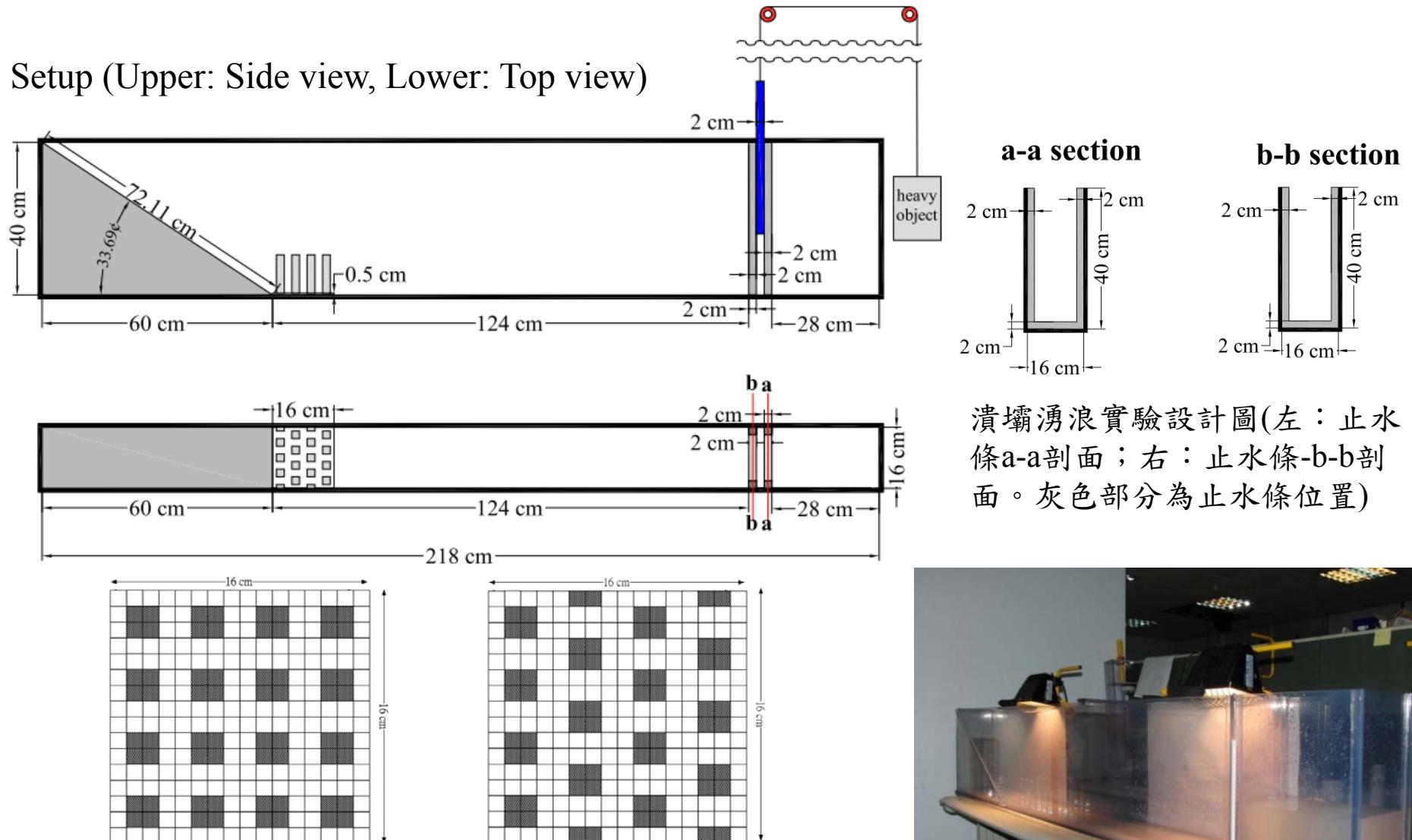


## Velocity comparisons



# Validation on the breaking free-surface: The Dam-Break Benchmark Problem

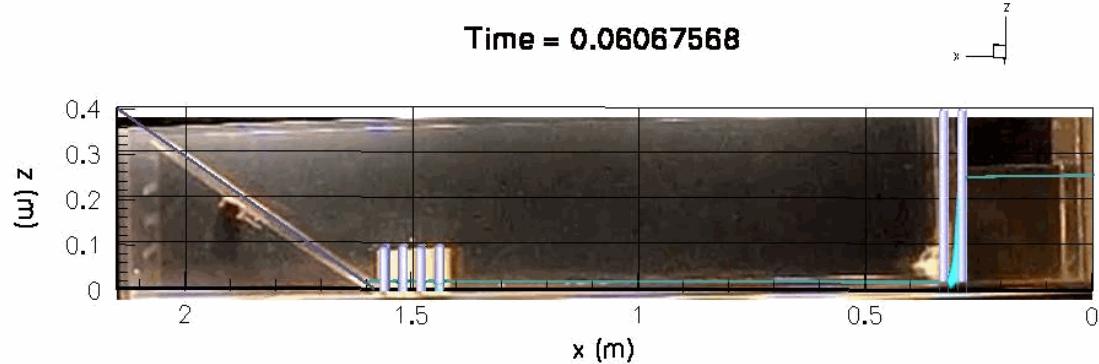
Setup (Upper: Side view, Lower: Top view)



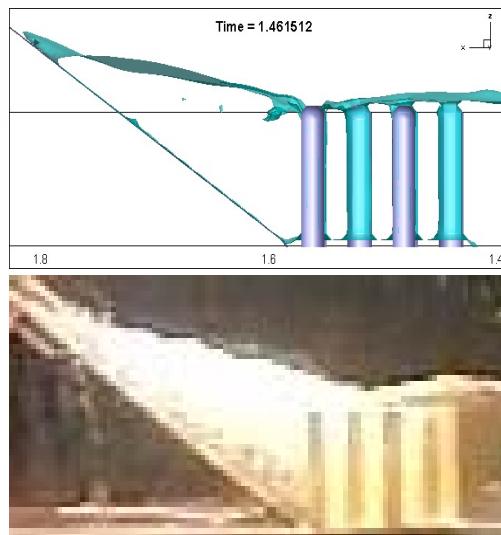
正交排列（左）與交錯排列（右）之方柱結構物分布。灰色部分為方柱位置，網格間距為1 cm



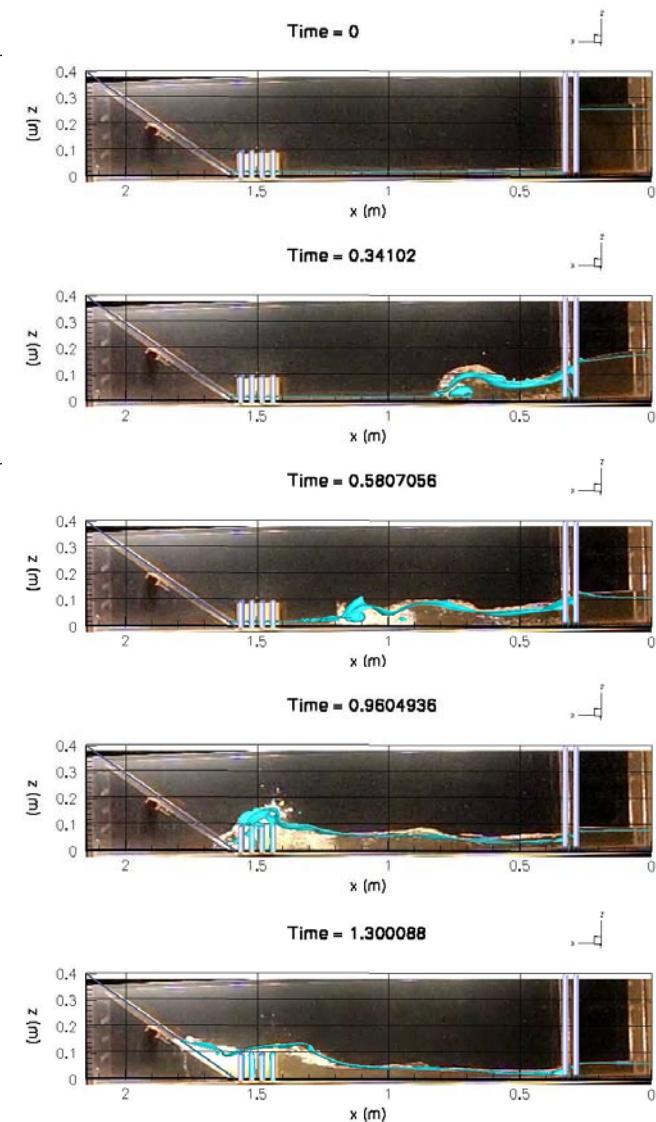
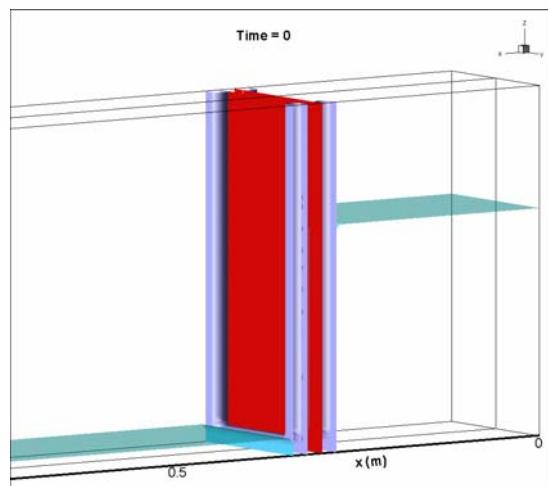
## - 複雜基樁陣列之碎波表面驗證（第一年）：



撞擊至複雜墩座亦可  
精確模擬。



其中擋水閘門之開啟即  
是運用流固耦合之技術



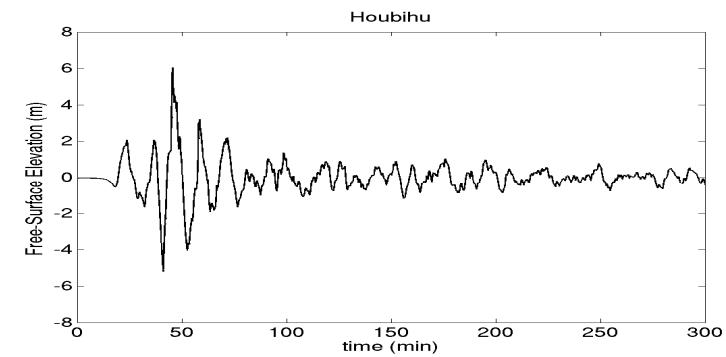
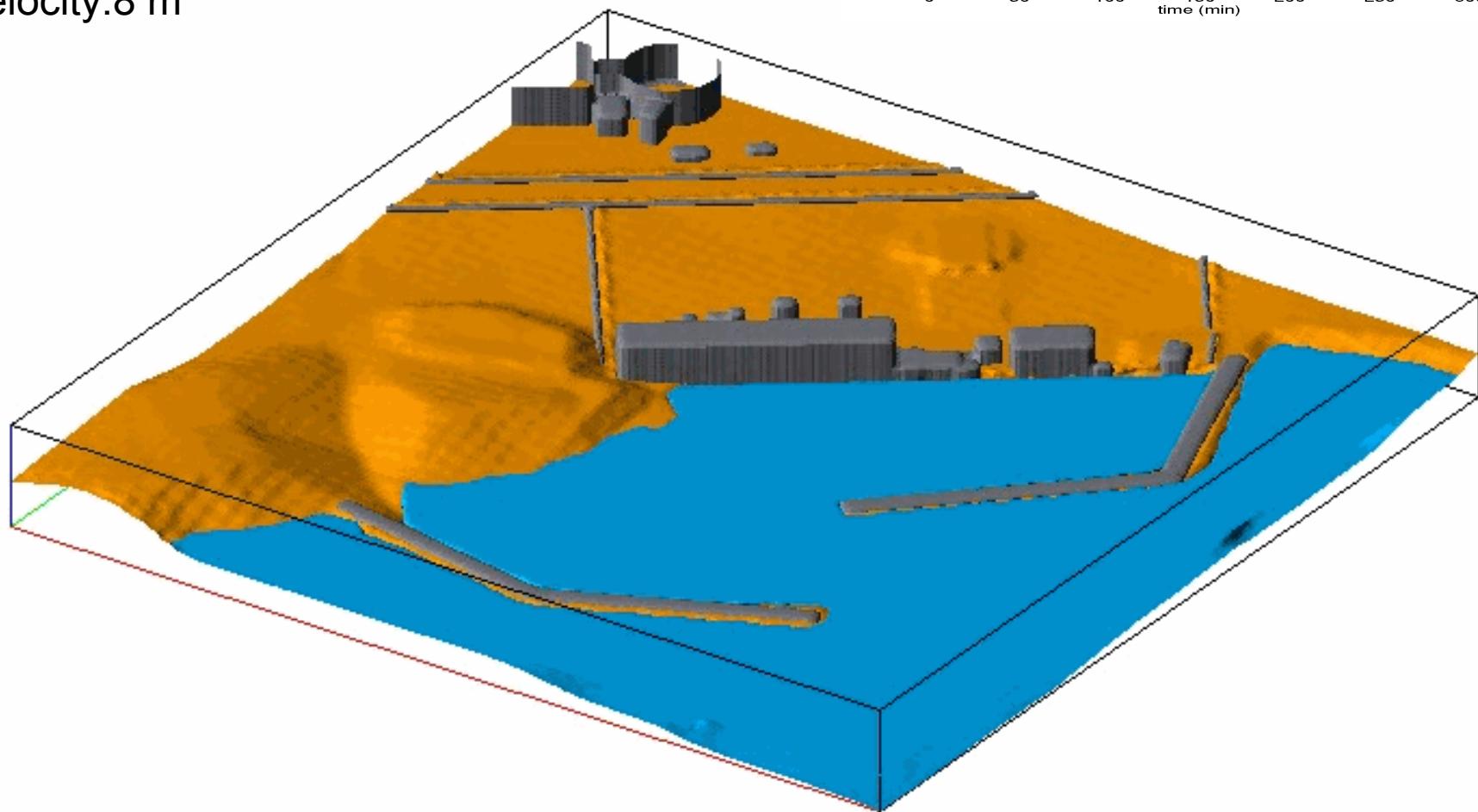
(與實驗比對顯示，所開發之模式在困難度極高之碎波模擬方面亦有優秀之表現)<sup>17</sup>

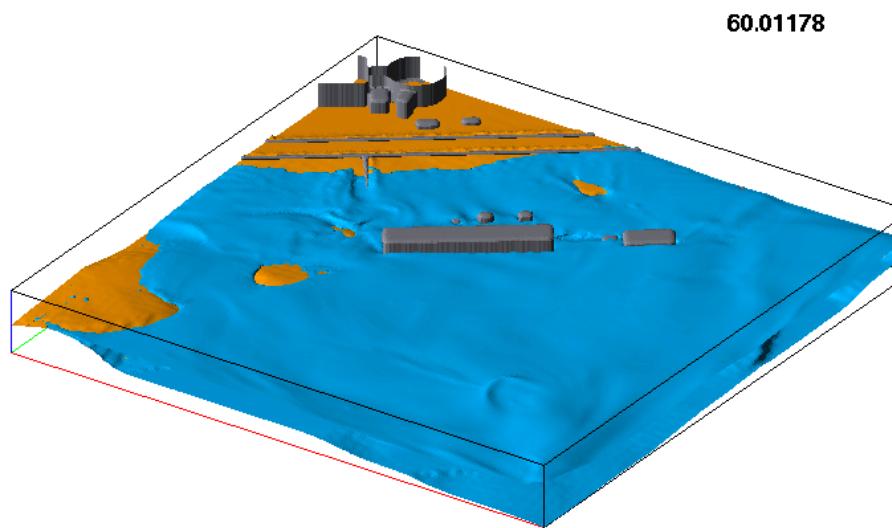
# Maanshan nuclear power plant



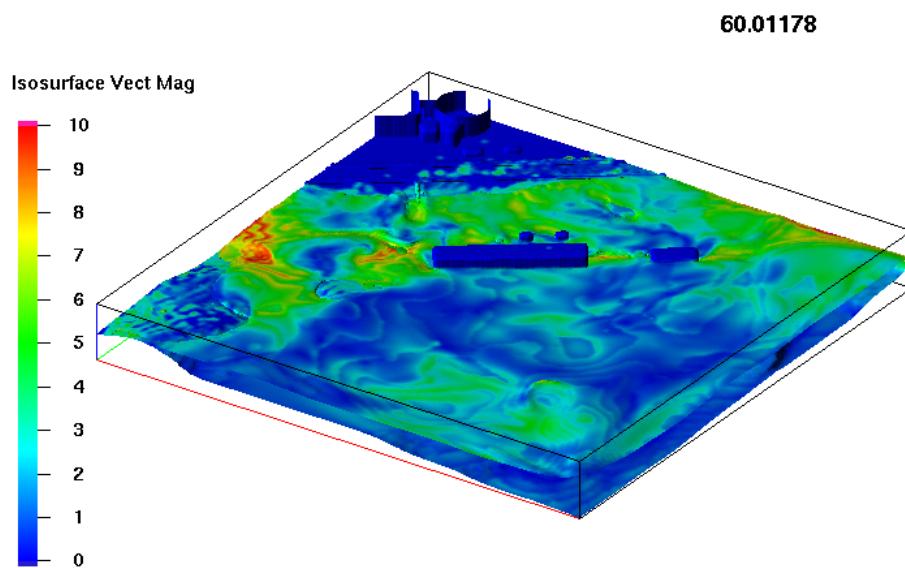
# Simulation Result

$dx=dy=2.5\text{ m}$ ,  $dz=1\text{ m}$   
Wave height: 6 m  
Velocity: 8 m

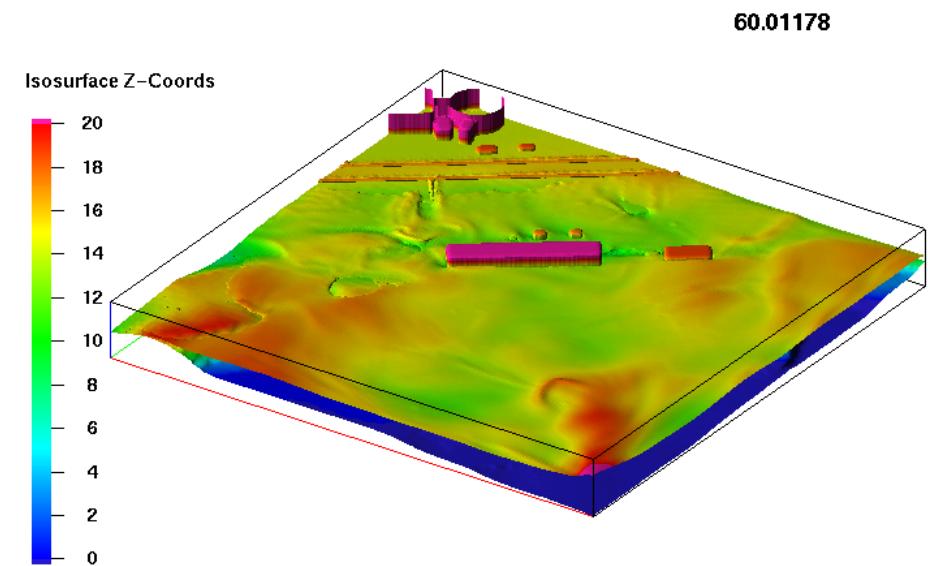




Velocity distribution

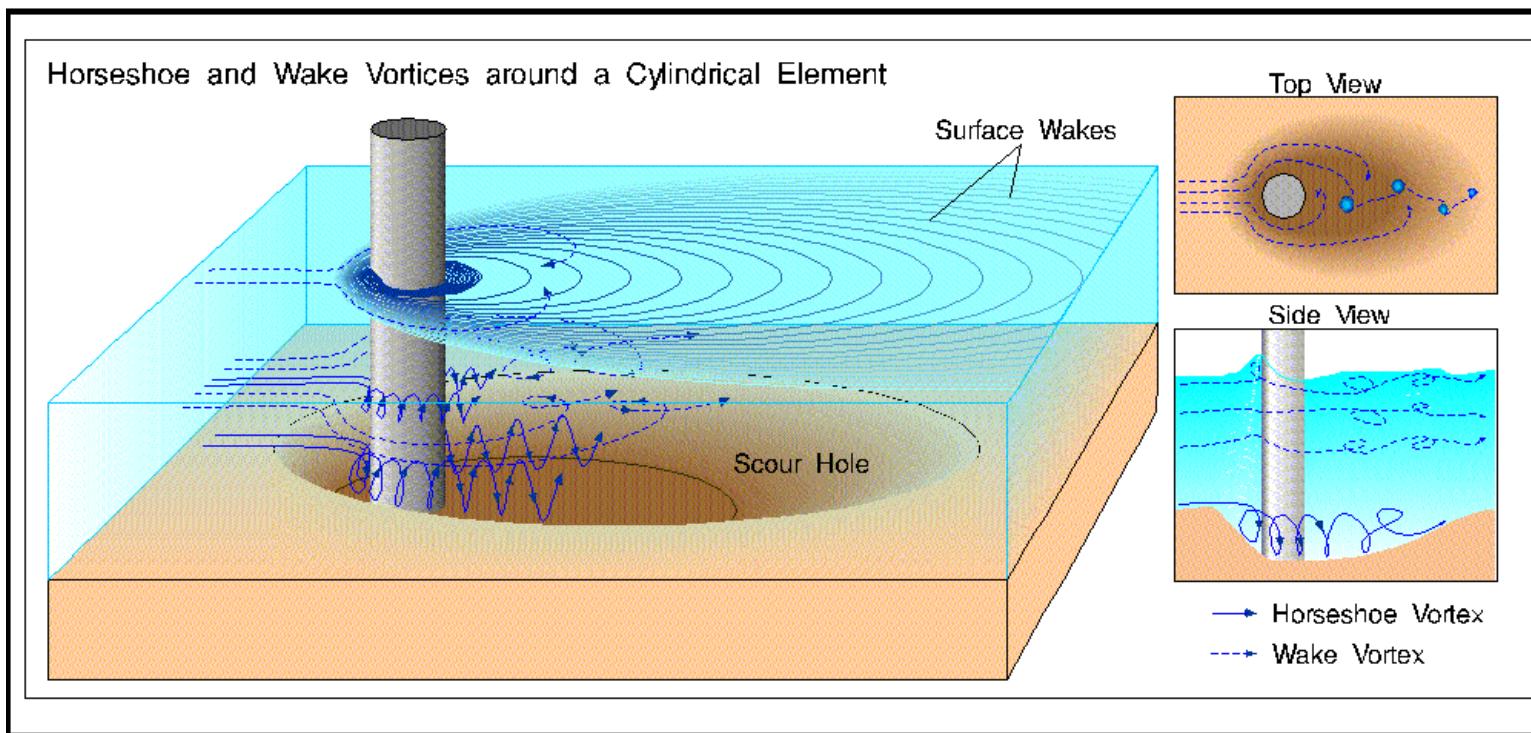


Surface elevation



# How do people solve scour problems?

- 1. Conceptual description: No exact numbers on the scour depth.



(Evaluation of potential bridge scour in Missouri, USGS)

[http://mo.water.usgs.gov/current\\_studies/Scour/images/LocalScour.gif](http://mo.water.usgs.gov/current_studies/Scour/images/LocalScour.gif)

## 2. Empirical or Semi-empirical Formulae

- Lacey's formula (1930)

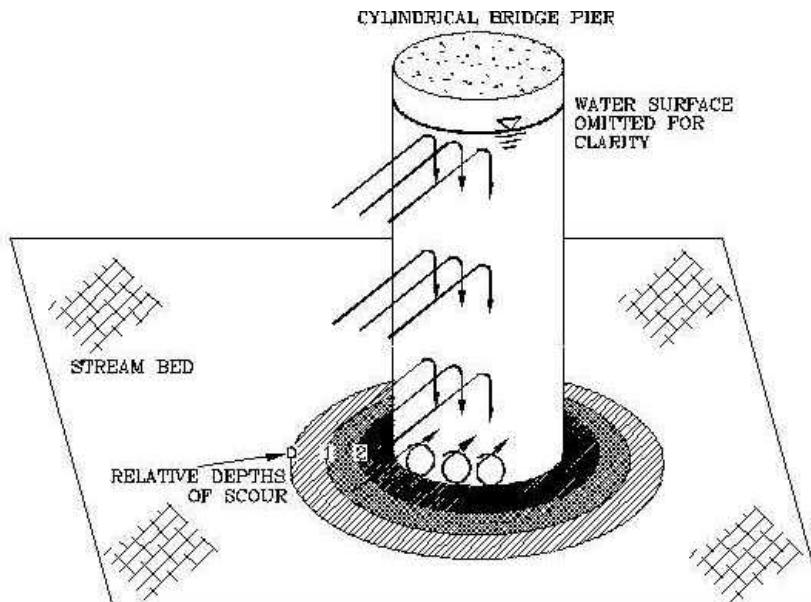
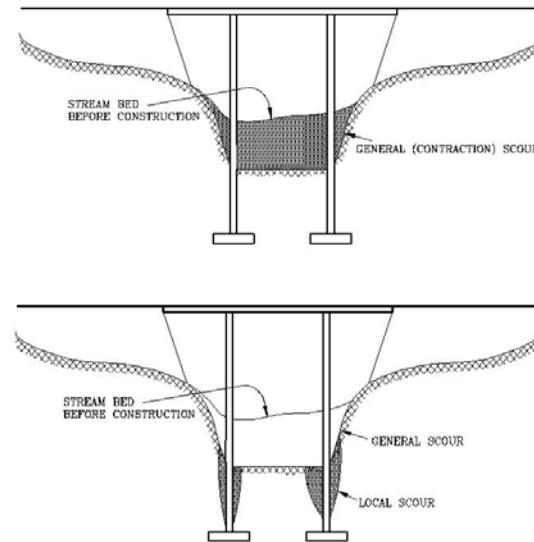


Figure 9-21. Local Scour Due to Eddies



### Clear Water Contraction Scour Equation

Compute the average depth in the contracted cross section including contraction scour with Equation 9-18. ◆

$$y_2 = 0.2138 \left( \frac{Q_2^2}{D_{30}^{2/3} W_2^2} \right)^{3/7}$$

[http://onlinemanuals.txdot.gov/txdotmanuals/hyd/bridge\\_scour.htm](http://onlinemanuals.txdot.gov/txdotmanuals/hyd/bridge_scour.htm)

# No Surprise that Big Differences on the Scour Depth

Sometimes the differences can reach one order of magnitude.

**Table 3.** Scour depths estimated using equations of different investigators.

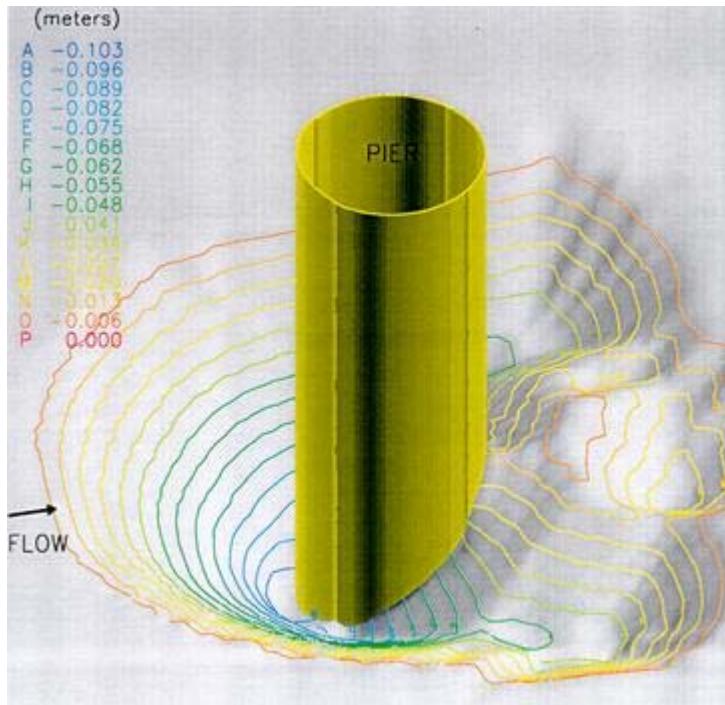
Investigator	$d_s$ (m)
Melville (1992)	4.00
Lim (1997)	4.03
Froehlich (1989)	3.88
Richardson <i>et al</i> (2001)	8.90
Oliveto & Hager (2002)	9.90
Dey & Barbhuiya (2004b)	5.90

## **Local scour at abutments: A review**

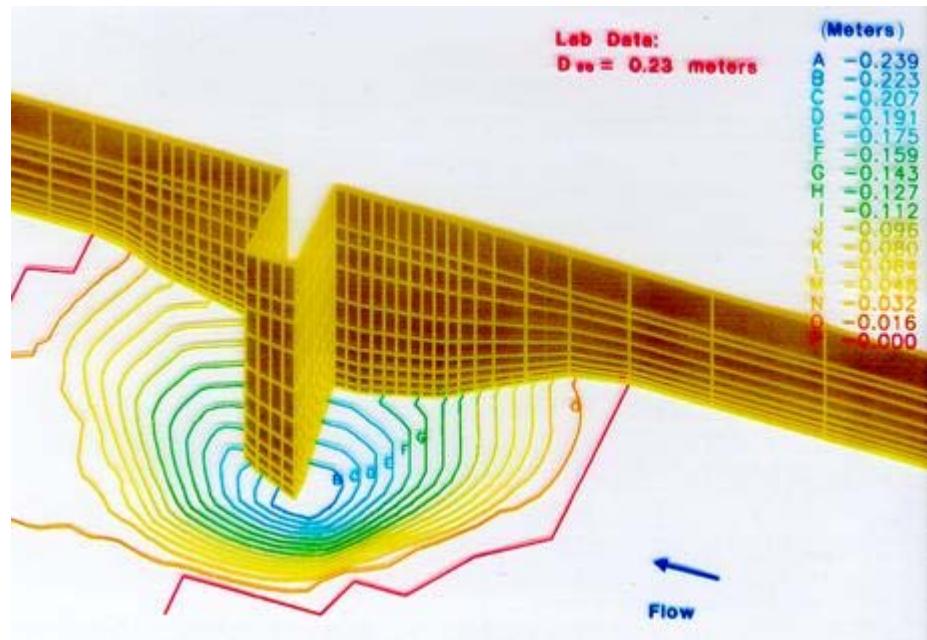
ABDUL KARIM BARBHUIYA<sup>1</sup> and SUBHASISH DEY<sup>2\*</sup>

*Sādhanā* Vol. 29, Part 5, October 2004, pp. 449–476. © Printed in Ind<sup>ia</sup>

### 3. The Modern Scour Models: CCHE3D model (State of the art, so far.)



Local Scour around a Bridge Pier  
Simulated by CCHE3D Model



Local Scour around a Spur-Dyke Simulated by  
CCHE3D Model

[http://www.ncche.olemiss.edu/content/research/sedimentgroup/simulation\\_of\\_local\\_scour.htm](http://www.ncche.olemiss.edu/content/research/sedimentgroup/simulation_of_local_scour.htm)

Flat free-surface assumption, one-layer sediment

# HOWEVER, it requires tons of empirical coefficients

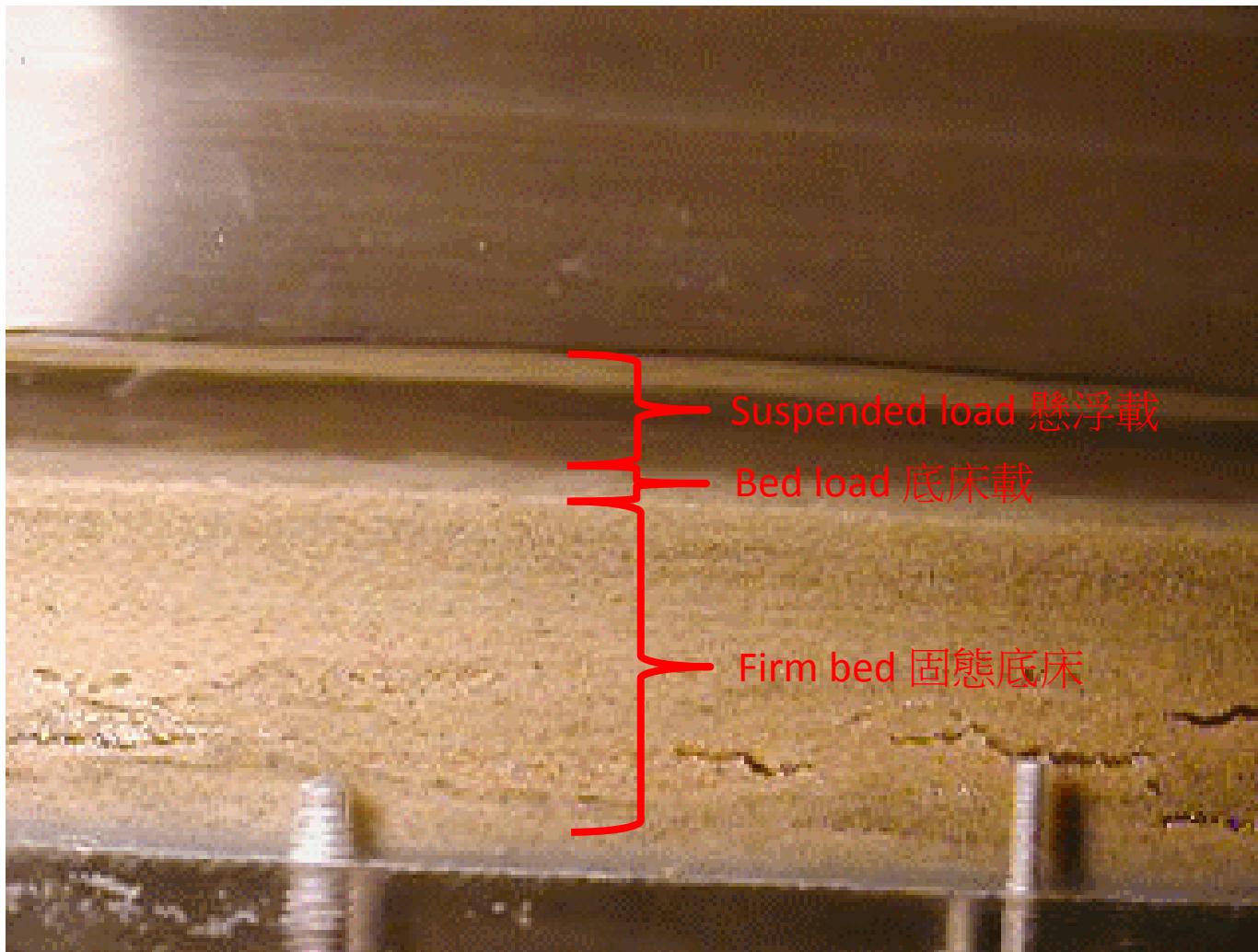
## List of symbols

$B$	channel or flume width;	$T$	time to equilibrium scour depth;
$b_d$	width of cylindrical pier experiencing the same drag as that on abutment;	$T_R$	dimensionless time, $t(\Delta gd)^{0.5}/LR$ ;
$b_s$	width of analogous pier;	$T^*$	time when $d_t = 0.632d_s$ ;
$C_D$	drag coefficient of sediment particles;	$t$	time;
$D$	pier diameter;	$U$	average approaching flow velocity;
$d, d_{50}$	median diameter of sediment particles;	$U_a$	$0.8U_{cn}$ ;
$d_{16}$	16% finer particle diameter;	$U_c$	critical velocity for sediment particles;
$d_{50a}$	$d_{max}/1.8$ ;	$U_{cn}$	critical velocity for armour particle size $d_{50a}$ ;
$d_{84}$	84% finer particle diameter;	$u, v, w$	time-averaged velocity components in $(x, y, z)$ or $(\theta, r, z)$ ;
$\hat{d}_l$	ratio of scour depth at abutment to scour depth in equivalent long contraction;	$\hat{u}$	$u/U$ ;
$d_{max}$	maximum particle size of a nonuniform sediment;	$u_*$	shear velocity of approaching flow;
$d_s$	equilibrium scour depth in uniform sediment;	$u_{*c}$	critical shear velocity for sediment particles;
$d_{st}$	scour depth at time $t$ ;	$u_{*cn}$	critical shear velocity for armour particle size $d_{50a}$ ;
$F_d$	$U/(\Delta gd)^{0.5}$ , densimetric Froude number;	$\hat{v}$	$v/U$ ;
$F_r$	$U/(gh)^{0.5}$ , approaching flow Froude number;	$\hat{w}$	$w/U$ ;
$F_{rc}$	$U_c/(gh)^{0.5}$ , approaching flow Froude number corresponding to critical velocity;	$w_s$	settling velocity of sediment particles;
$f_l$	Lacey's slit factor, $1.76d^{0.5}$ ;	$X$	$\theta_c^{-0.375} F_d^{0.75} (d/h)^{0.25} [0.9(l/h)^{0.5} + 1]$ ;
$g$	gravitational acceleration;	$\hat{x}$	$x/l$ ;
$h$	approaching flow depth;	$x, y, z$	Cartesian coordinates;
$h^*$	flow depth in floodplain;	$\hat{y}$	$y/l$ ;
$K_{1,2}, k_{1,2}$	coefficients;	$\hat{z}$	$z/l$ ;
$K_d$	particle size factor;	$\alpha$	$1 - l/B$ , opening ratio;
$K_G$	channel geometry factor;	$\Delta$	$s - 1$ ;
$K_{hl}$	flow depth – abutment length factor;	$\phi_s$	side slope angle of scour hole;
$K_I$	flow intensity factor;	$\eta_{1-3}$	coefficients;
$K_s, K_s^*$	abutment shape factor and adjusted abutment shape factor respectively;	$\theta, r, z$	cylindrical polar coordinates;
$K_\theta, K_\theta^*$	abutment alignment factor and adjusted abutment alignment factor respectively;	$\theta_a$	angle of attack;
$K_\sigma$	function depending on $\sigma_g$ ;	$\theta_c$	$u_{*c}^2/(\Delta gd)$ , shield's entrainment function;
$L_R$	reference length $l^{2/3}h^{1/3}$ ;	$\theta_t$	turning angle between bottom streamline and main flow direction,
$l$	transverse length or protrusion length of abutment;		$1.485 F_r^{0.13} (l/h)^{0.06}$ ;
$l^*$	width of floodplain;	$\rho, \rho_s$	mass densities of water and of sediment particles respectively;
$M$	discharge ratio;	$\sigma_g$	geometric standard deviation;
$m$	coefficients depending on bed sediment size;	$\tau_o$	bed shear stress of approaching flow;
$N, N^*$	Manning roughness coefficients for main channel and for floodplains respectively;	$\tau_c$	critical shear stress of sediment particles;
$N_s$	shape number;	$\tau_{cont}$	shear stress due to contraction;
		$\hat{\tau}_{cont}$	$\tau_{cont}/\tau_o$ , bed shear stress due to contraction;
		$\tau_{nose}$	bed shear stress at nose region of abutment;

# Problems of the Scour Models

- Most of the models ignore the free-surface effect.
  - The flat boundary assumption is inappropriate for strong scouring problems.
- Sediment transport model is developed based on the assumptions of uniform or gently changed flow field.
  - Not suitable for the rapid scouring problems.
- Too many parameters to be determined or tuned.
  - It is not feasible for the practical implementation.
- Most of the models consider one fluid with one bed material only.
  - You will never see a nature river behaves like this.

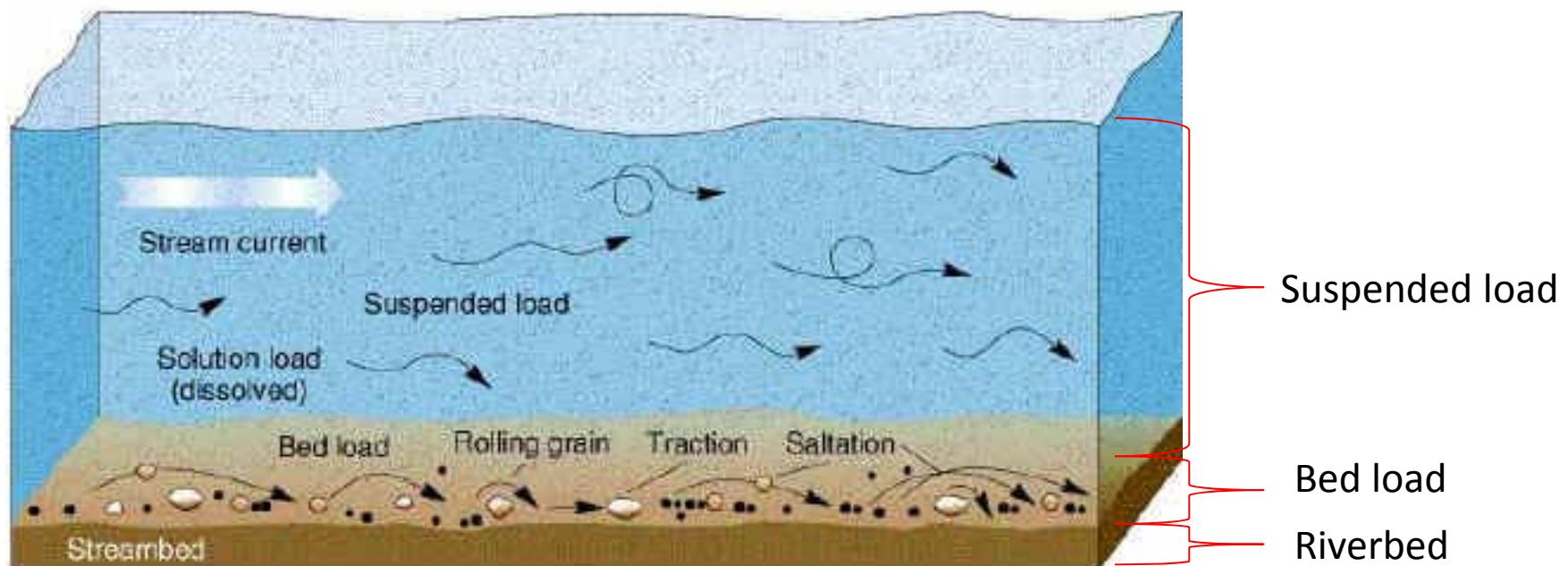
# The real sediment transport



(2002 at Cornell)

# Concept of Sediment Transport

- As shear stress is greater than critical stress, the sediment starts to move.



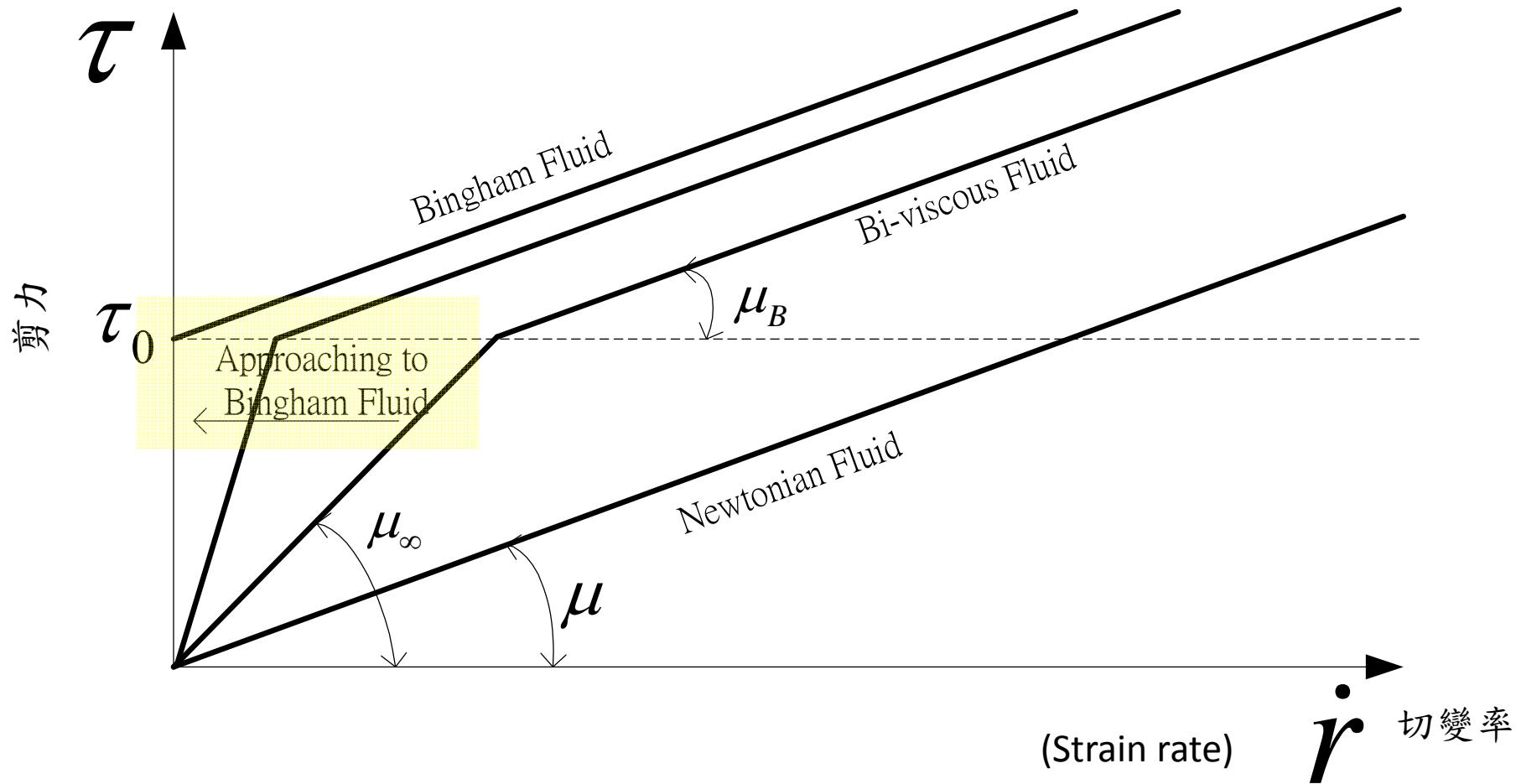
<http://www.medinaswcd.org/streams.htm>

**It sounds like the Bingham fluid, doesn't it?**

# Bingham and Bi-viscous Fluids

Bi-viscous becomes Bingham as Mu\_inf goes infinite

(Shear stress)



# Bingham model

本構關係式 (Constitutive Model)

剪應力 Shear stress

$$\tau = 2\mu(\bar{D})\bar{D}$$

切變率 strain rate

賓漢黏滯係數 Bingham viscosity

降伏應力 Yield stress (Bingham yield)

$$\mu(\bar{D}) = \begin{cases} \mu_B + \frac{\tau_0}{\sqrt{\frac{1}{2}\bar{D}:\bar{D}}} & \text{if } \frac{1}{2}\tau : \tau > \tau_0^2 \quad (\text{液態}) \\ \mu_\infty \text{ and } \bar{D} = 0 & \text{if } \frac{1}{2}\tau : \tau \leq \tau_0^2 \quad (\text{固態}) \end{cases}$$

(拿掉此項就回歸為牛頓流體)

以極大值表示固體行為  
A large number indicating the solid behavior

# Bingham + Navier-Stokes

Governing equations :

Incompressible Navier – Stokes Equation

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \mathbf{u}) = -\frac{1}{\rho} \nabla p + \frac{1}{\rho} \nabla \cdot \mu_{eff} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) + \mathbf{g}$$



$$\mu_{eff} = \sum_{i=1}^m f_m \mu_m$$

# 1. Pressure Gradient Channel Flow (Bird et al. 1983)

## Newtonian Fluid

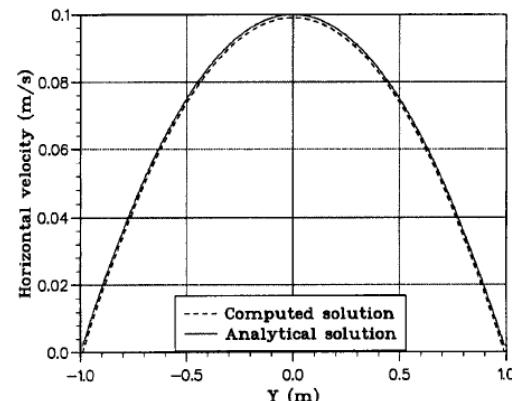
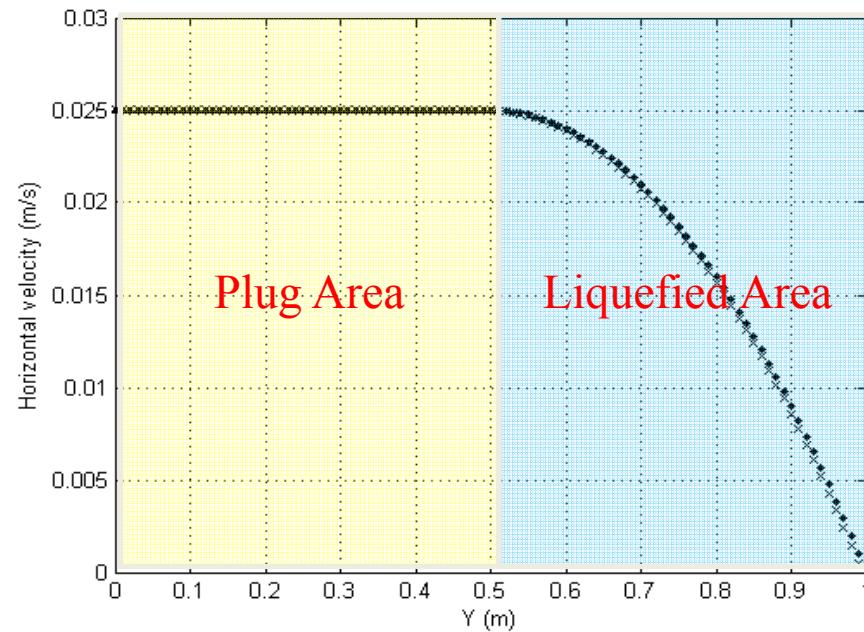


FIG. 2. Comparison between Computed and Analytical Velocity Profiles for Newtonian Fluid

## Analytical Solution of Bingham Fluid in a Channel

$$u(y) = \frac{(P_0 - P_L)B^2}{2\mu_B L} \left[ 1 - \left( \frac{y}{B} \right)^2 \right] - \frac{\tau_0 B}{\mu_B} \left( 1 - \frac{y}{B} \right) \quad y_0 \leq y \leq B$$

$$u(y) = u(y_0) = u_M \quad 0 \leq y \leq y_0$$



$$\mu_B = 5.0 \text{ Pa} \cdot \text{s}$$

$$\tau_0 = 0.5 \text{ Pa}$$

$$\mu_\infty = 1e6 \text{ Pa} \cdot \text{s}$$

## Bingham Fluid

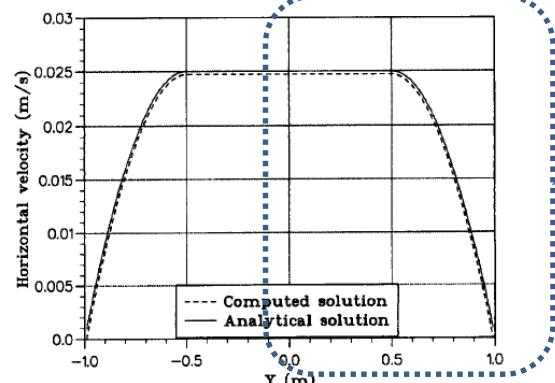


FIG. 3. Comparison between Computed and Analytical Velocity Profiles for Bingham Fluid

## 2. Spreading of Bingham fluid on an inclined plane

Liu and Mei (1989) 推導出斜板上之賓漢流理論解，並與同時進行之實驗結果相符。

### Experiment settings

Length : 332 cm   Width : 7.62 cm   Height : 15.24 cm

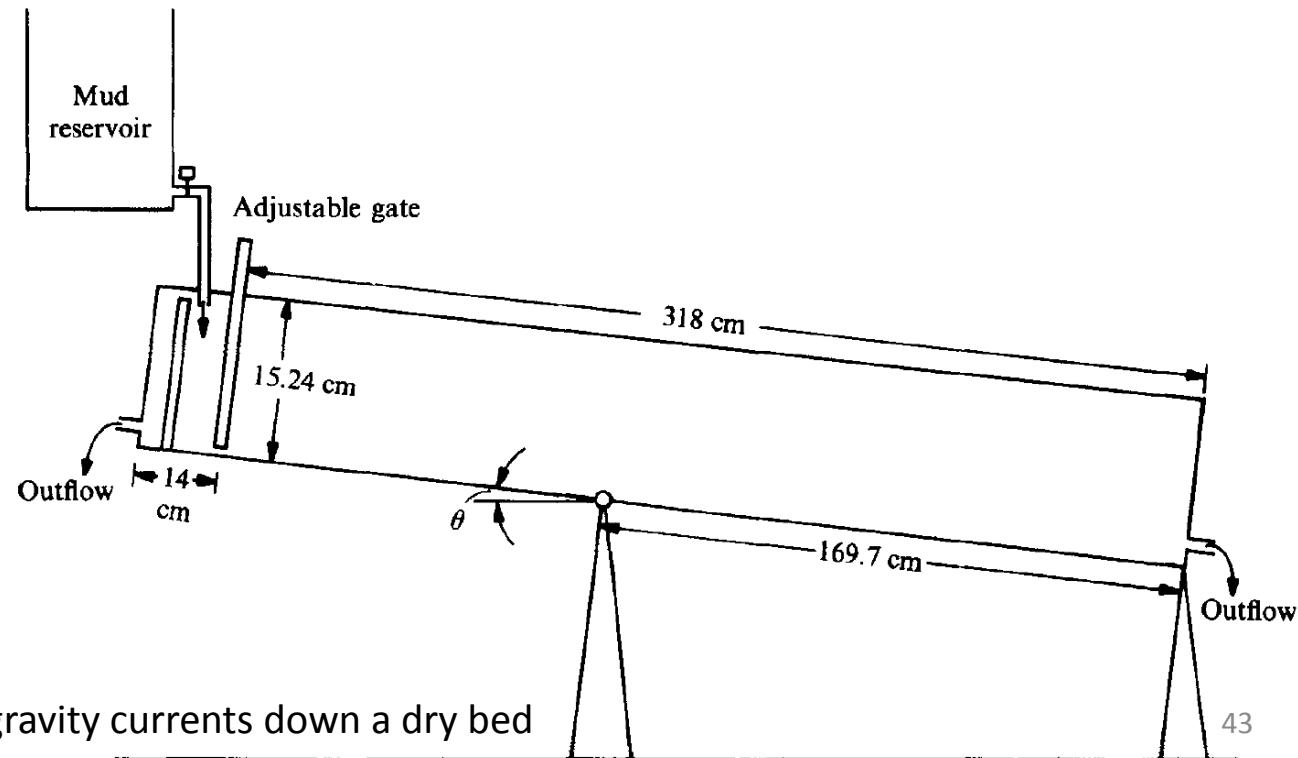
$\theta$ : 1.47°

Material : Kaolinite mixed with tap water

$\rho$ : 1.106 g/cm<sup>3</sup>

$\tau_0$  : 0.875 Pa

$\mu$ : 0.034 Pa · S



# Spreading of Bingham fluid on an inclined plane

## Numeric settings

Domain : 200.0 cm \* 0.05 cm \* 1.0 cm

Cells : 4000 \* 1 \* 20

$\theta: 1.47^\circ$

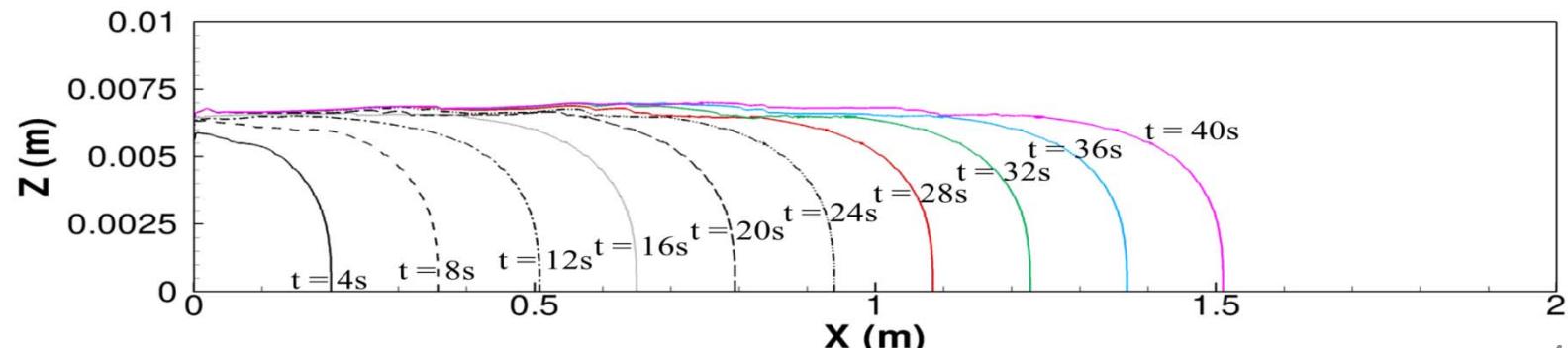
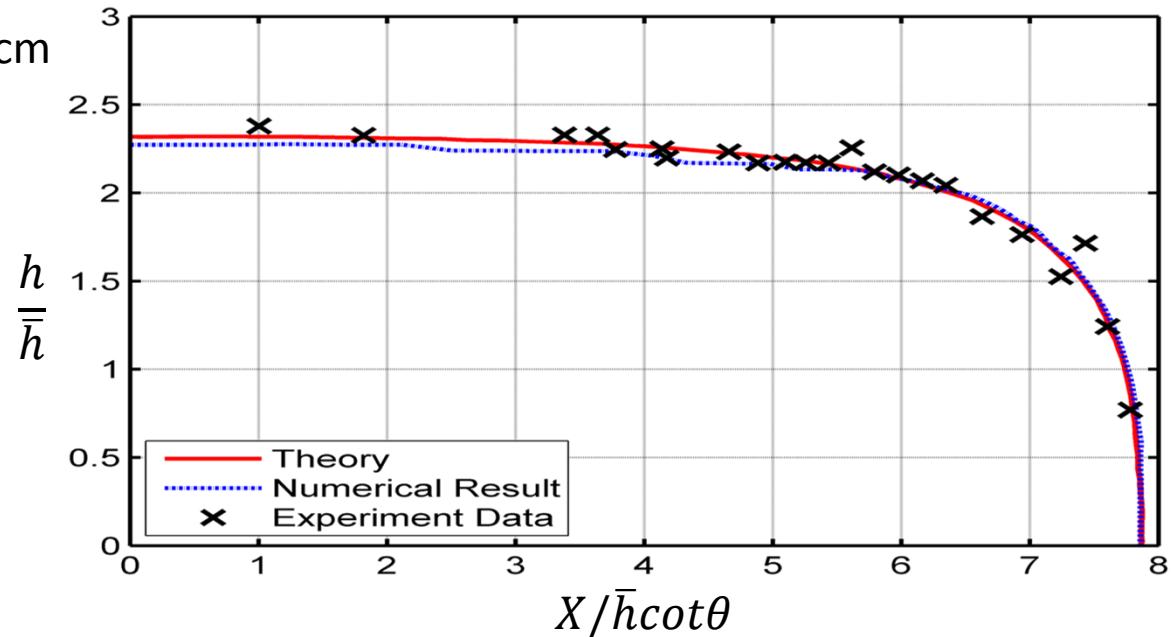
$dx = dy = dz = 0.05 \text{ cm}$

$\rho: 1.106 \text{ g/cm}^3$

$\tau_0: 0.875 \text{ Pa}$

$\mu: 0.034 \text{ Pa} \cdot \text{S}$

$\mu_{inf}: 10^{10} \text{ Pa} \cdot \text{S}$



### 3. Failure of Gypsum Tailings Dam East Texas, 1966

Initial Height of Dam : 11 m

Material : Gypsum Tailings

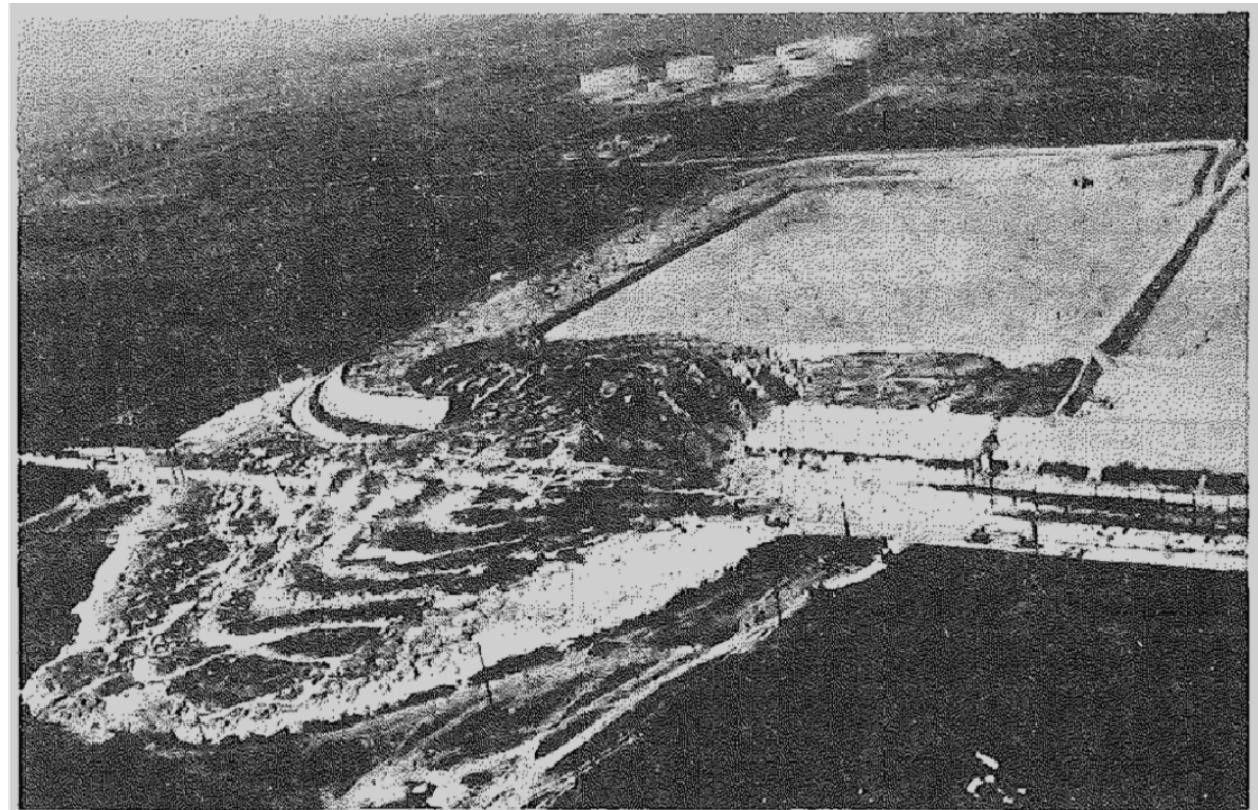
Bed Slope :  $0^\circ$

Properties of Tailings :

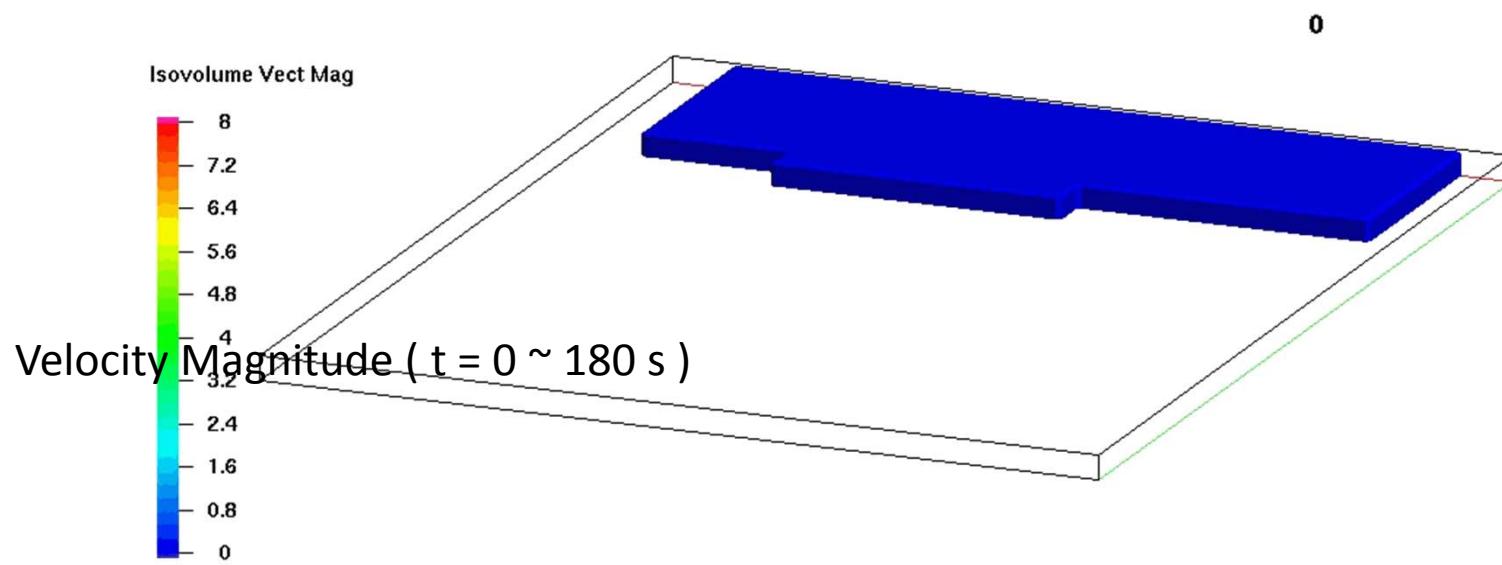
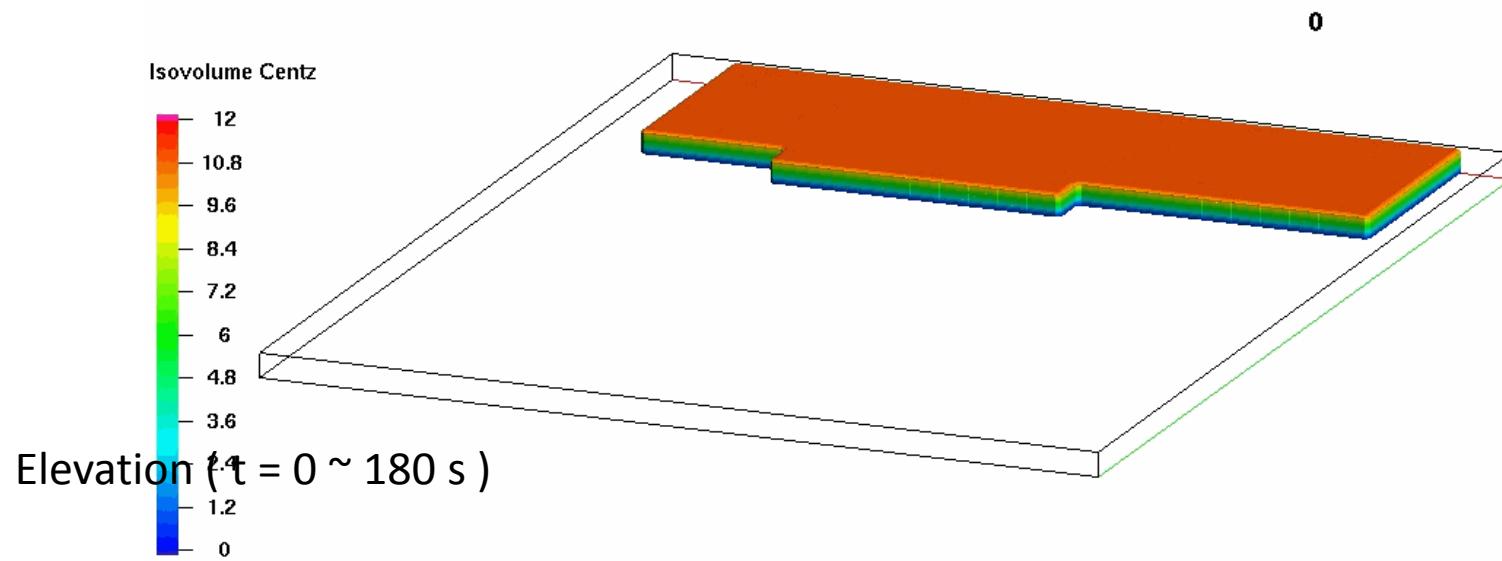
$$\rho = 1400.0 \text{ kg/m}^3$$

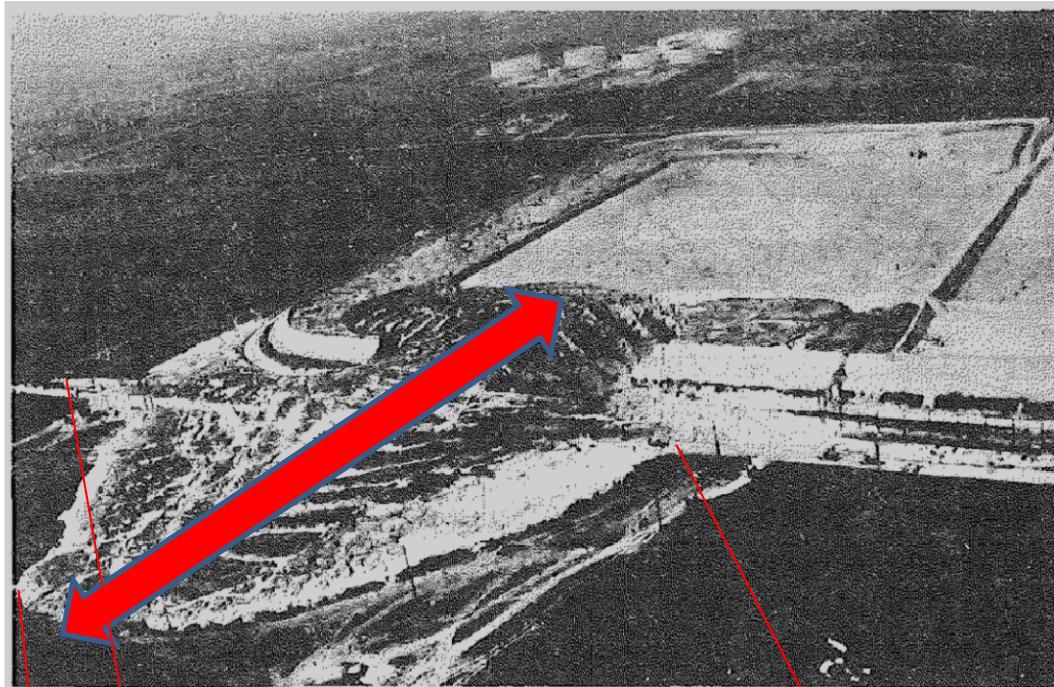
$$\tau_0 = 1000.0 \text{ Pa}$$

$$\mu = 50.0 \text{ Pa} \cdot S$$



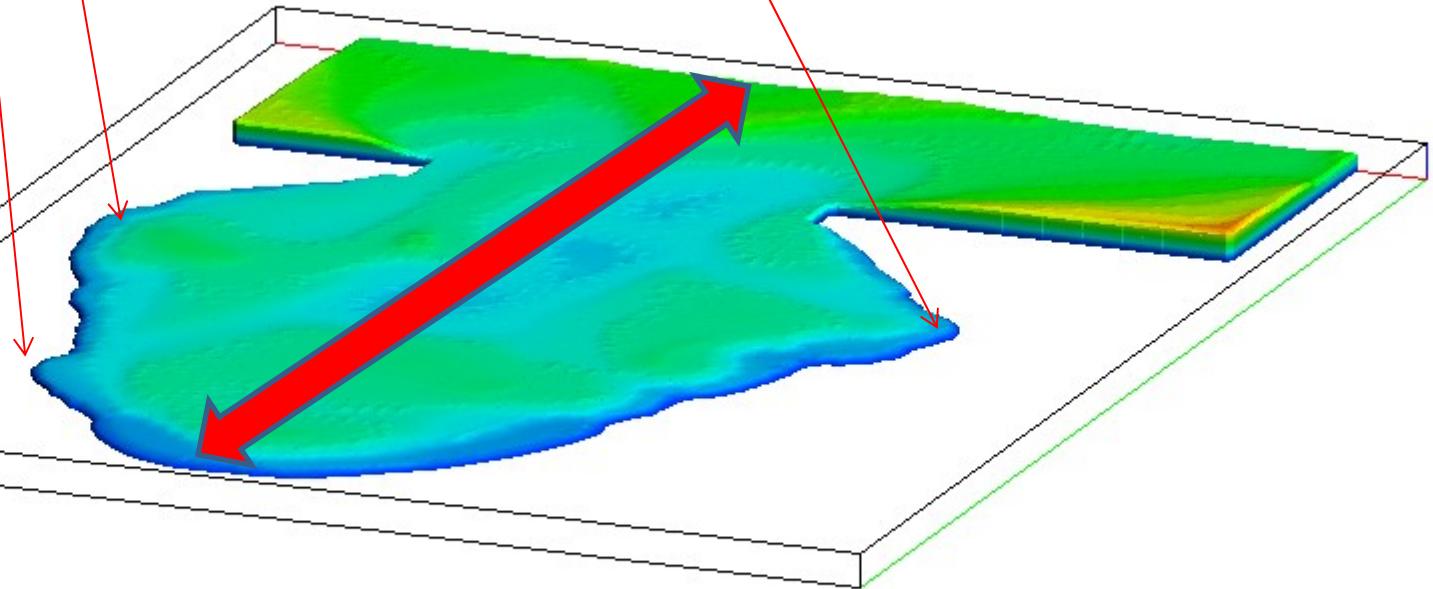
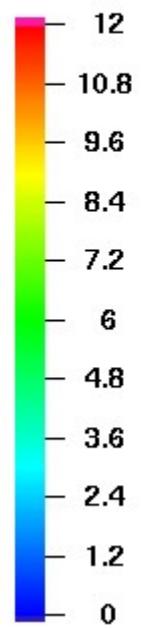
Flow of Liquefied Tailings from Gypsum Tailings Impoundment (1966)





200.20549

Isovolum Centz

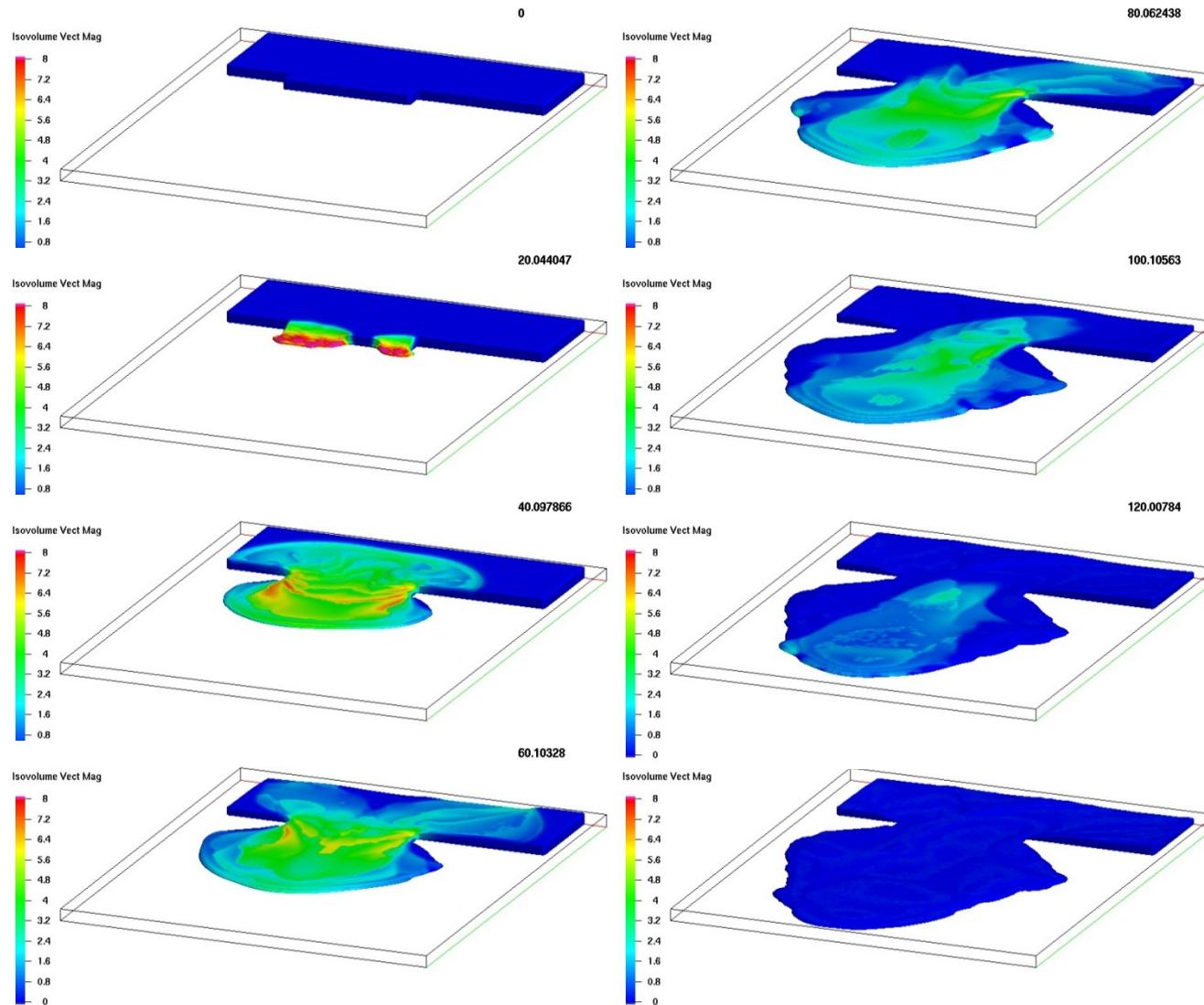


Flow surface after freezing time computed by NS-VOF model

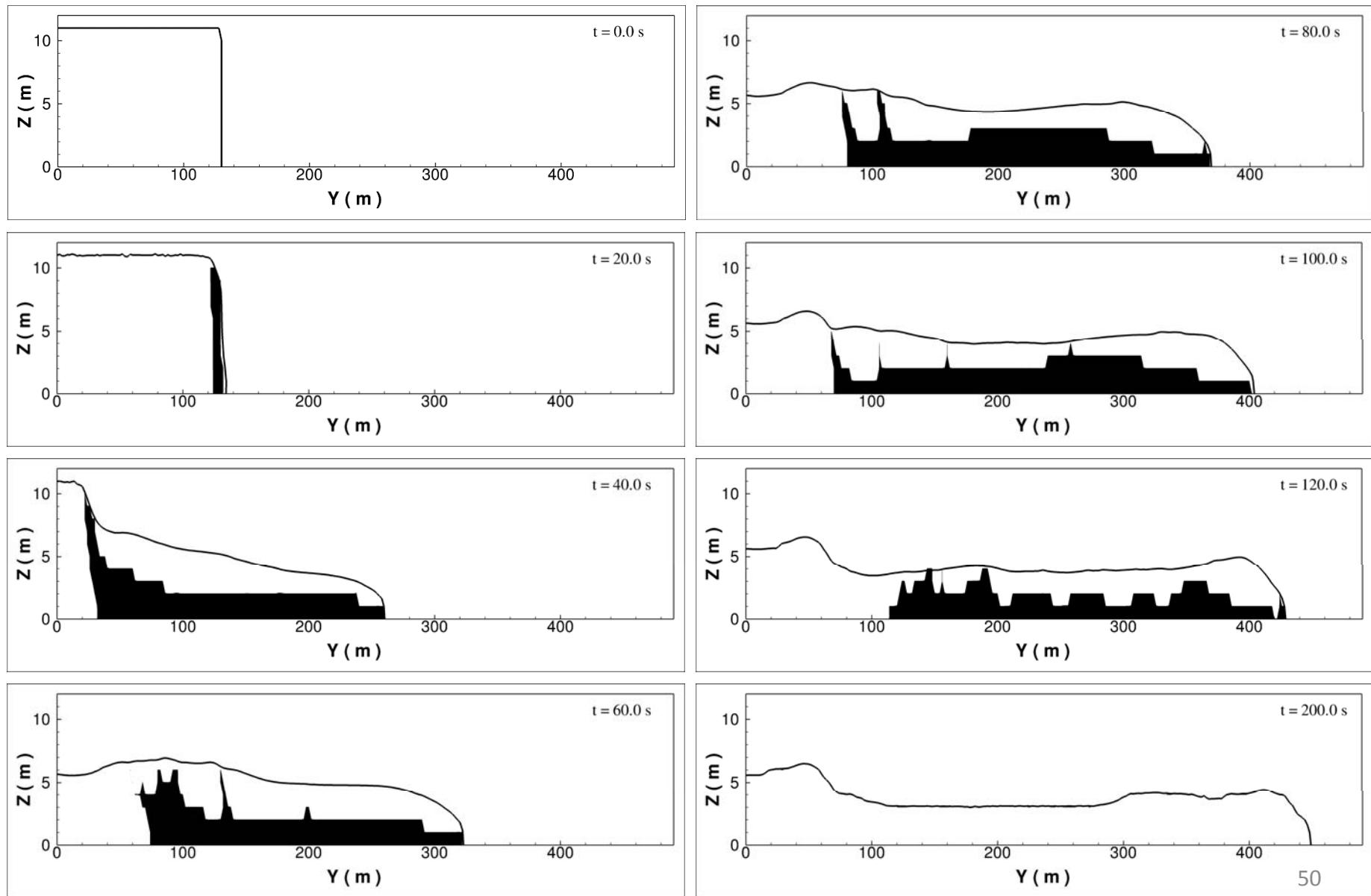
# Failure of Gypsum Tailings Dam East Texas, 1966

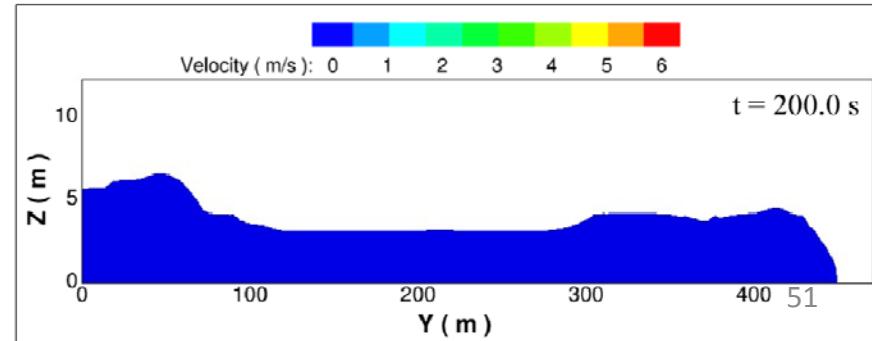
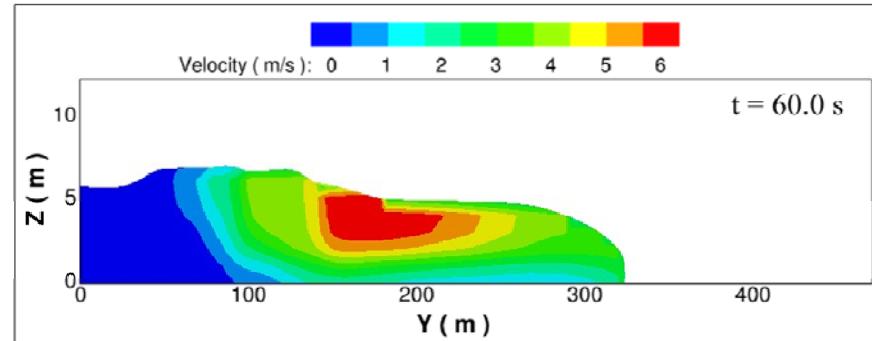
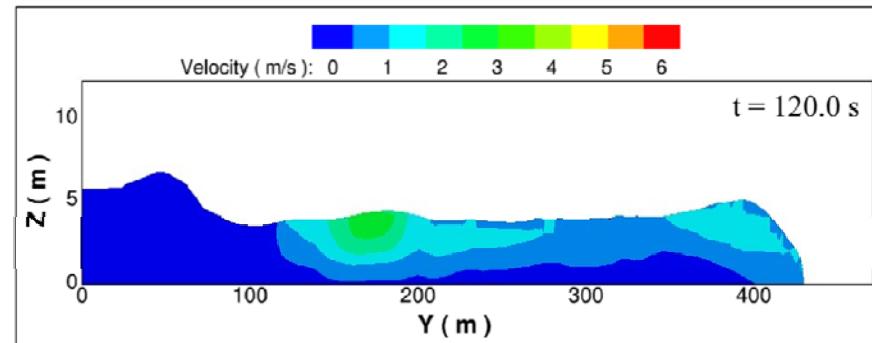
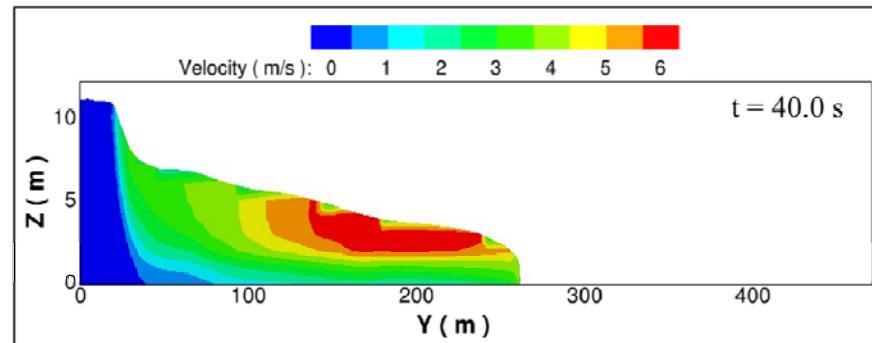
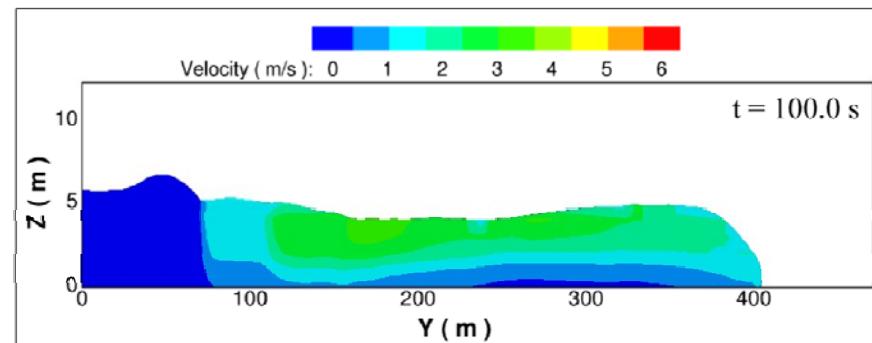
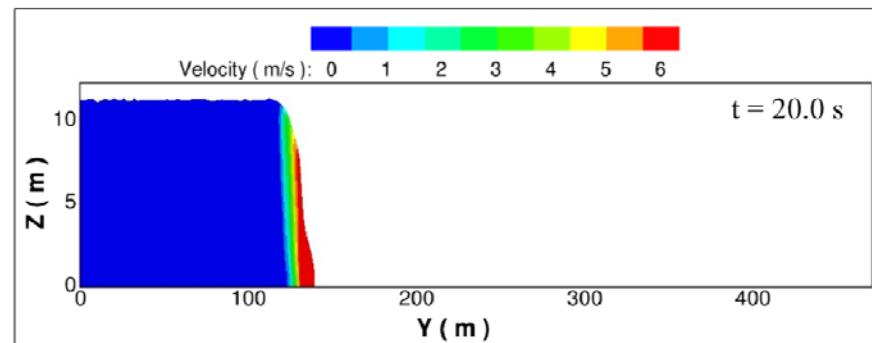
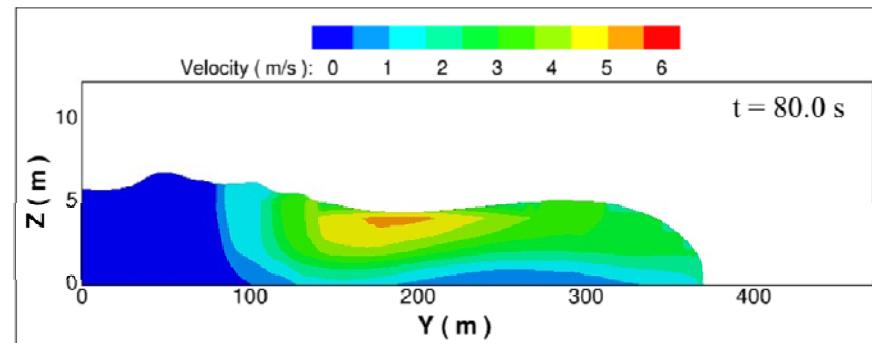
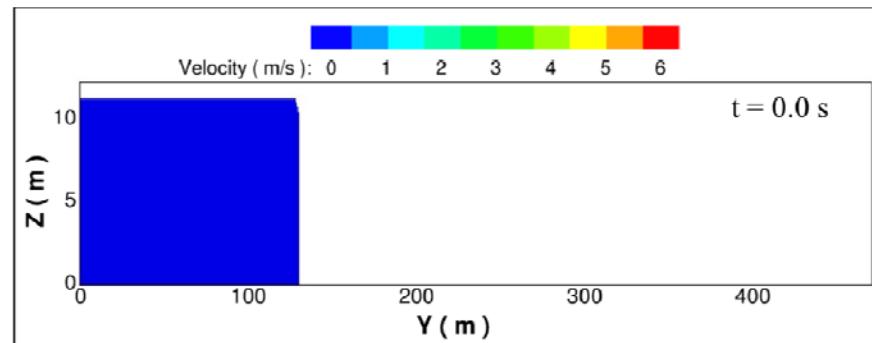
	Inundation distance ( m )	Freezing time ( s )	Mean velocity ( m/s )
<b>Observed values</b>	300	60-120	2.5-5.0
<b>Theoretical results from charts</b>	550	132	4.2
<b>Result using TFLOW <i>( Jeyapalan, 1983 )</i></b>	470	85	5.5
<b>Result computed by Pastor et al. <i>( 2004 )</i></b>	170	$\cong 120$	1.4
<b>Result computed by Chen <i>( 2006 )</i></b>	200	$\cong 120$	1.7
<b>Result using NS-VOF model</b>	320	$\cong 140$	2.3

# Velocity Distribution

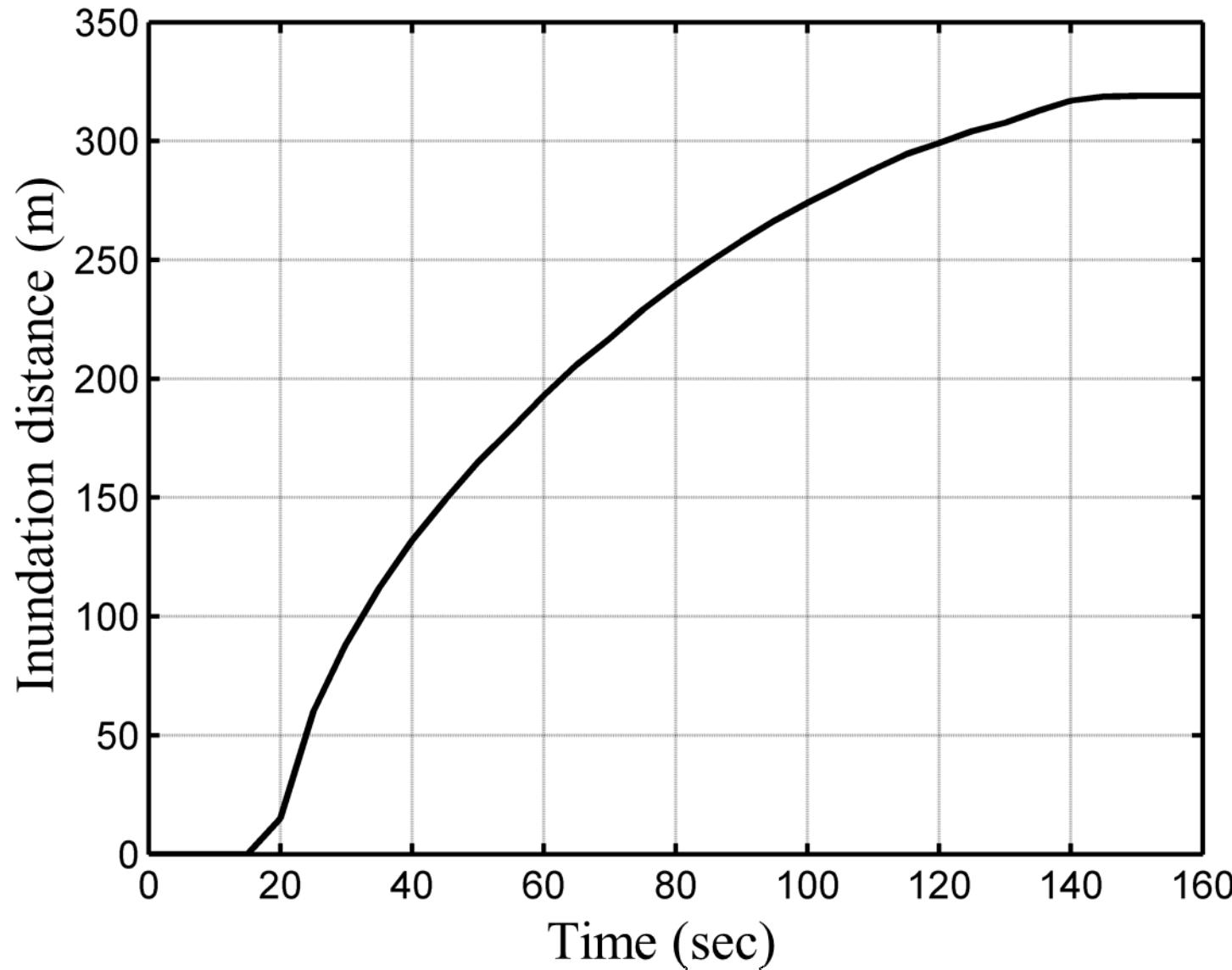


# Distribution of liquified area

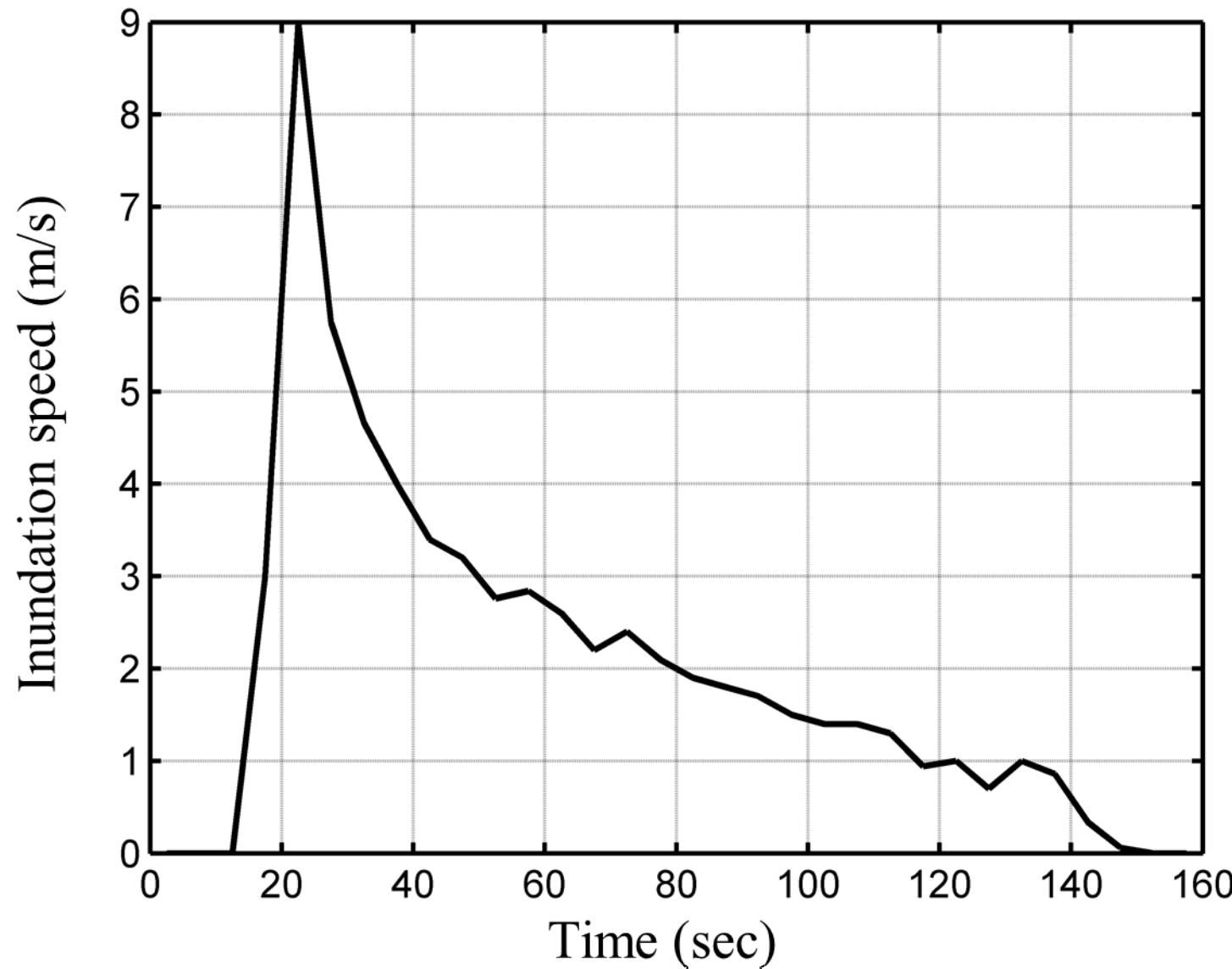




# Flooding distance



# Flooding velocity



## 4. Simulation on THE FAILURE OF SHUAN-YUAN BRIDGE

in the event of 2009 Typhoon Morakot



# 近期台灣地區橋梁受損之原因：

- 超出預期的洪水衝擊
- 難以預測的基礎沖刷與掏空
- 橋墩受大量塊體撞擊受損
- 橋墩受強烈洪水泥沙磨損
- 土石流巨大推移力與抬昇力導致橋面板流失
- 堰塞湖潰壩導致瞬間流量大增



超出設計的洪水衝擊橋墩將導致  
基礎淘刷 支承力減弱 力矩增大



雙園大橋斷橋時之水理情況：

上游出現波狀水躍，造成底床劇烈變動與沖刷  
河道轉向（變狀流河道）



# 基礎嚴重淘刷



# 橋墩保護層受泥沙磨損

基樁裸露 台東大橋岌岌可危



<http://www.libertytimes.com.tw/2008/new/sep/26/today-south12.htm>

# 浮木撞擊與堆積

撞擊導致結構鬆散，堆積導致斷面束縮而沖刷嚴重



<http://www.wretch.cc/blog/crazyisland5/16644394>

# 土石流

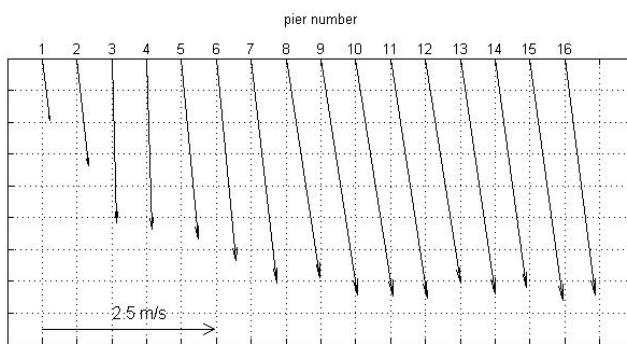
濃濁土石流，部分夾帶巨石，對橋梁造成威脅



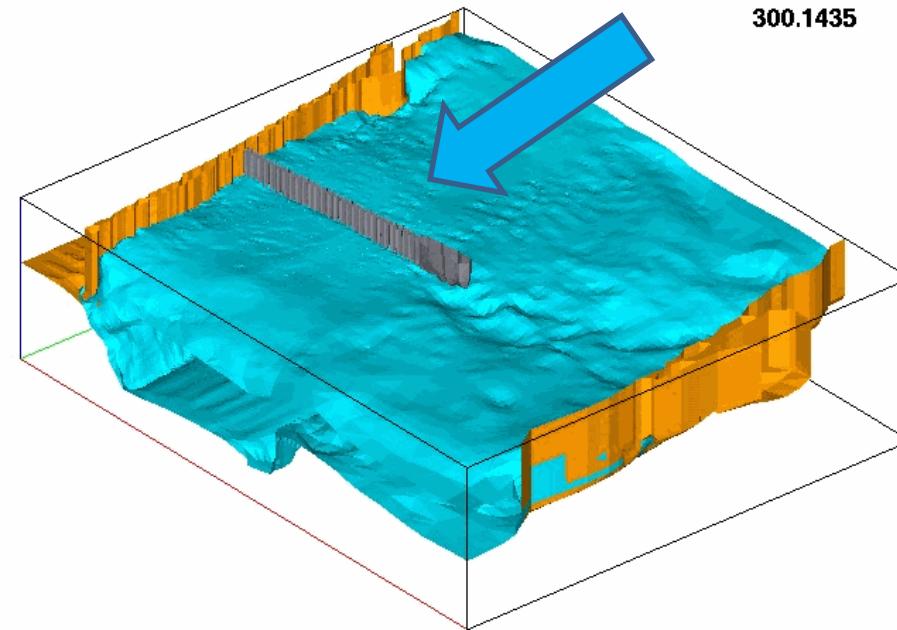
# Problems to be Solved...

- Flood impact on the structures
- Severe local scour
- Blockage effect from the drifting woods
- Mudslide, Landslide
- Boulder impact
- Why failure?

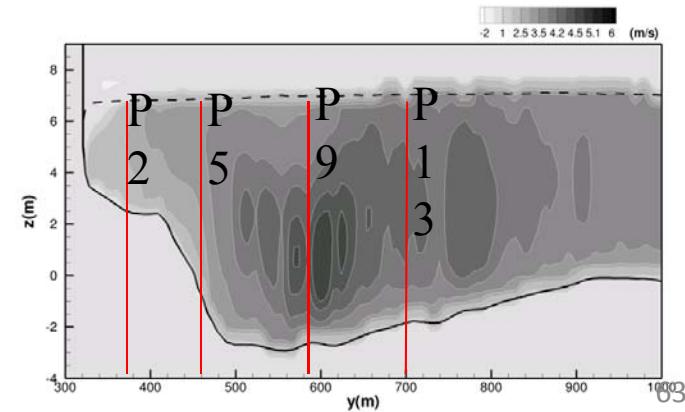
## – Hydrodynamic Analysis



模擬結果可提供各墩墩前速度大小與方向。可作為小範圍高解析度之邊界條件



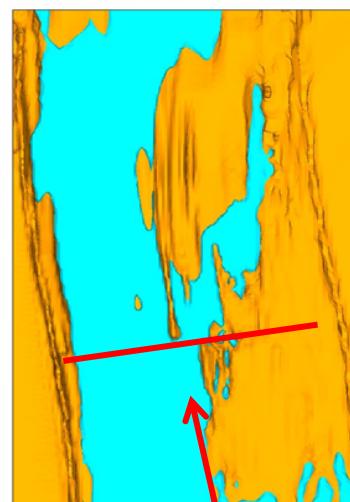
Incorporating the DEM data directly



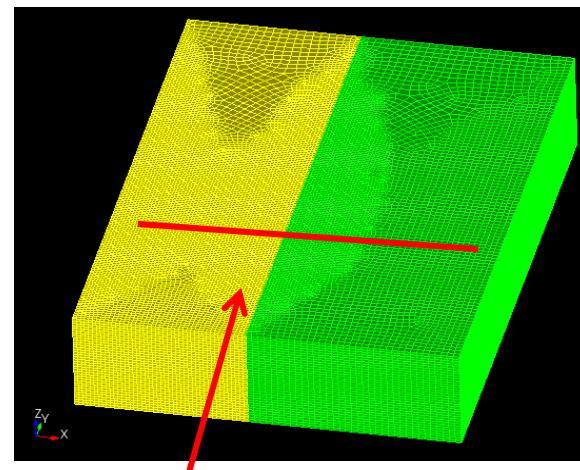
計算域選定：

上、下游入、出流處盡量取河道  
平直、流況穩定、遠離橋梁處

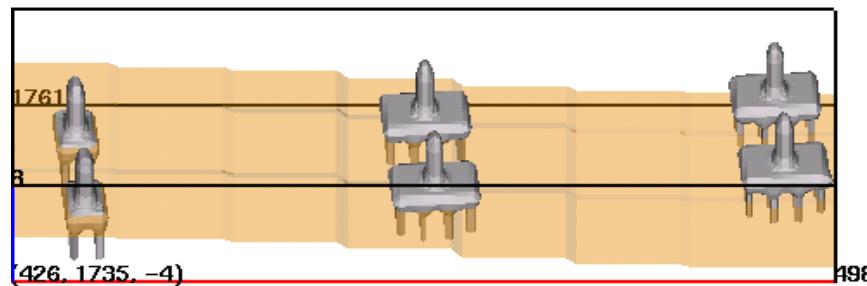
模擬之初始條件



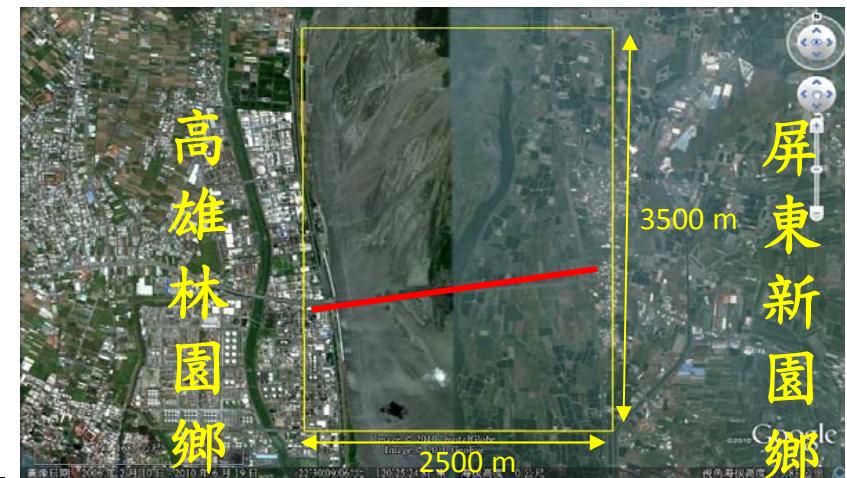
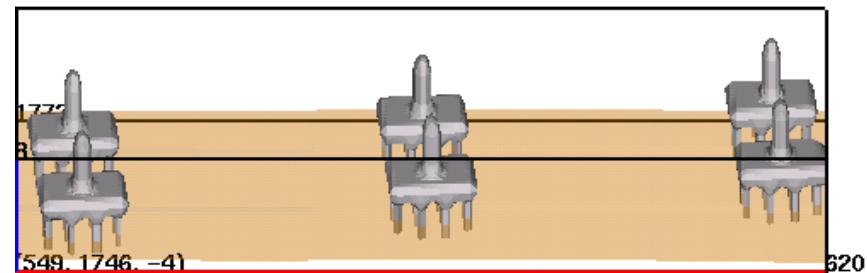
雙園大橋位置



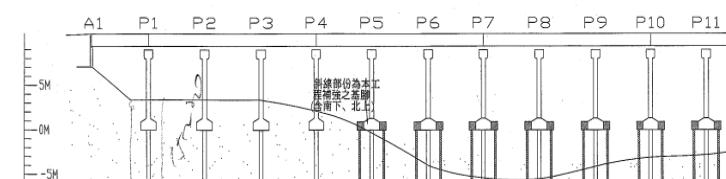
P4~P6橋墩



P8~P10橋墩



底圖來源：  
Google Earth

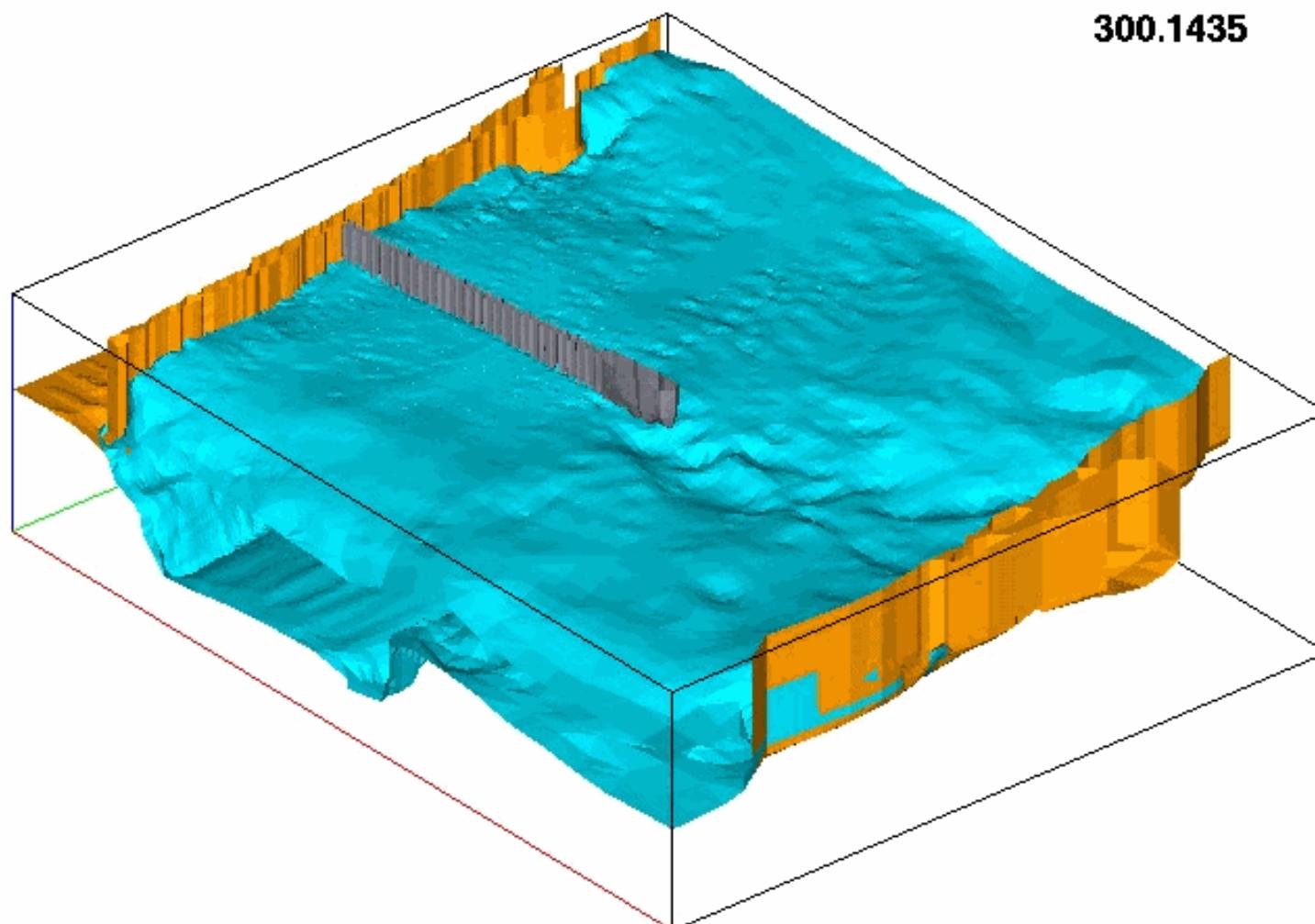


網格數：60萬

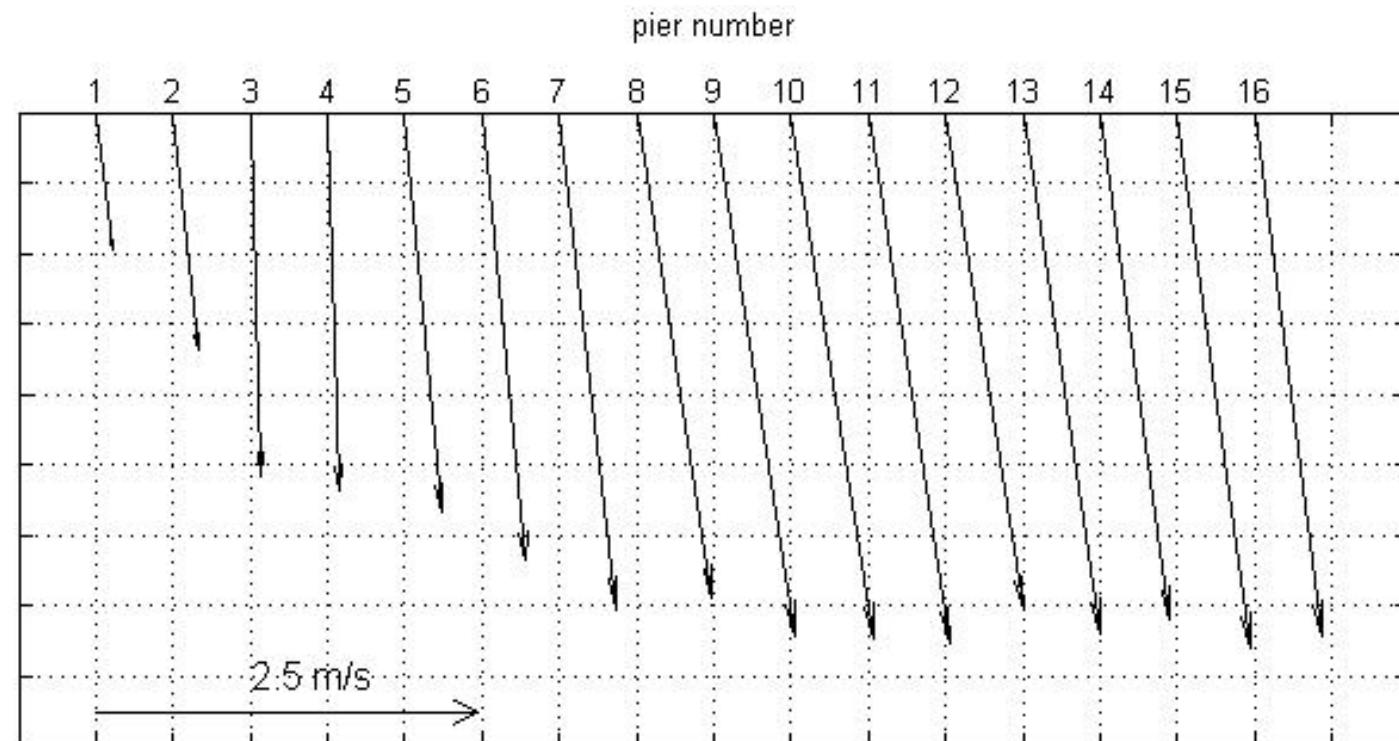
初始水深：底床至基帽上4公尺處

入流邊界：平均流速3.5 m/s，上游入流水位為8公尺

下游邊界：靜水壓邊界設定，設為4公尺

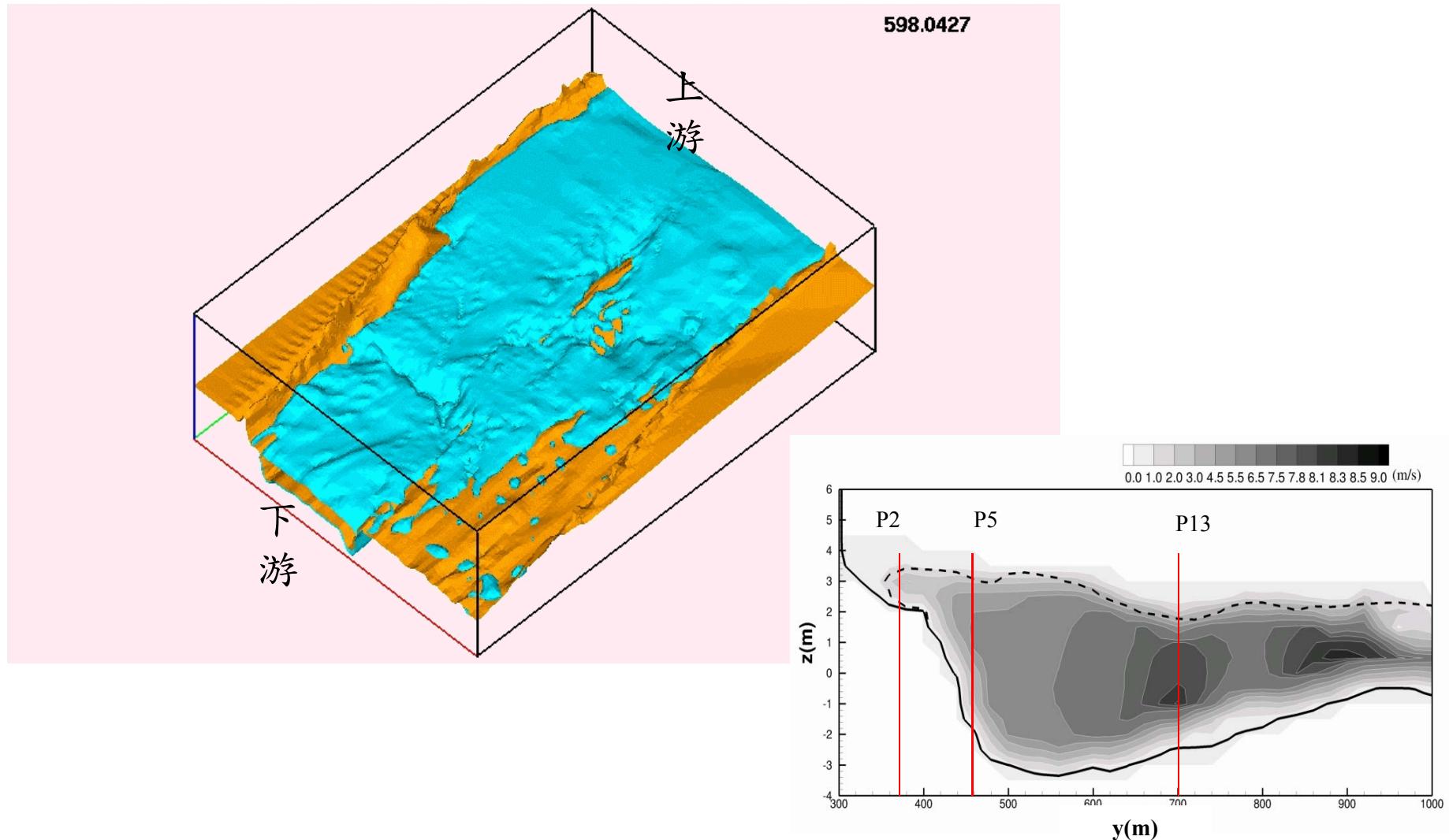


## 各橋墩前攻角與速度



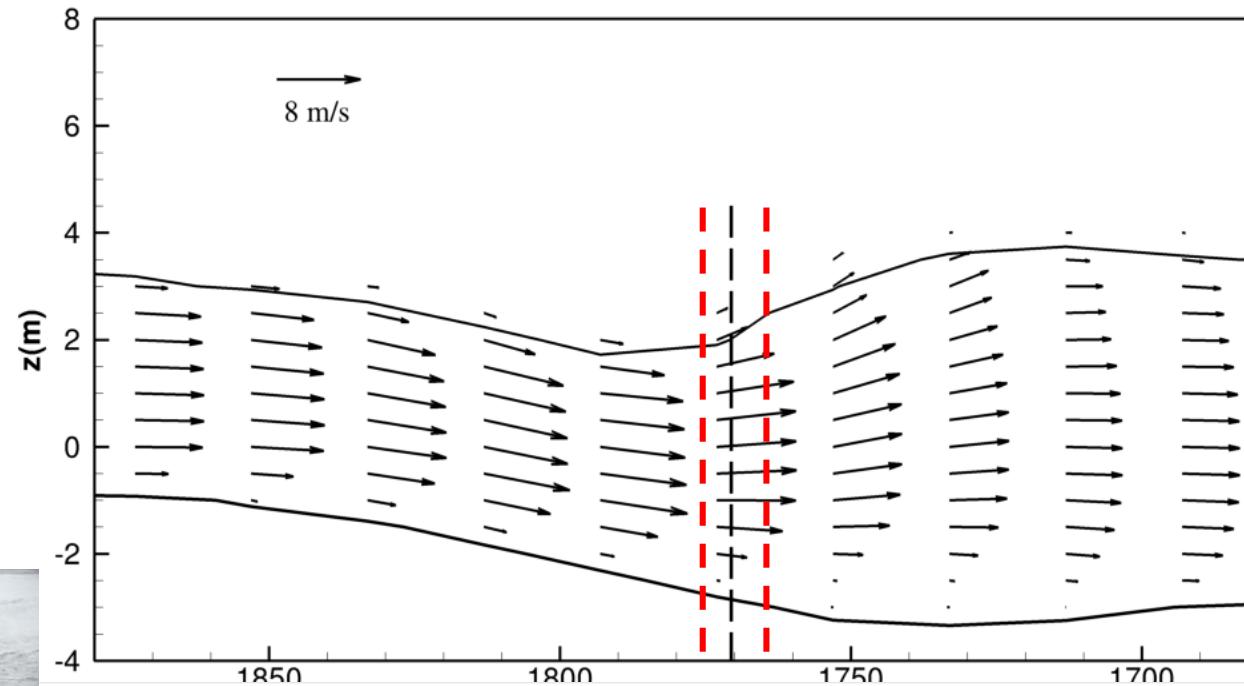
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
攻角	-8	-1	-2	-2	-5	-5	-7	-11	-11	-11	-11	-11	-10	-9	-9	-8

模擬目標：掌握各橋墩前之流況，並以達穩態之模擬結果為主。

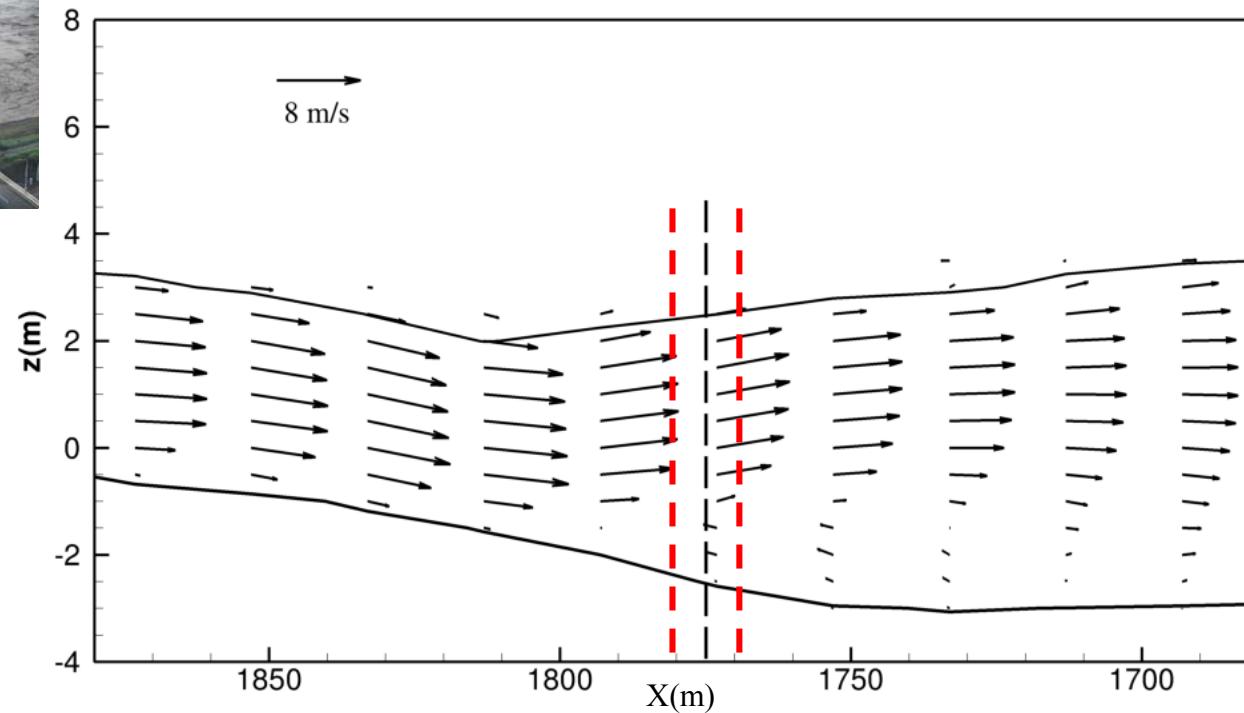




P13橋墩

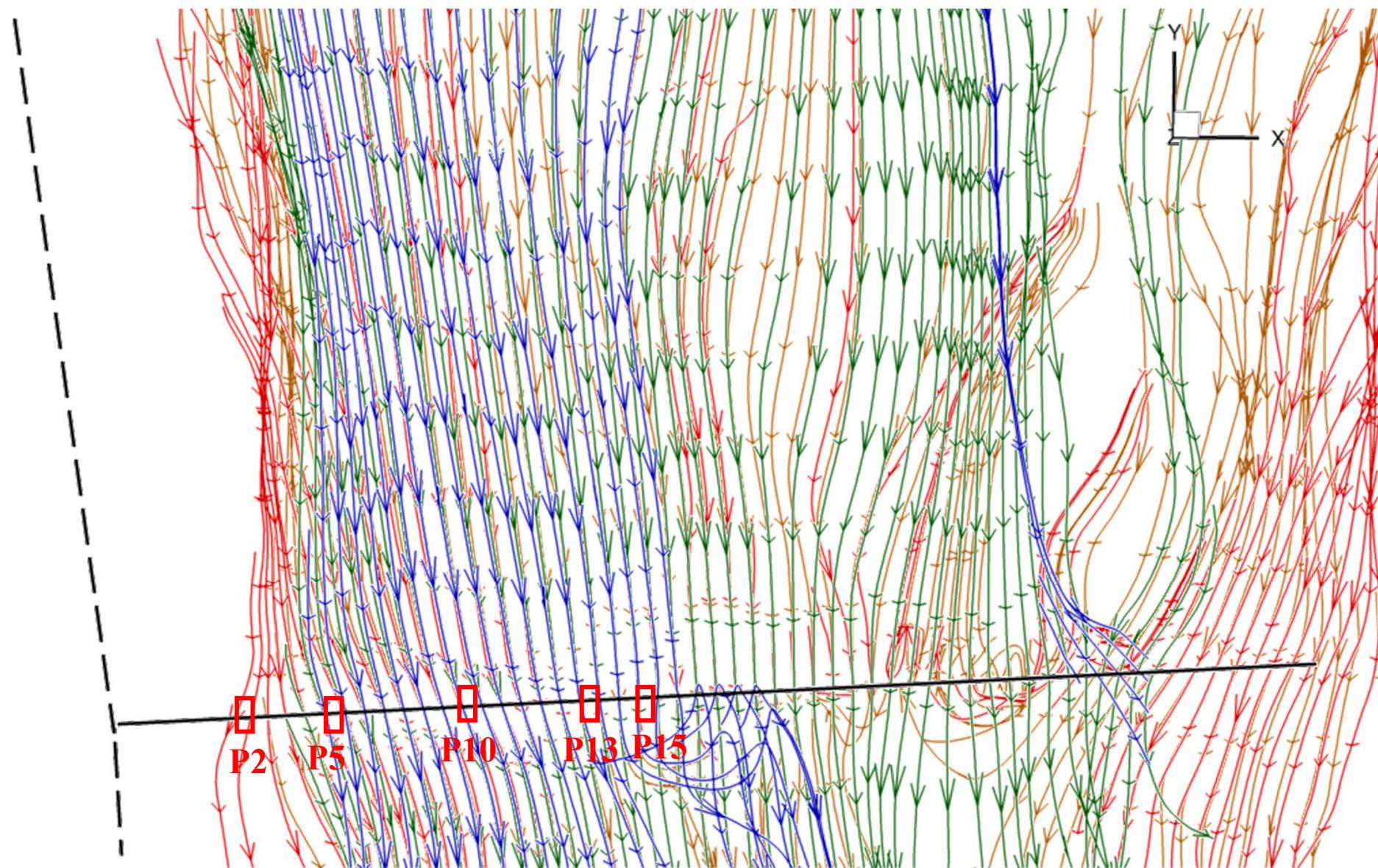


P15橋墩



# 流線分布

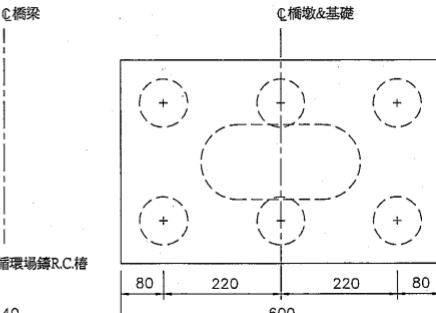
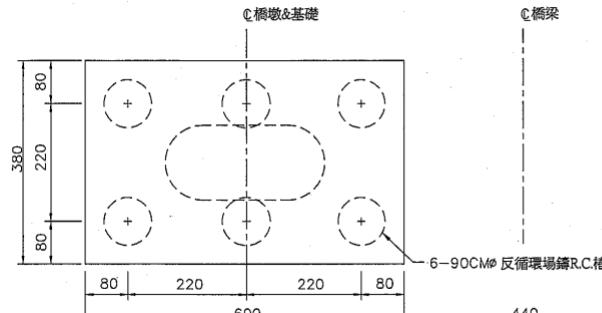
藍線：-1.5 m ,綠線：0 m ,黃線：1.5 m ,紅線：2.5 m



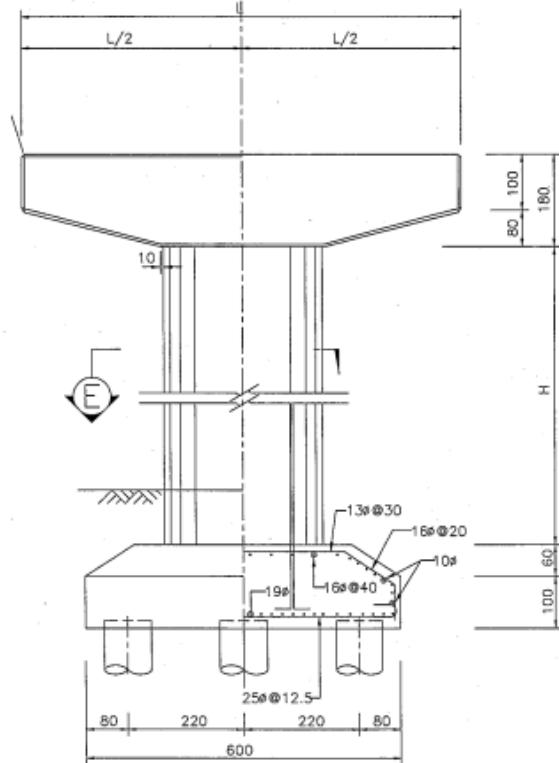
# 雙圓橋橋墩局部沖刷分析

## 橋墩型式說明

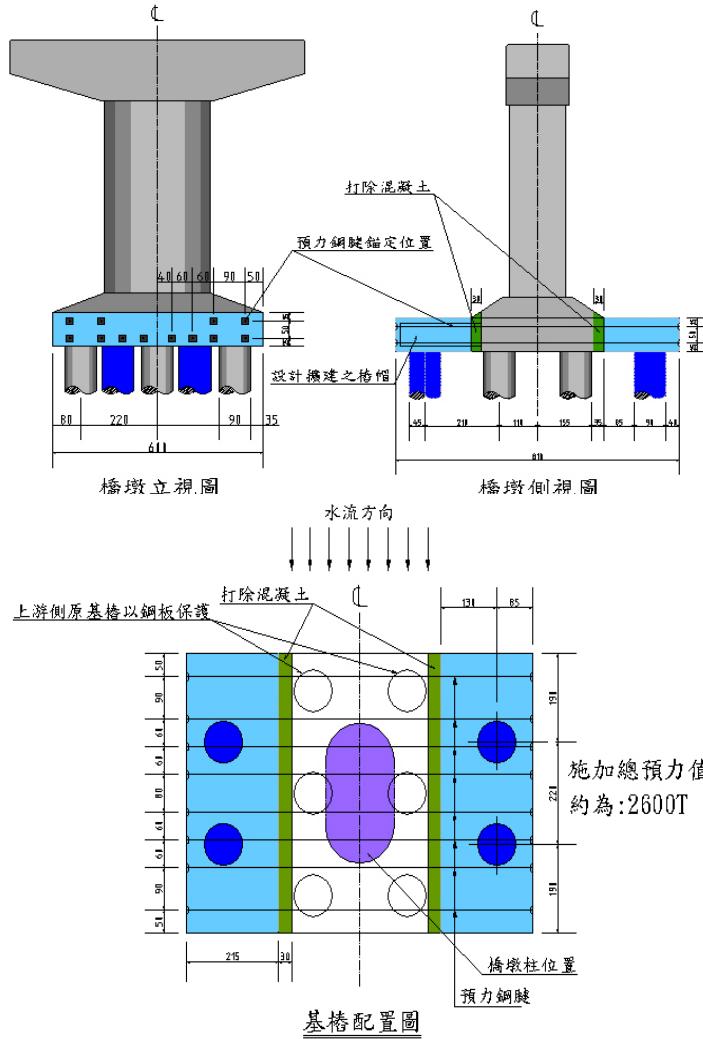
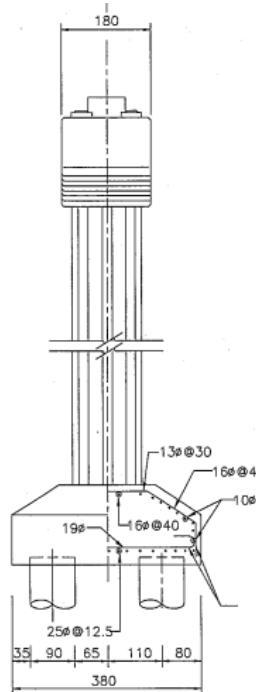
俯視圖



側視圖



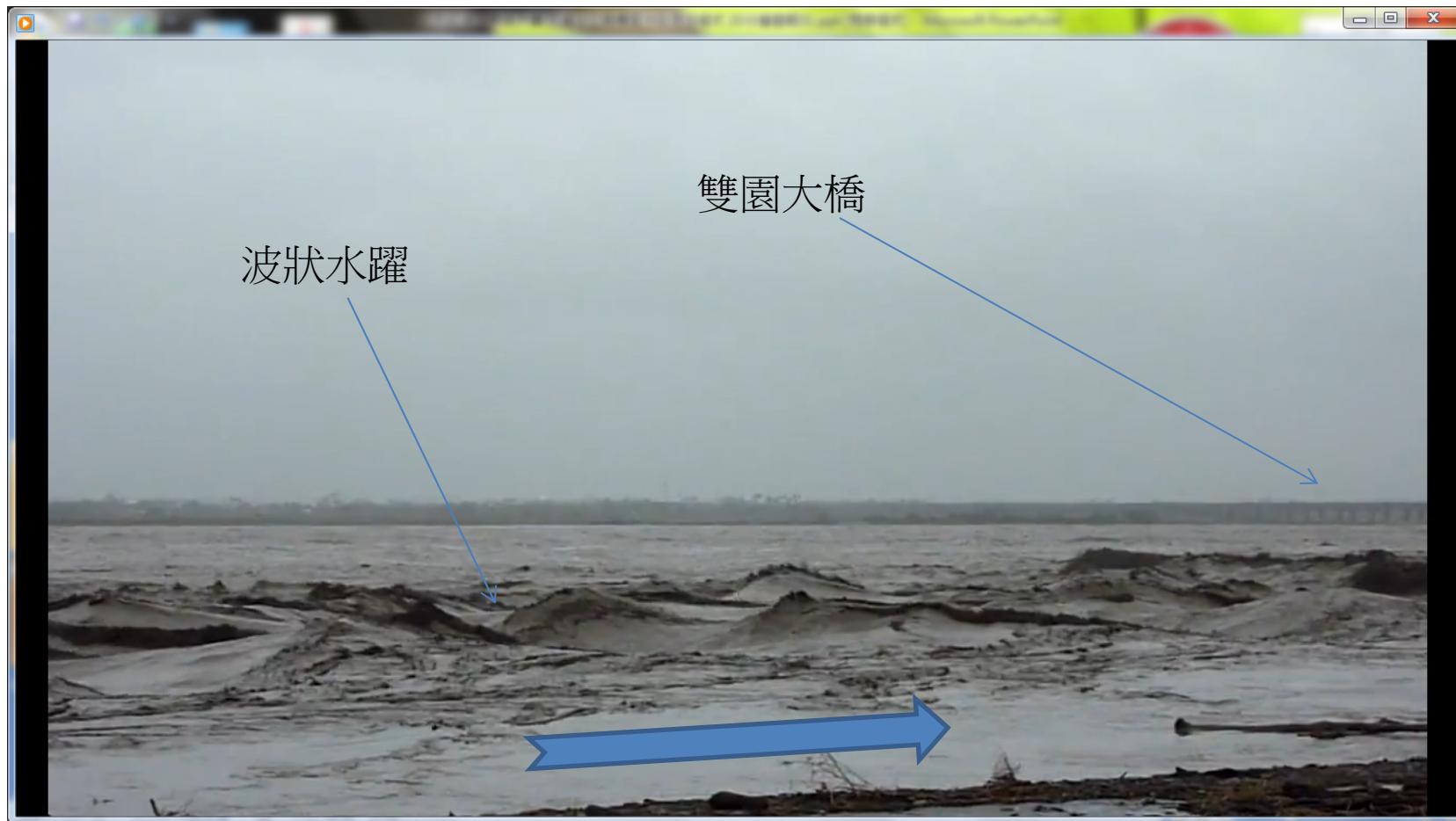
立視圖



於民國90年抽換下游側部分預力梁31跨，共90根I型預力混凝土梁，位於深槽之30座橋墩基礎(編號P5至P14、P22至P25、P30)，以基礎擴座補強，每座基礎補4支直徑0.9米、長50米之鋼筋混凝土樁，並以預力鋼鍵錨定舊椿帽，再施作新椿帽連結新基樁。

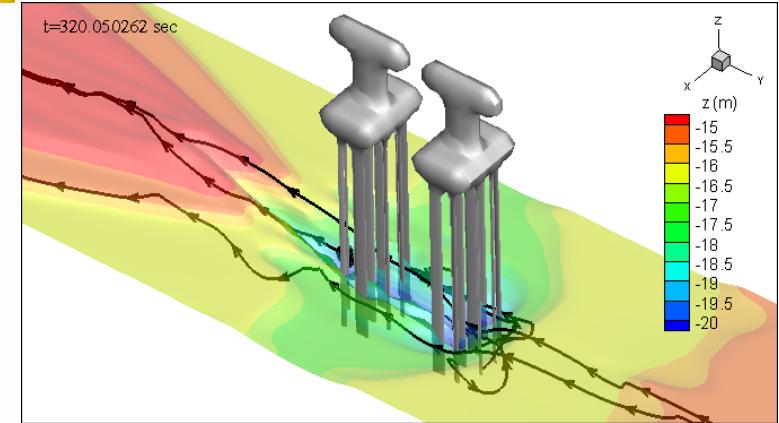
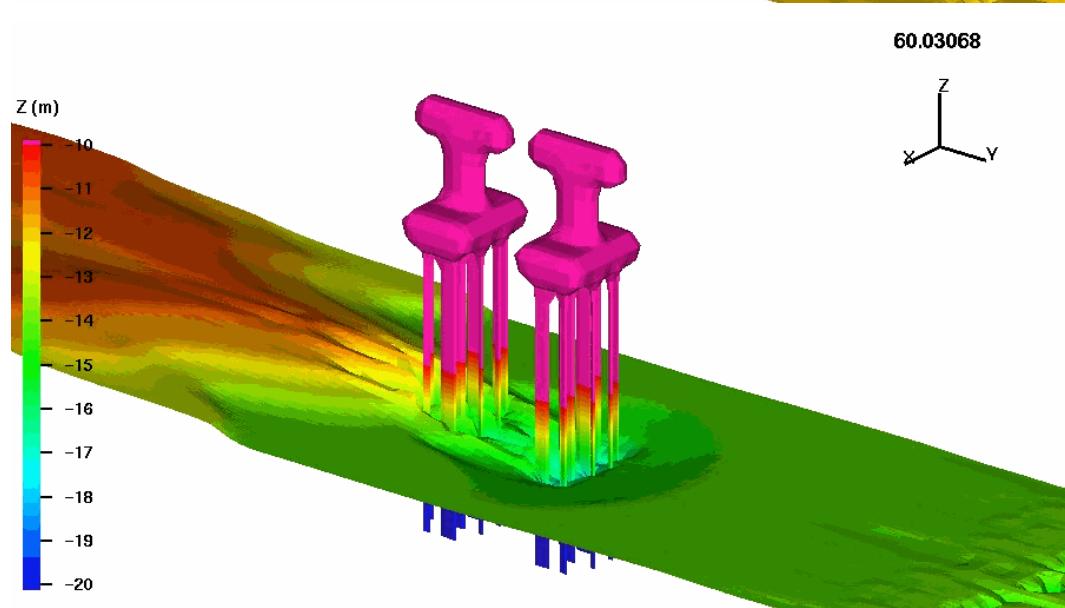
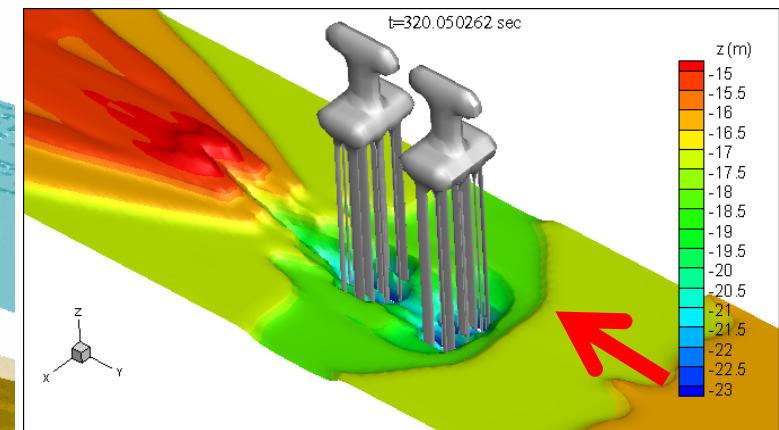
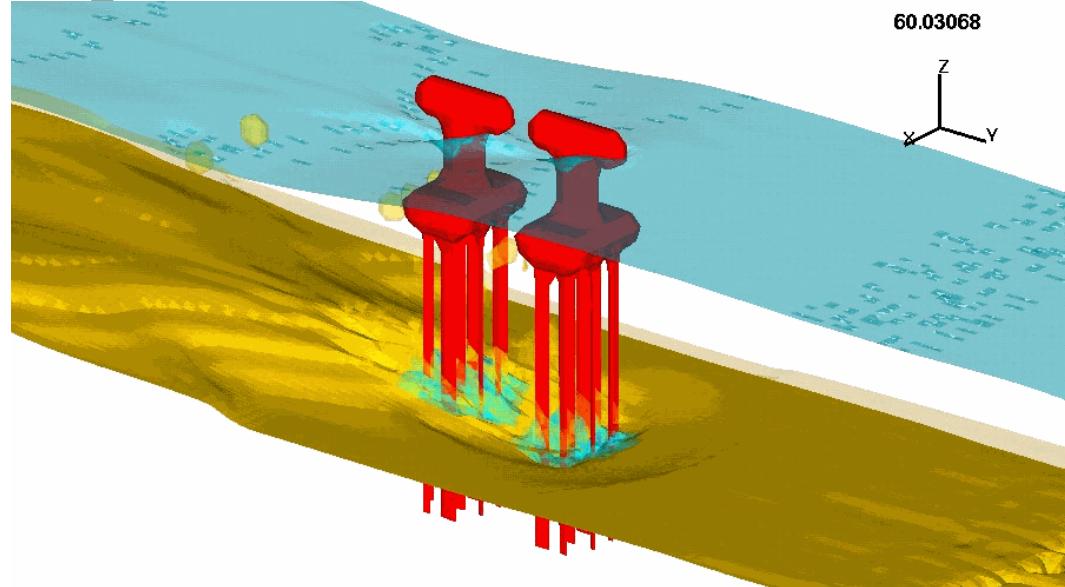
# 基礎沖刷

波狀水躍的發生，通常意味底泥鬆軟：  
基樁之局部沖刷嚴重



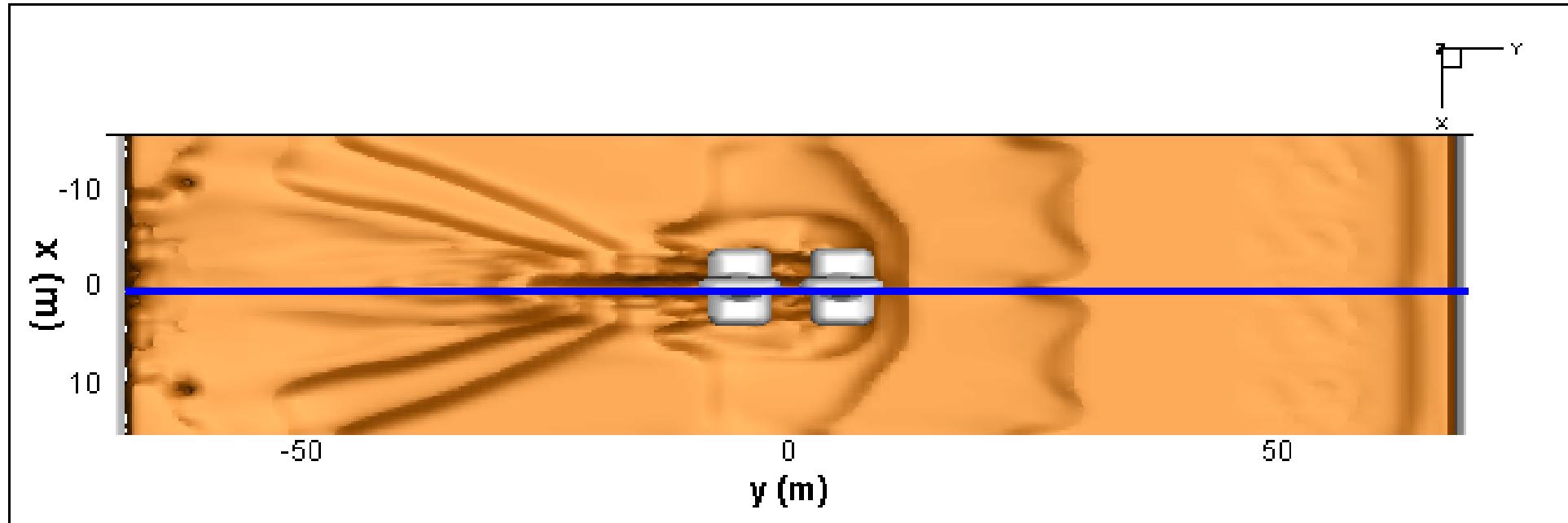
# Local scour induced by the strong flood

mud\_vof=0.05

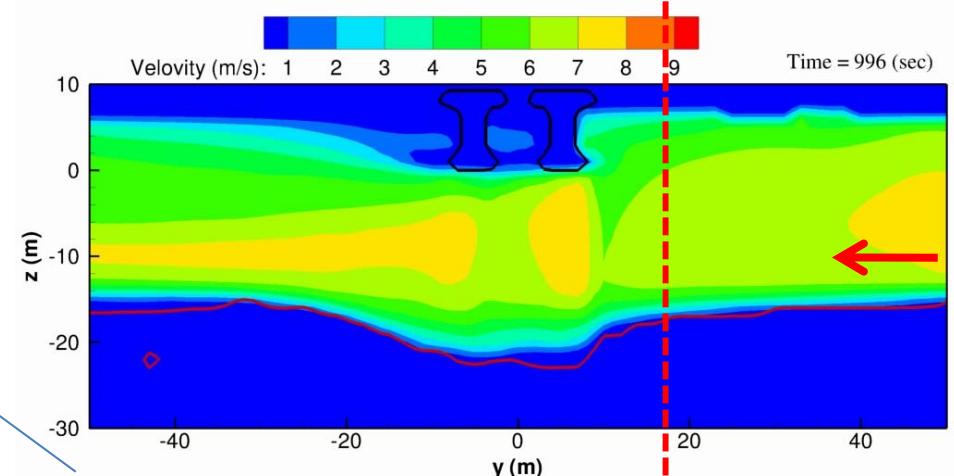
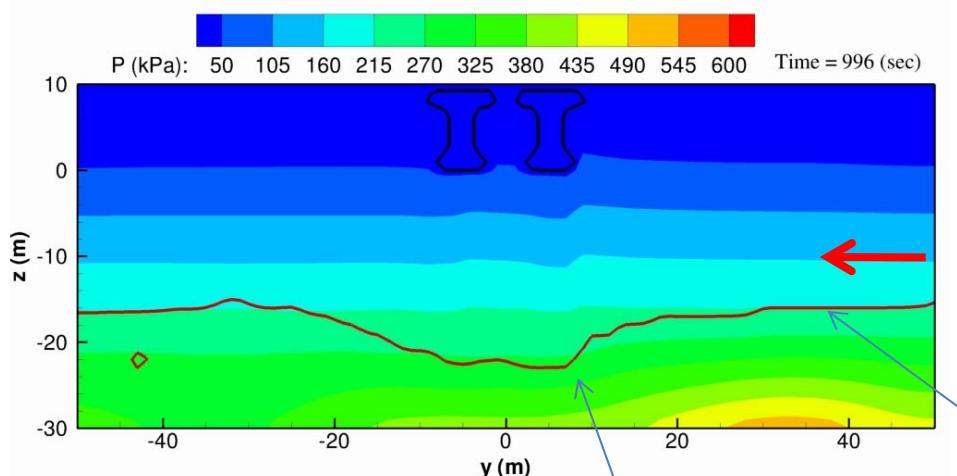


(陳孟志製)

# Y-Z剖面分析—X= 0 m

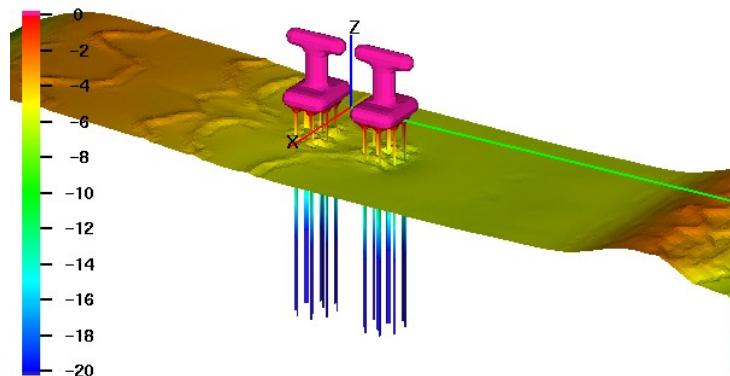


墩前10m處流速平均為3.45m/s



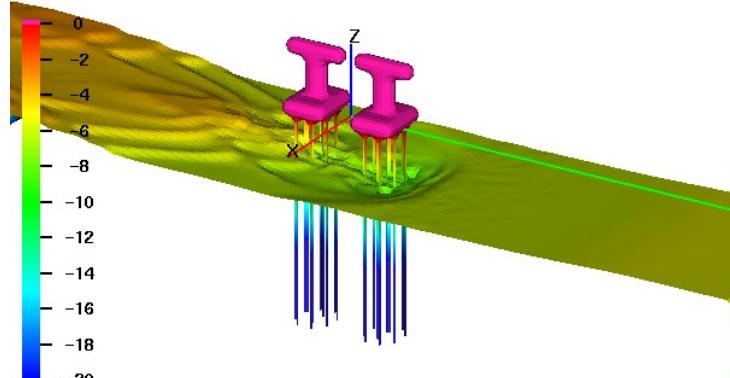
# 流速與沖刷深度之探討

流速 = 2 m/s  
Isosurface Z-Coods



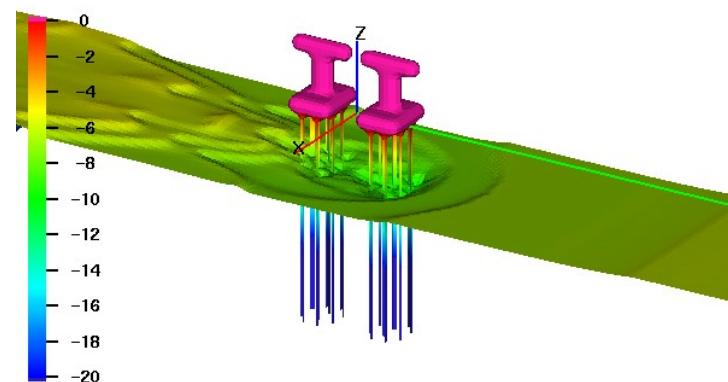
1800.0563

流速 = 4 m/s  
Isosurface Z-Coods



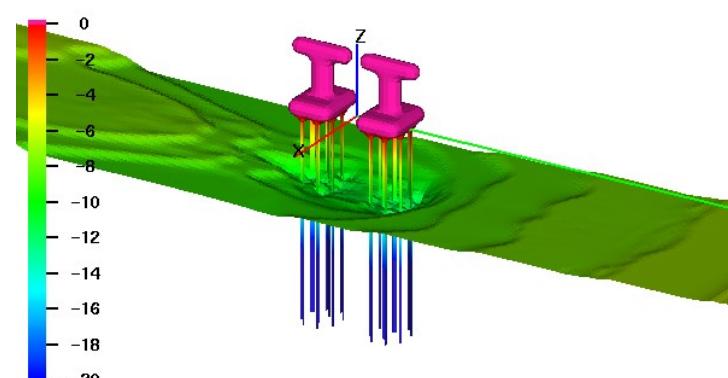
1810.0301

流速 = 6 m/s  
Isosurface Z-Coods

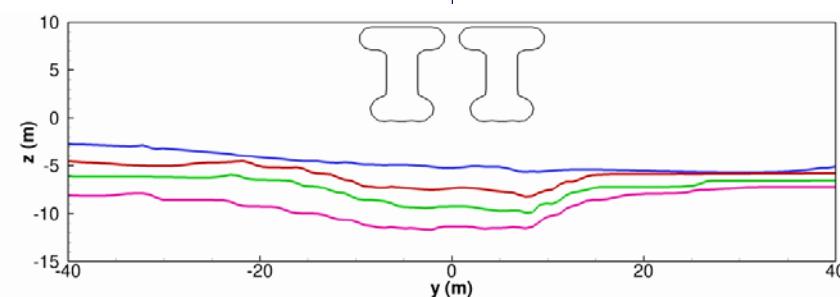


1800.0167

流速 = 8m/s  
Isosurface Z-Coods



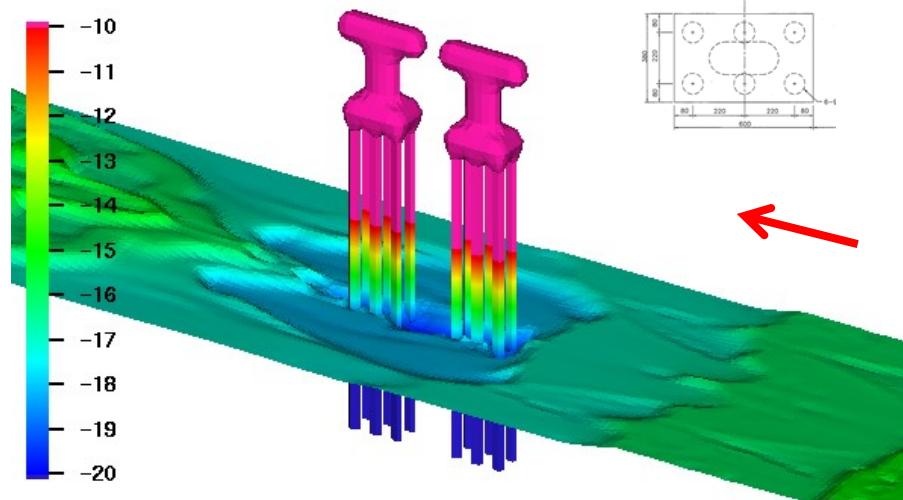
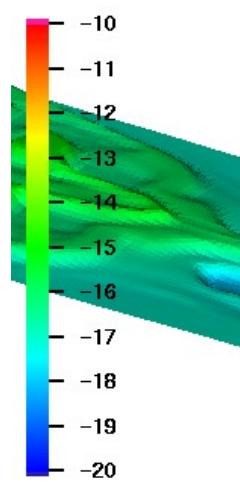
1800.0065



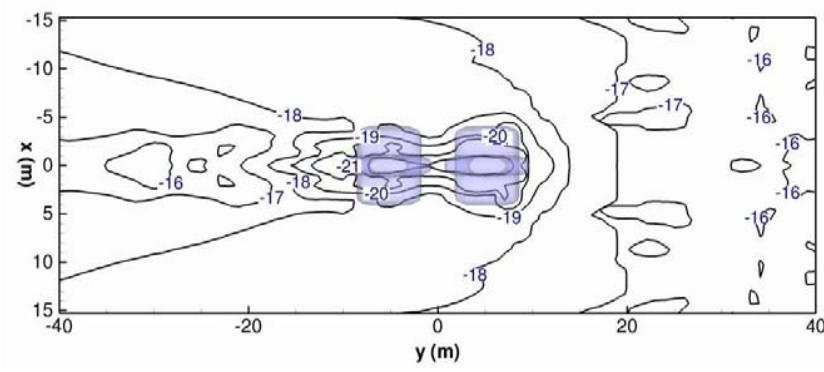
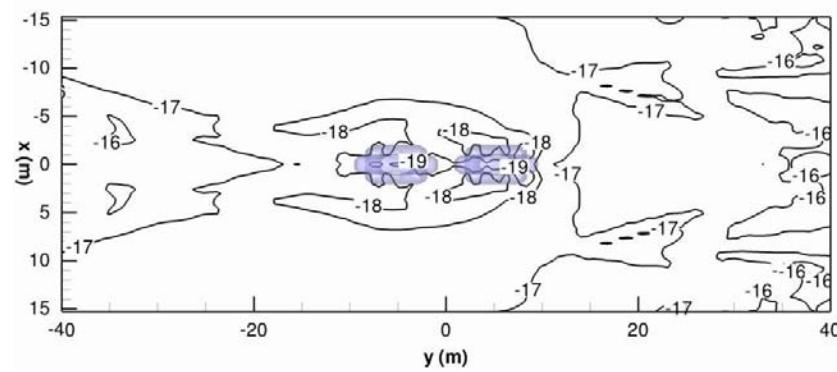
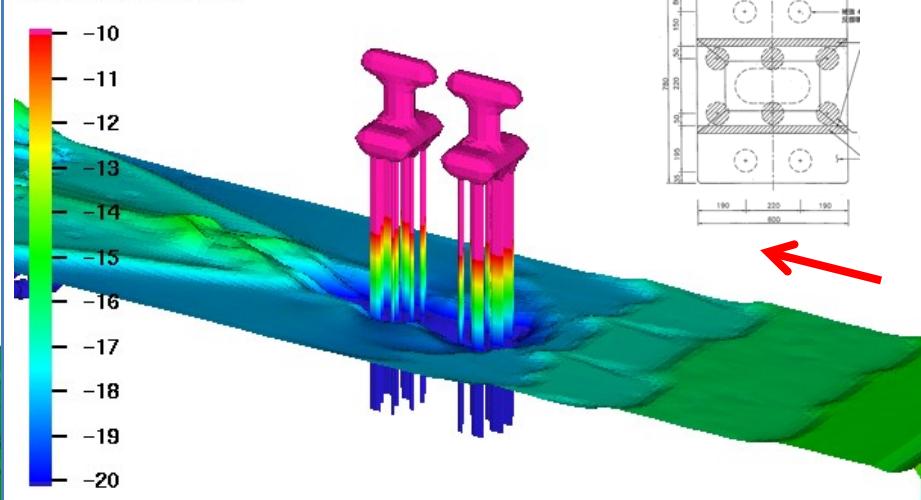
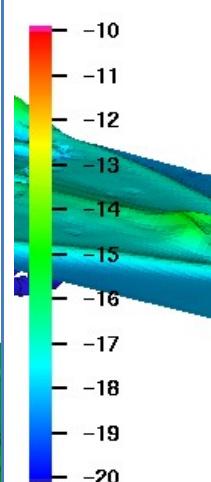
# 補樁橋墩之沖刷坑發展



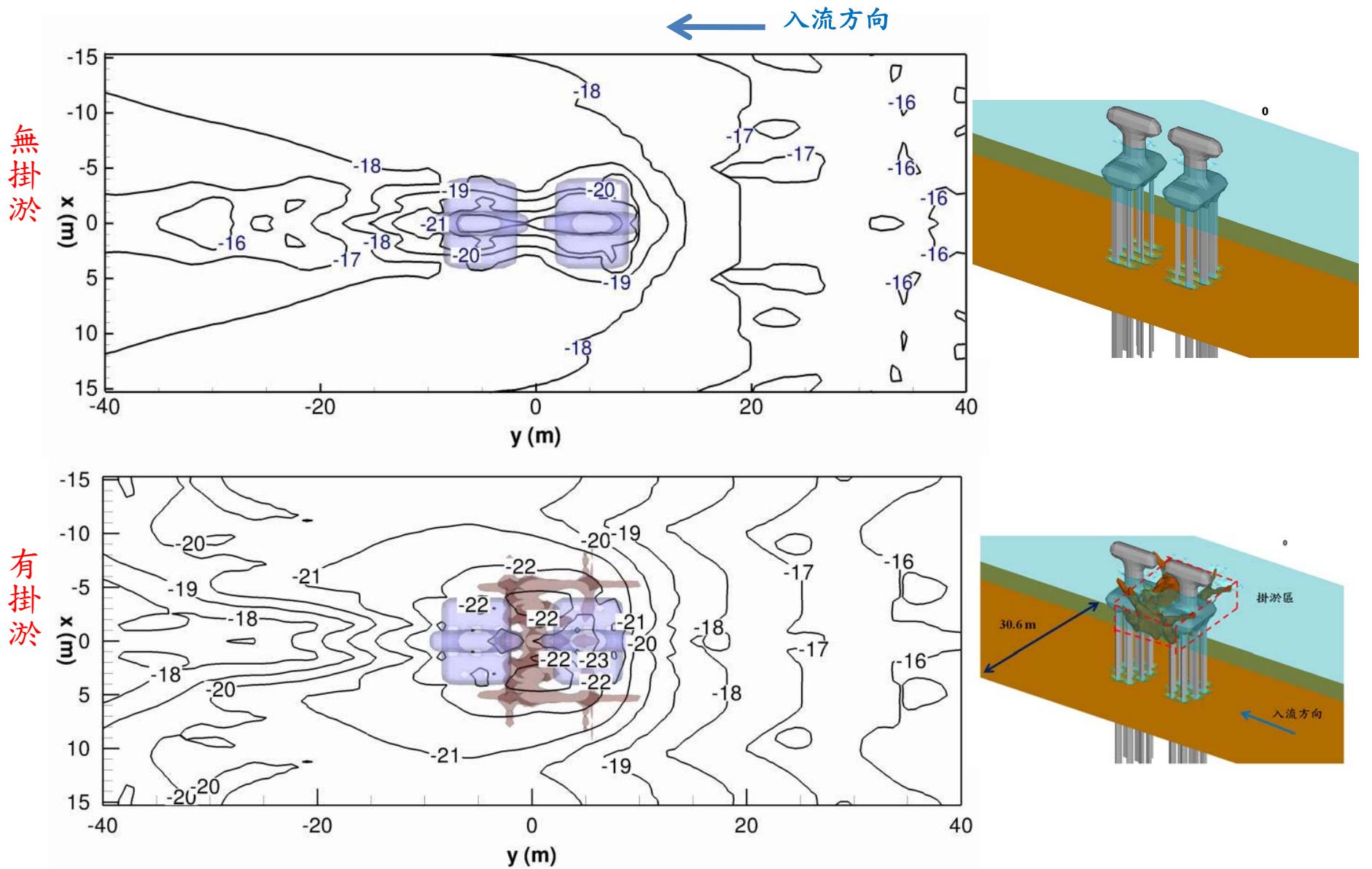
Isosurface Z-Coods



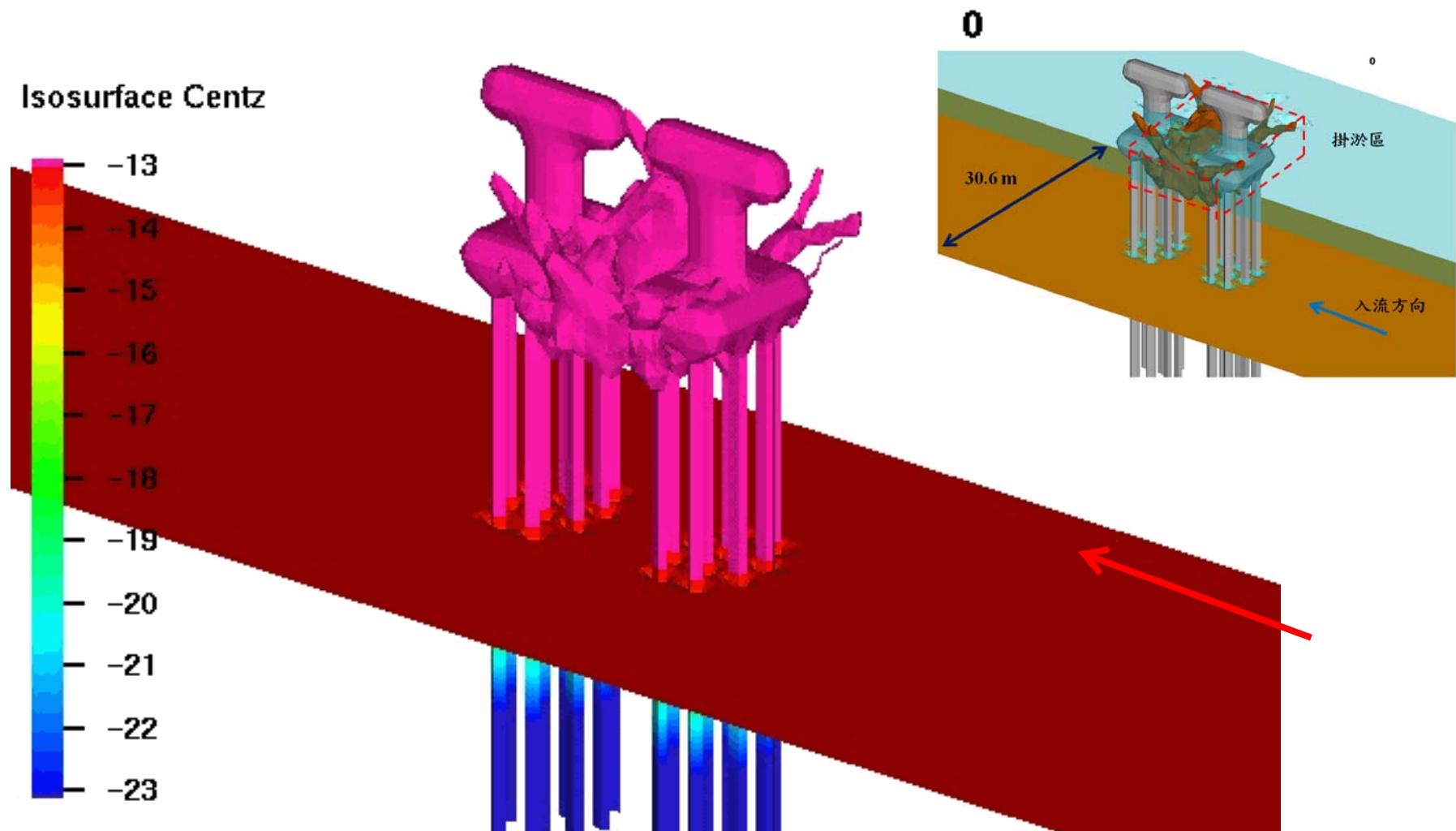
Isosurface Z-Coods



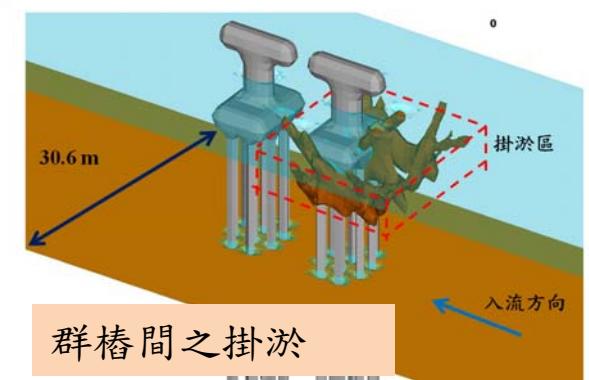
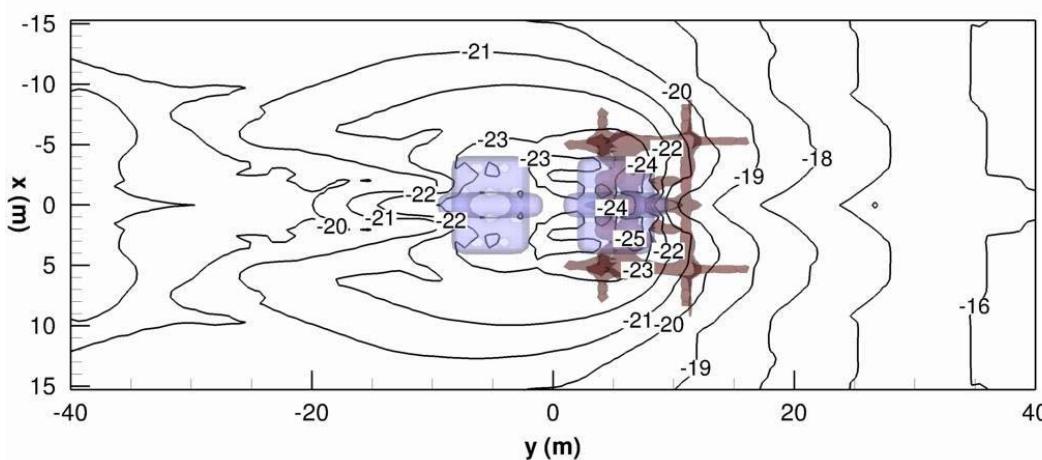
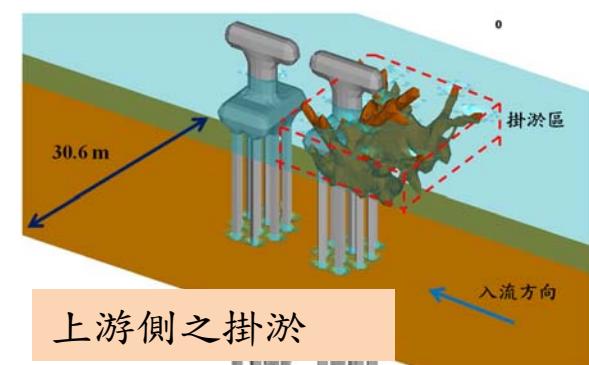
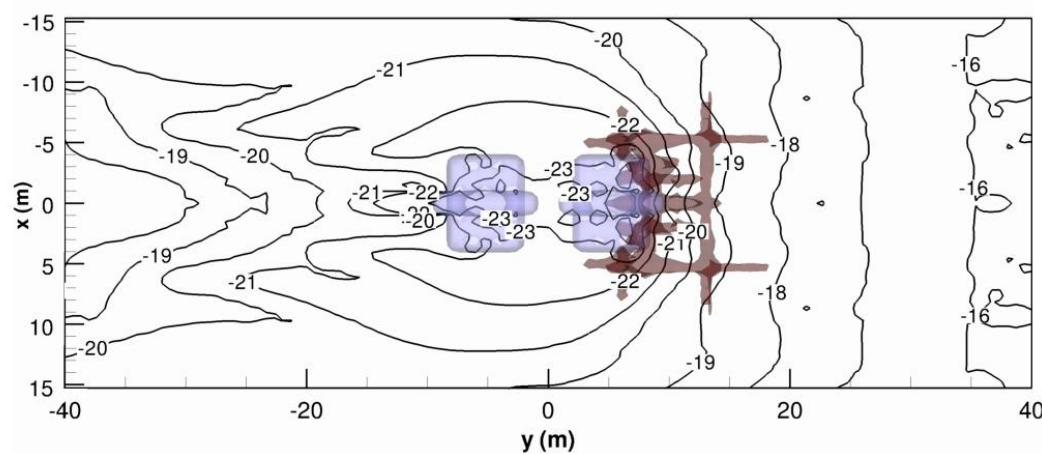
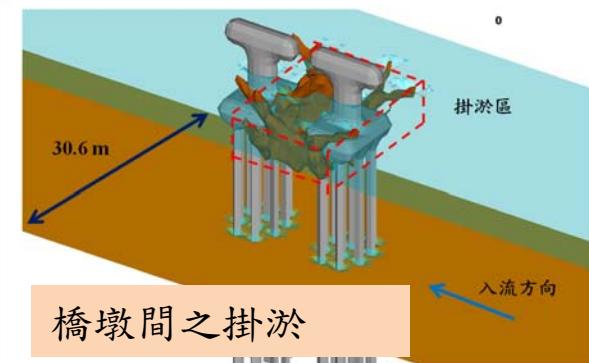
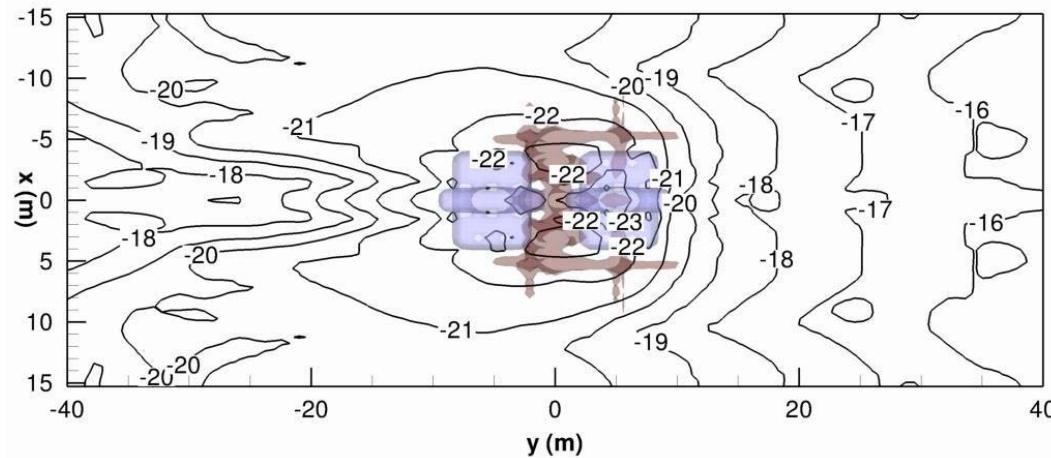
# 有無浮木掛淤之冲刷坑比較



# 橋墩間掛淤之沖刷坑發展

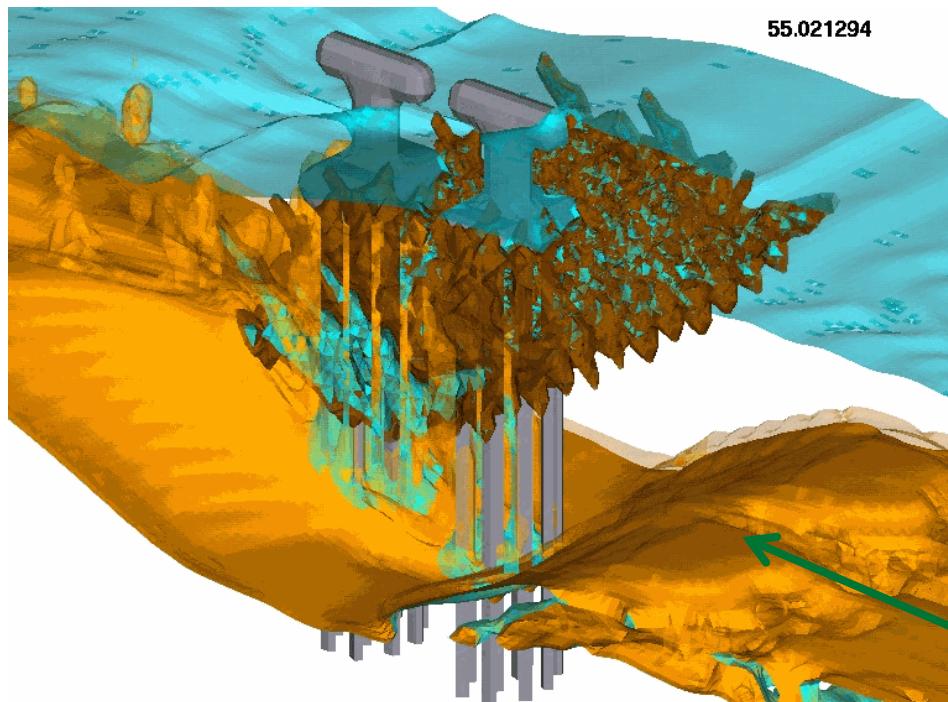


## 掛淤型態之沖刷坑比較

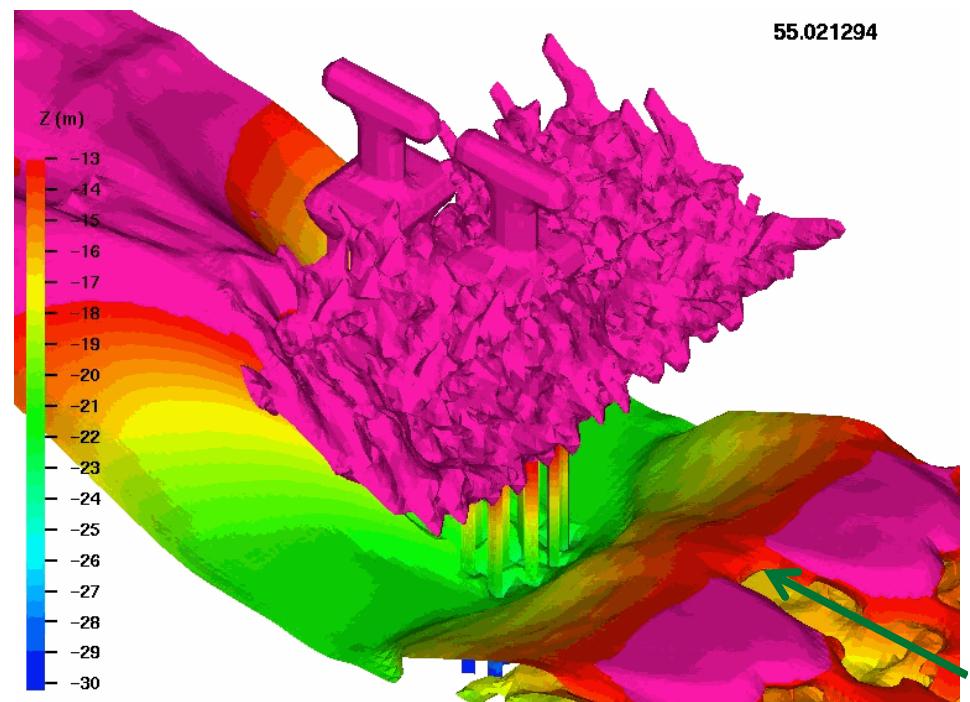


- 甚至模擬極端掛淤案例之沖刷坑發展

自由液面之變化



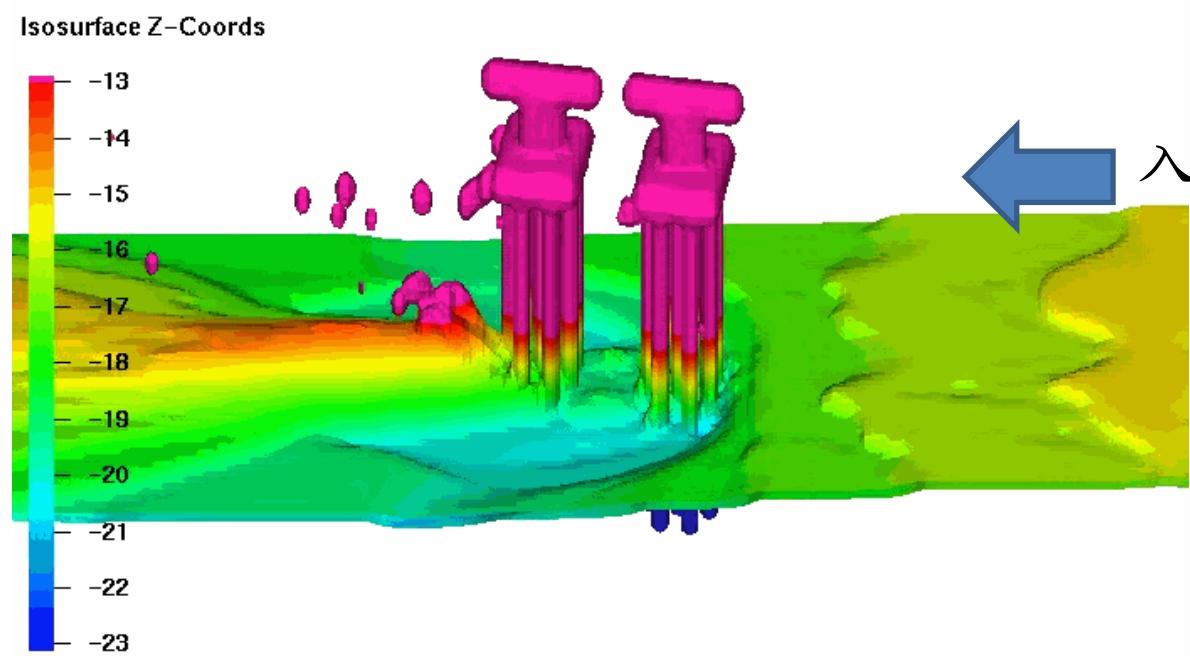
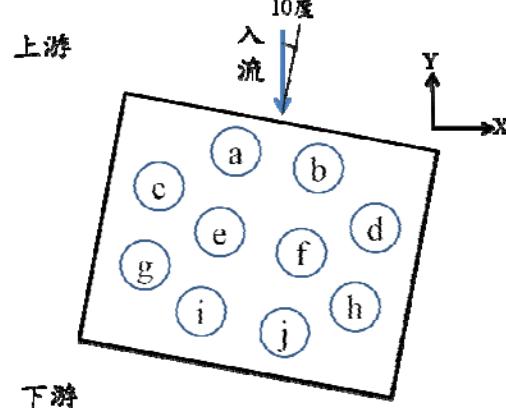
沖刷坑之變化



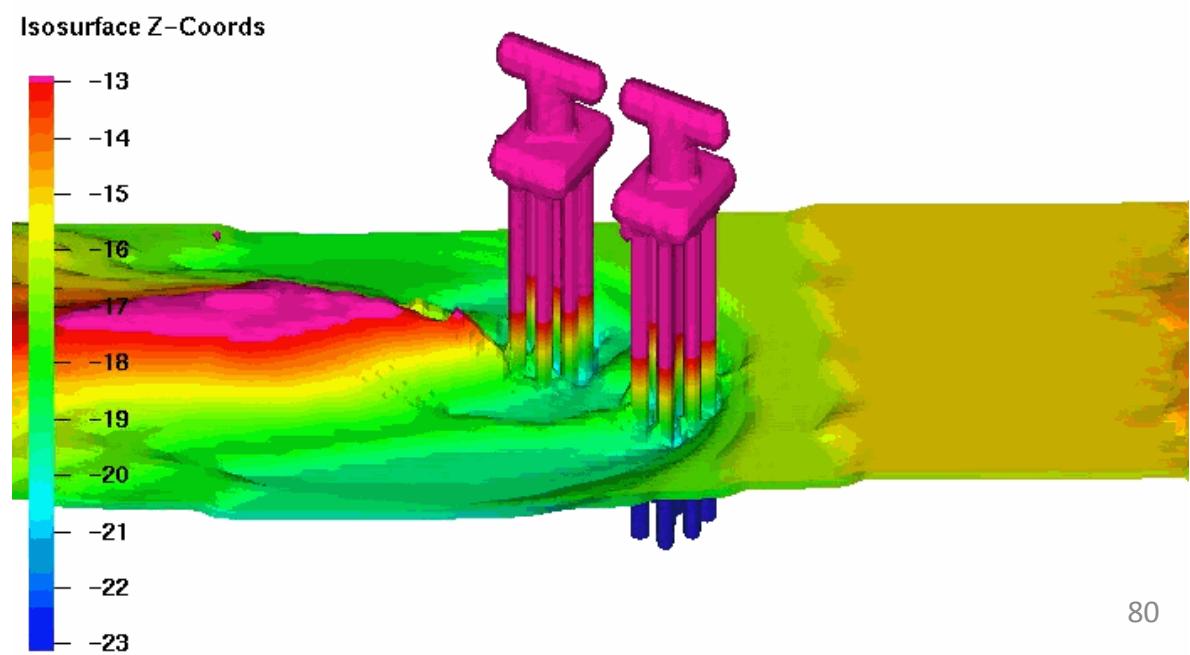
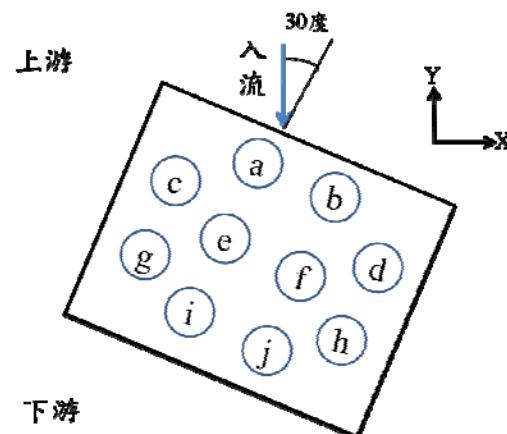
結果亦顯示，極端情況下，沖刷坑範圍明顯加大，然而深度卻增加有限。

不同攻角問題也有探討

攻角 10 度

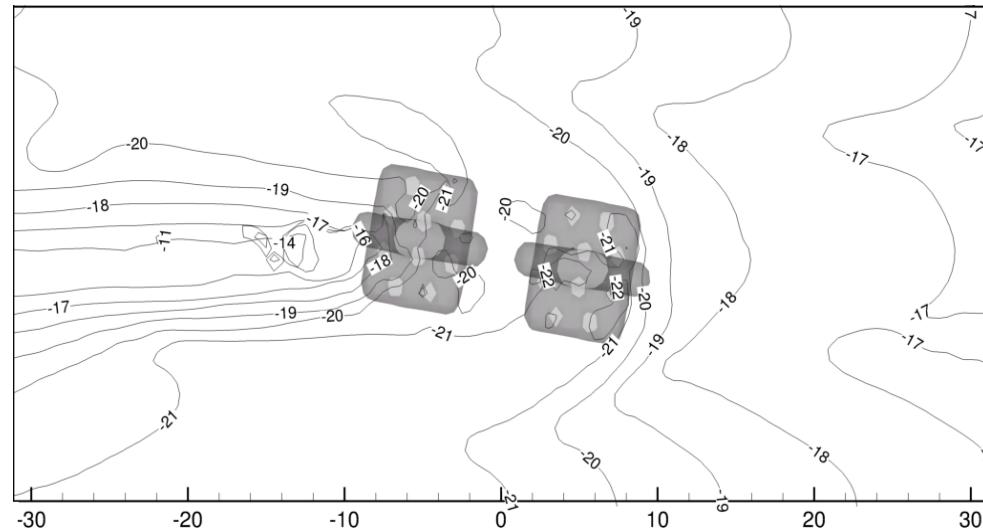


攻角 30 度

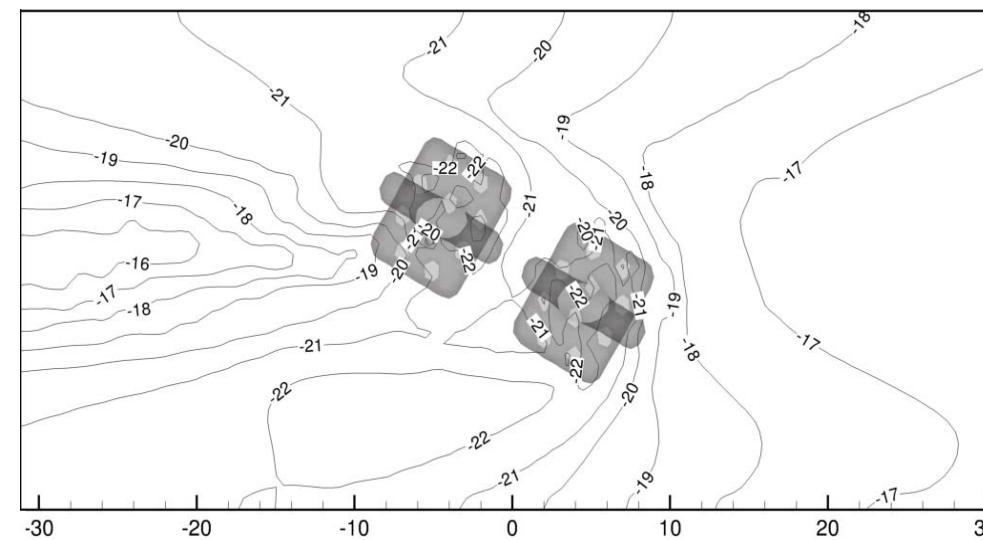


結果顯示，來流攻角改變，在高流速情況下，對最大沖刷深度影響有限。

攻角 10 度

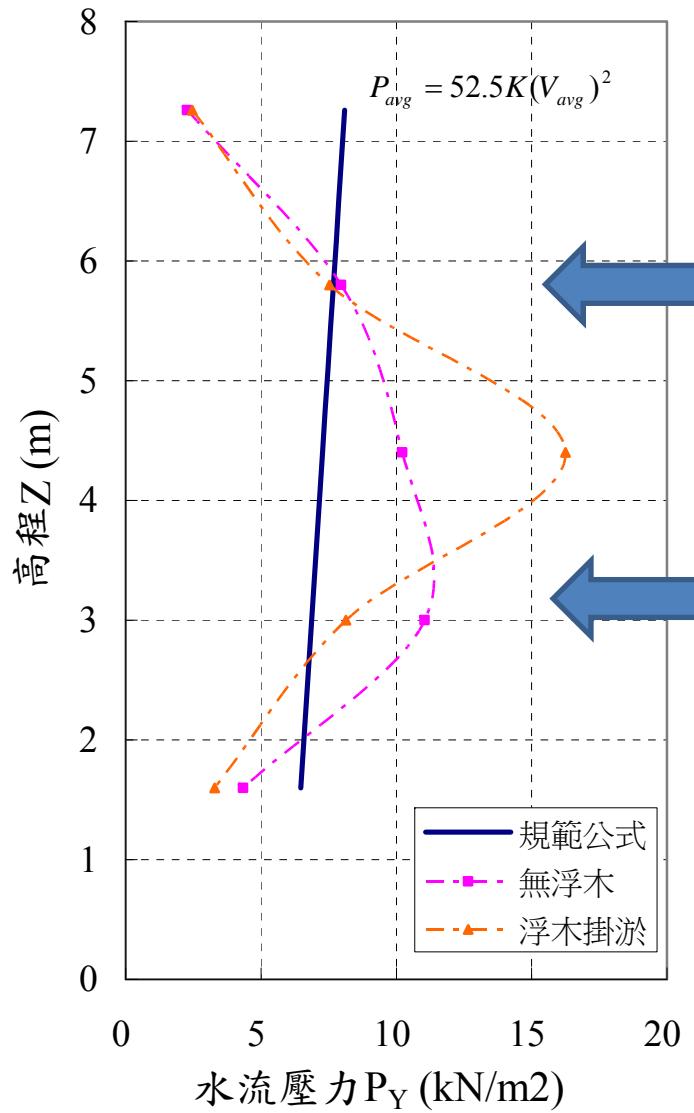


攻角 30 度

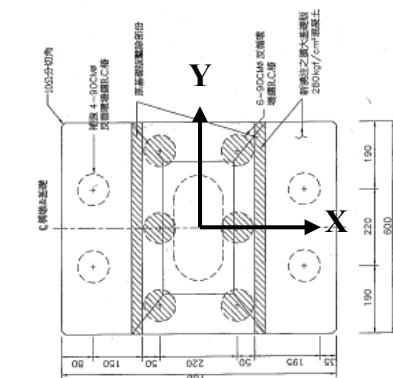
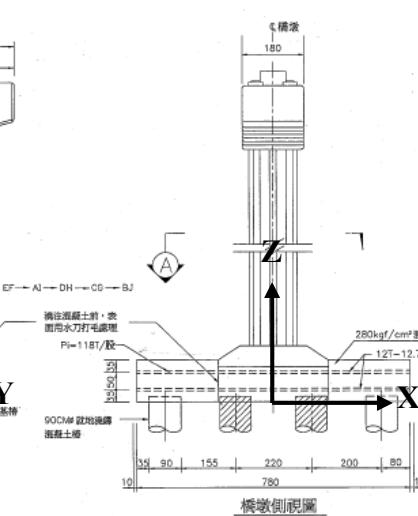
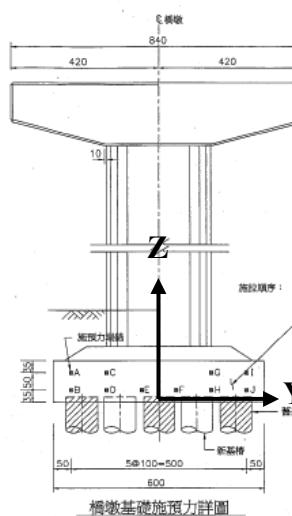
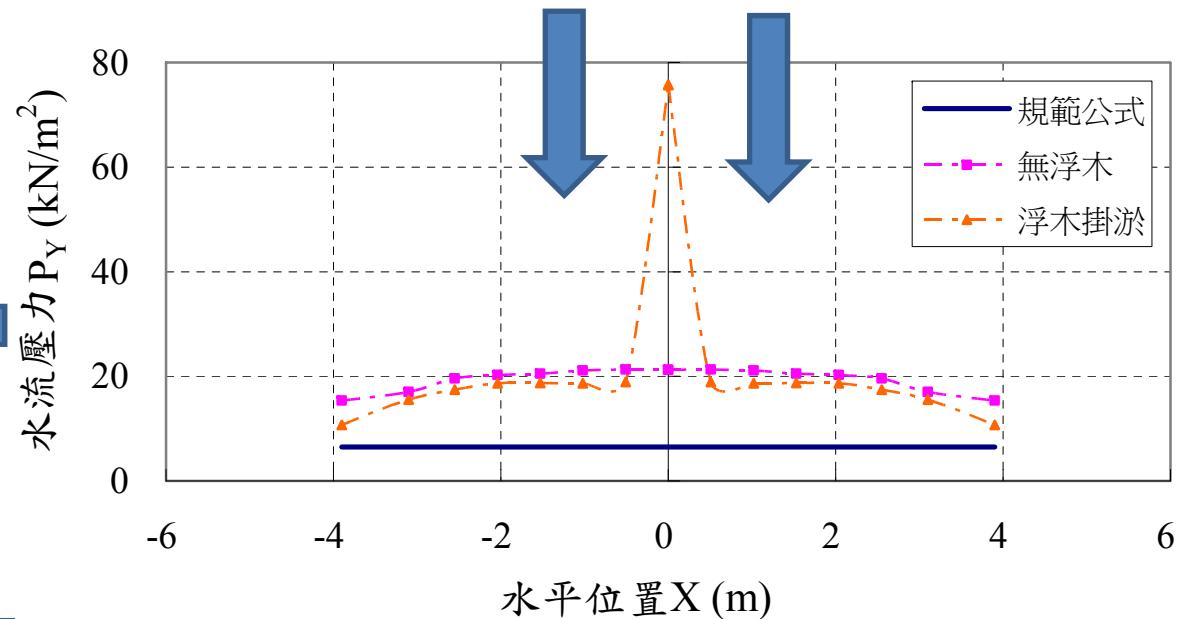


## 單墩模型側推分析

# 橋墩柱水流壓力

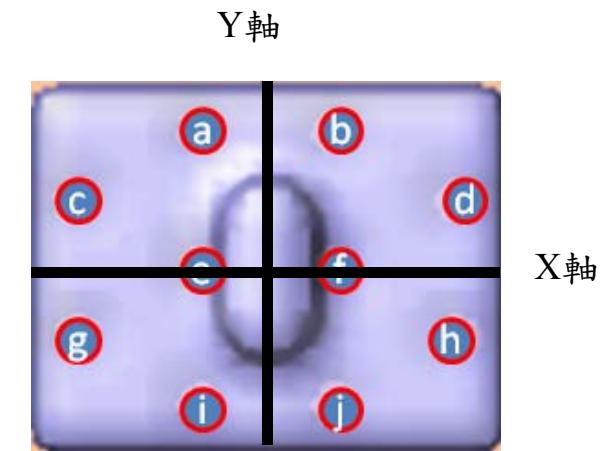
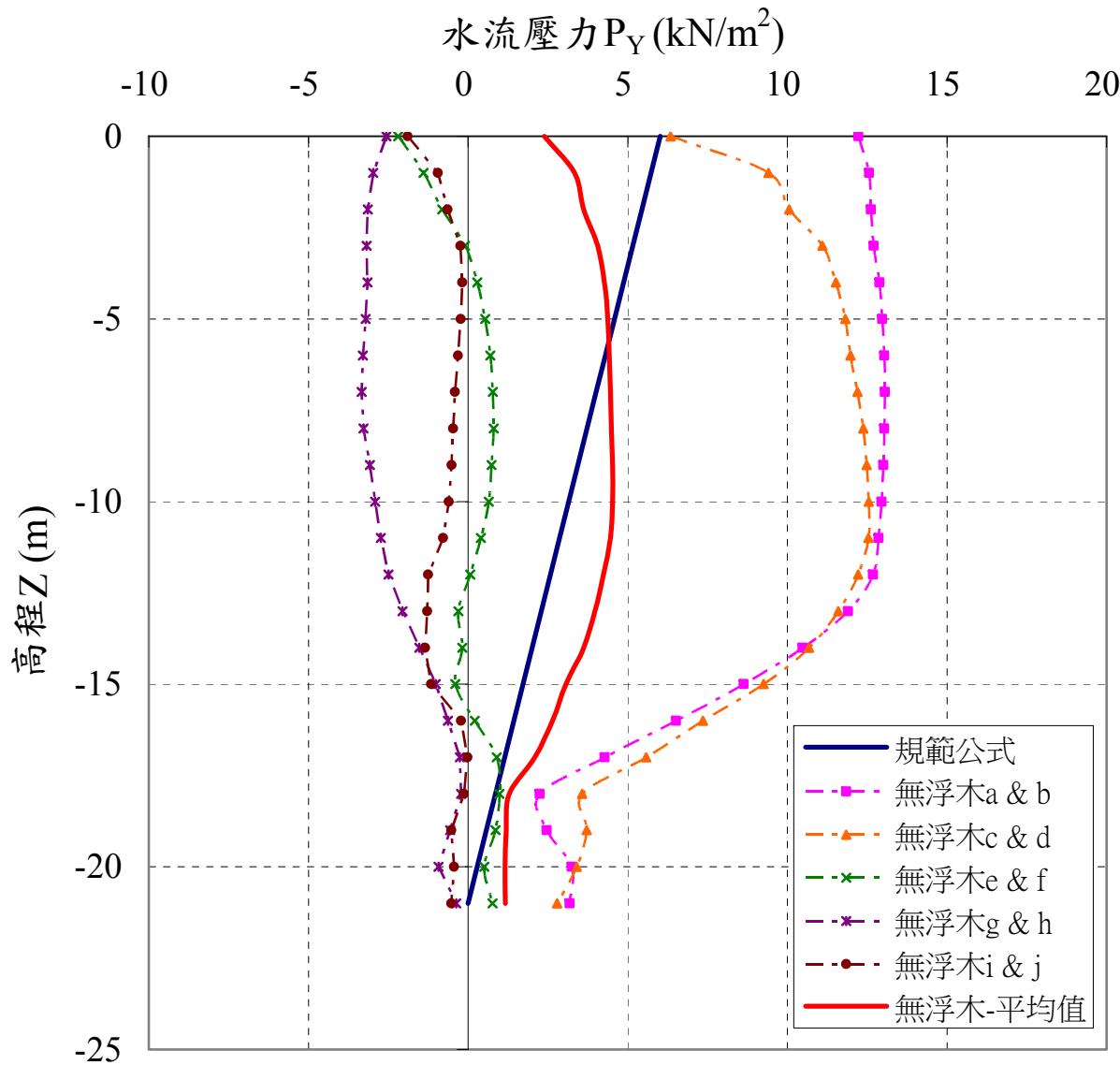


# 樁帽水流壓力



圖中平均值係為 a ~ j 之水流壓力平均值。

## 基樁水流壓力（無浮木）



原有基樁：

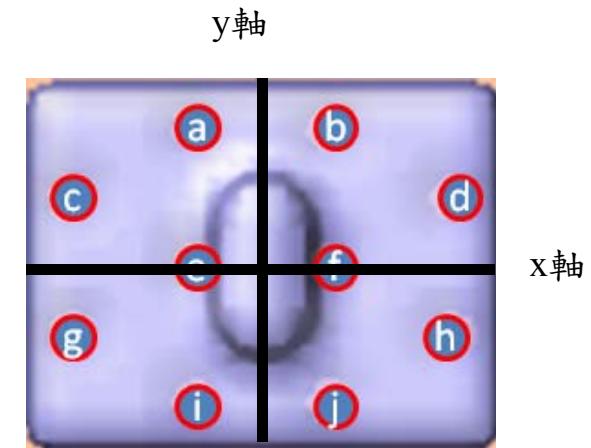
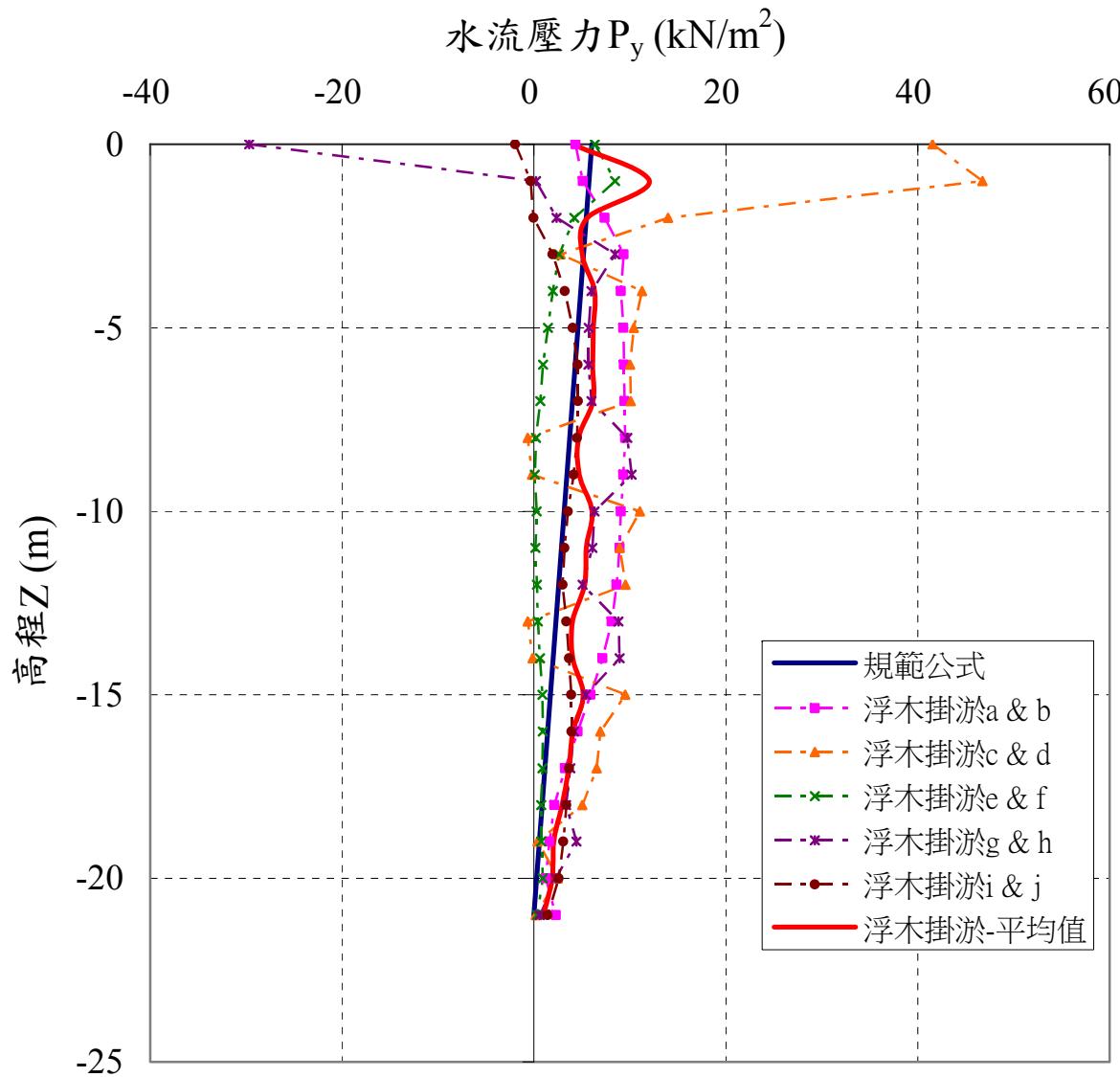
a、b；e、f；i、j

補強新增基樁：

c、d；g、h

# 基樁水流壓力（含浮木掛淤）

圖中平均值係為 a ~ j 之水流壓力平均值。



原有基樁：

a、b；e、f；i、j

補強新增基樁：

c、d；g、h

# Comparison to the Field Survey Data

## Maximum Scour Depth:

Right in front of the bridge piers:

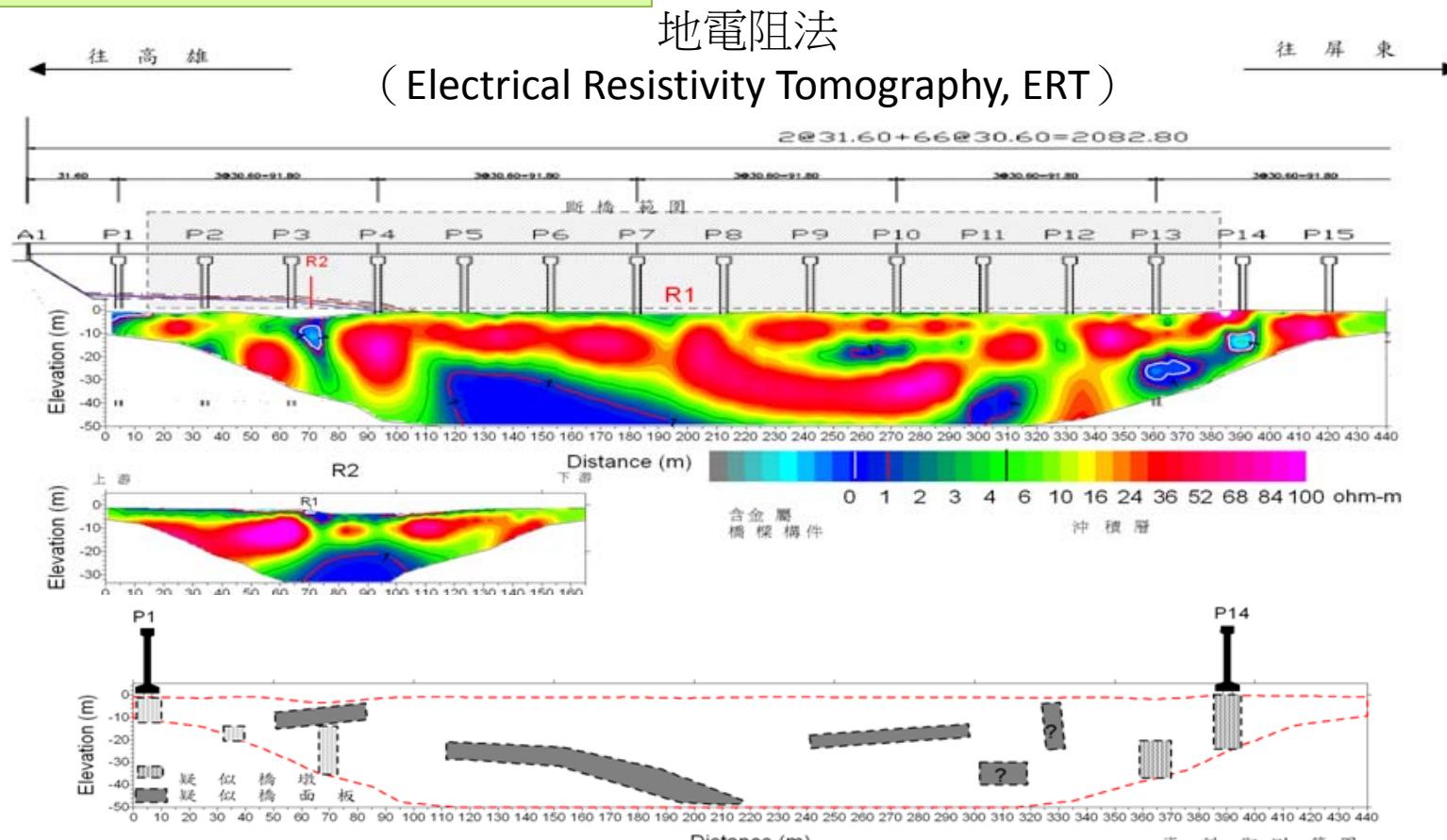
Field survey: about 23 m.

Numerical: 23 m.

30 m upstream away from the bridge piers:

Field survey: 15 m

Numerical: 15 m



雙圓橋殘橋地電阻影像調查成果解釋圖

## 5. SCOUR AROUND THE SEMICIRCULAR ABUTMENT

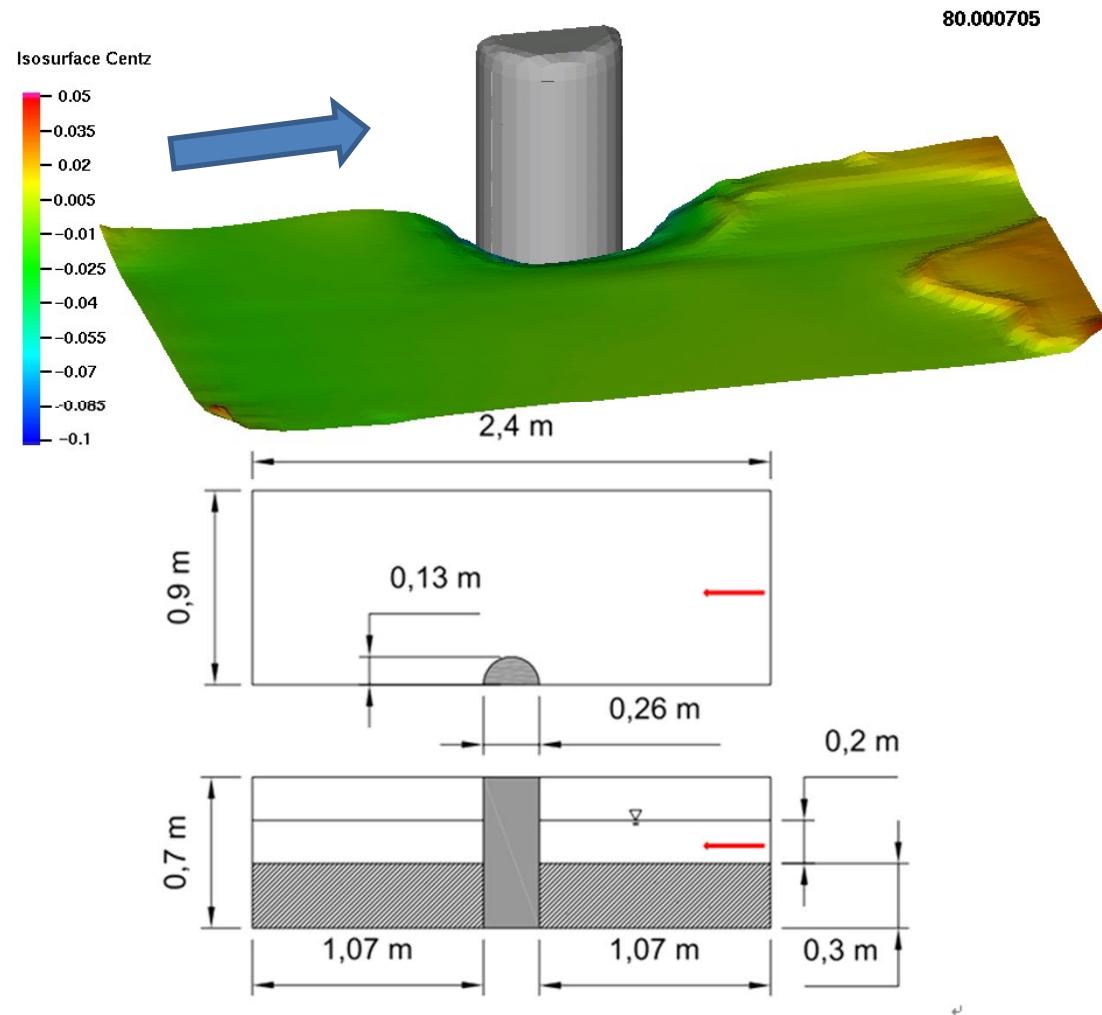
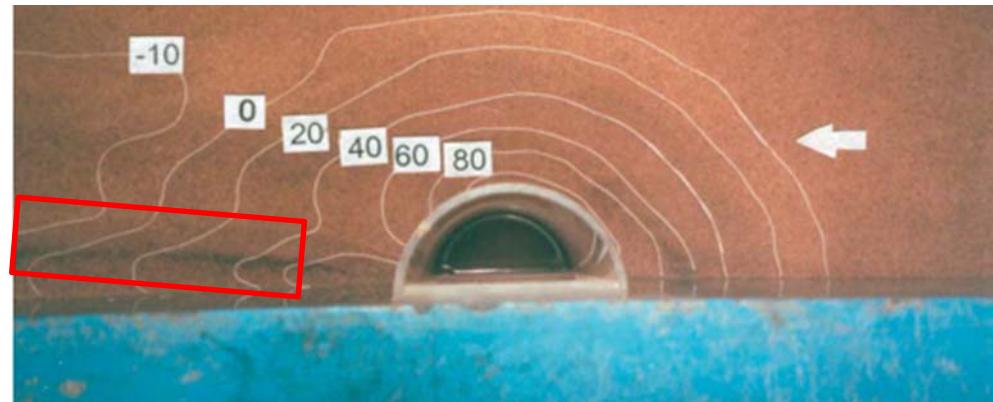
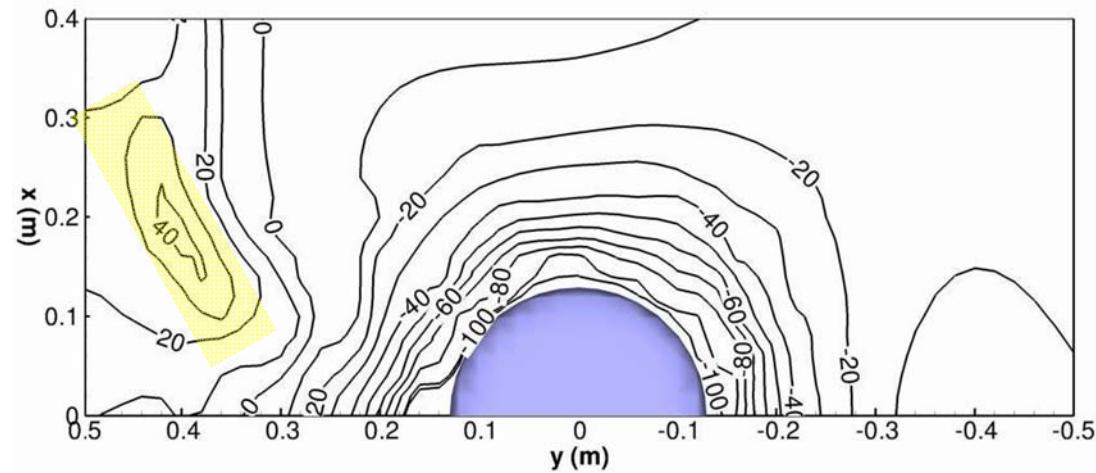


圖 5.1 Dey and Barbhuiya (2005)實驗設置示意圖。上圖為頂視圖，下圖為側視圖。圖中灰色為半圓橋墩，斜線為鋪砂底床，紅上箭頭代表入流方向。

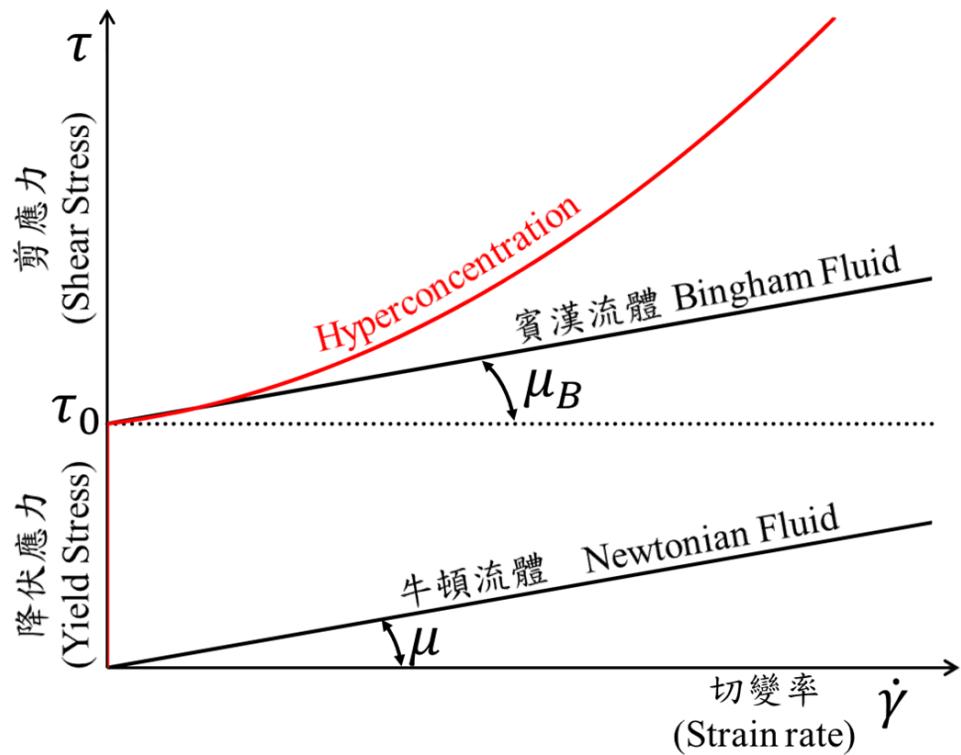
Snapshot of the experiment :



Numerical result without  
particle collision term :



# Rheology for Different non-Newtonian Fluids



The relationships of strain rate and shear stress for Newtonian, traditional Bingham, and quadition Bingham (hyperconcentration) fluids.

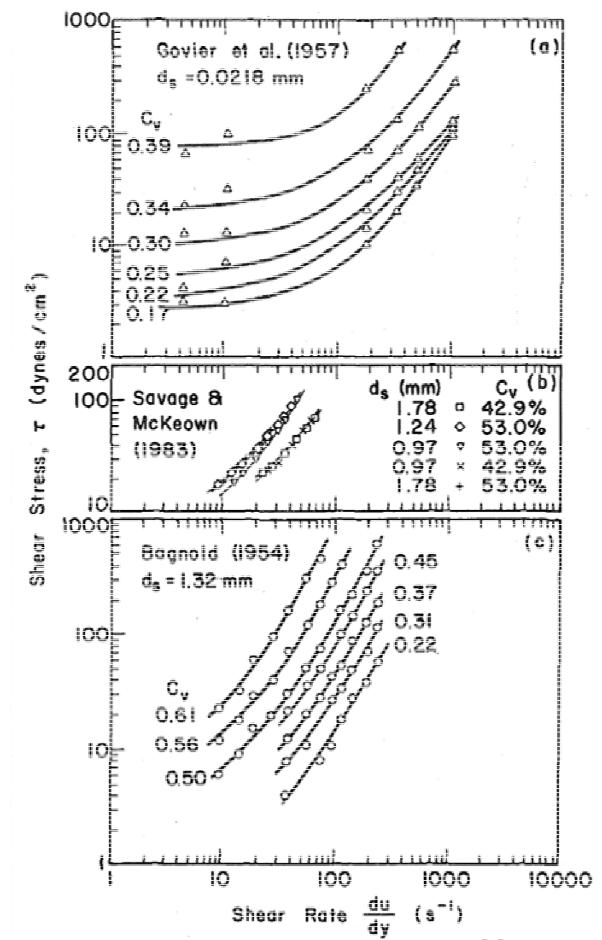


FIG. 1. Rheograms for Three Data Sets: Govier et al. (1957); Savage and McKeown (1983); and Bagnold (1954)

# Hyperconcentrated Sediment Flow

- O'Brien and Julien (1985) 提出方程式，可同時考慮黏滯性及顆粒碰撞特性

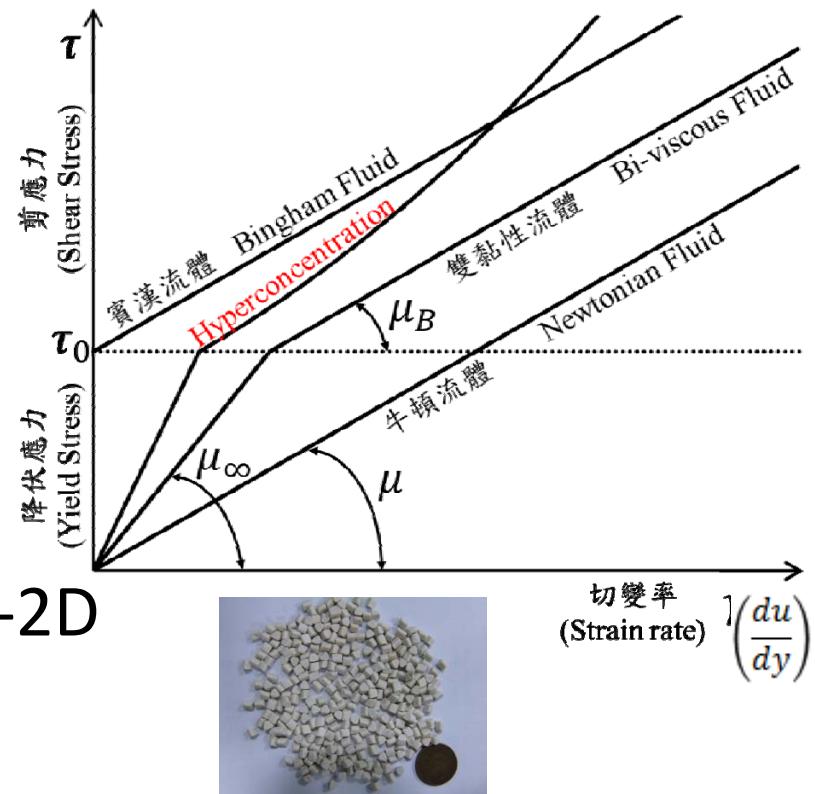
$$\tau = \tau_y + \eta \left( \frac{du}{dy} \right) + \zeta \left( \frac{du}{dy} \right)^2$$

↓      ↓      ↓

降伏應力    一次項    二次項

$$\tau = \tau_0 + \mu_b \cdot \bar{D} + \mu_c \cdot (\bar{D})^2$$

- Liu (2005) developed Debris-2D  
To simulate the debris flow.



# Hyperconcentrated Sediment Flow

$$\tau = \tau_c + \tau_{mc} + \tau_v + \tau_t + \tau_d$$

$\tau$  : 總應力

$\tau_c$  : 凝聚降伏應力(Cohesive Yield Stress)

$\tau_{mc}$  : 莫耳庫倫剪應力(Mohr-Coulomb Shear Stress)

$\tau_v$  : 黏滯剪應力(Viscous Shear Stress)

$\tau_t$  : 紊流剪應力(Turbulent Shear Stress)

$\tau_d$  : 離散剪應力(Dispersive Shear Stress)

$$\tau = \tau_0 + \mu_b \left( \frac{du}{dz} \right) + \mu_c \left( \frac{du}{dz} \right)^2, \tau \geq \tau_0$$

$\tau_0$  : 凝聚降伏應力(Cohesive Yield Stress) & 莫爾庫倫剪應力(Mohr-Coulomb Shear Stress)

$\mu_b$  : 黏滯剪應力(Viscous Shear Stress)

$\mu_c$  : 紊流剪應力(Turbulent Shear Stress) & 離散剪應力(Dispersive Shear Stress)

# Literature Review

Herschel – Bulkly Model (Herschel & Bulkly, 1925)、Bagnald Rheology Model (Bagnald 1954)

O'Brien and Julien (1985) proposed a quadratic rheological model to describe the rheological properties of hyperconcentrated sediment flow.

Julien and Lan (1991), O'Brien and Julien (2000) combined the quadratic rheological model with FLO-2D.

Liu (2006) used the quadratic rheological model in Debris-2D and applied it on field simulation.

(以上模式僅止於二維淺水波水靜力學方程式)

(欲求解三維水動力學方程式需解決1.液面、2.沖刷面、3.固液相變等棘手問題)

# 二次本構關係式導入三維模式

$$\text{剪應力 Shear stress} \quad \tau = 2\mu(\bar{D})\bar{D} \quad \text{切變率 strain rate}$$

賓漢黏滯係數  
Bingham viscosity

降伏應力  
Yield stress (Bingham yield)

二次項  
Quadratic term

$$\mu(\bar{D}) = \begin{cases} \mu_B + \frac{\tau_0}{\sqrt{\frac{1}{2}\bar{D}:\bar{D}}} + \frac{1}{2}\mu_c \cdot \bar{D} & , \quad \frac{1}{2}\tau:\tau \geq \tau_0^2 \quad (\text{液態}) \\ \infty \text{ and } \bar{D} = 0 & , \quad \frac{1}{2}\tau:\tau < \tau_0^2 \quad (\text{固態}) \end{cases}$$

$$\zeta = \rho_m l_m^2 + a_1 \rho_s \lambda^2 d_m^2$$

$\rho_m$  = the density of the mixture

$l_m$  = the mixing length of the mixture

$a_1$  = the empirical constant defined by Bagnold, 0.001

$\rho_s$  = the density of sediment particles

$\lambda$  = the linear concentration

$d_m$  = the diameter of sediment particles

$$\lambda = \left[ \left( \frac{C^*}{C_v} \right)^{1/3} - 1 \right]^{-1}$$

$C^*$  = the maximum volumetric sediment concentration, 0.615

$C_v$  = the volumetric sediment concentration

# 賓漢流參數校驗方式

- 取樣實驗部分，可於採取樣本後，使用流變計進行量測。常見之流變計有管式、旋轉式及移動球法流變計等。
- 藉由量測出流體之剪應力-切變率之關係後，以回歸分析之方式找出降伏應力、黏滯係數與顆粒碰撞係數。

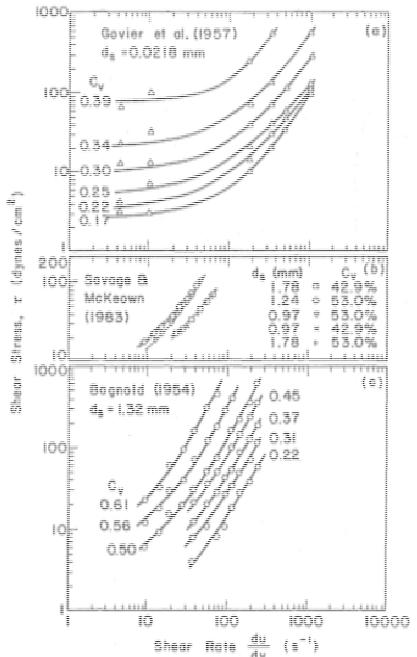
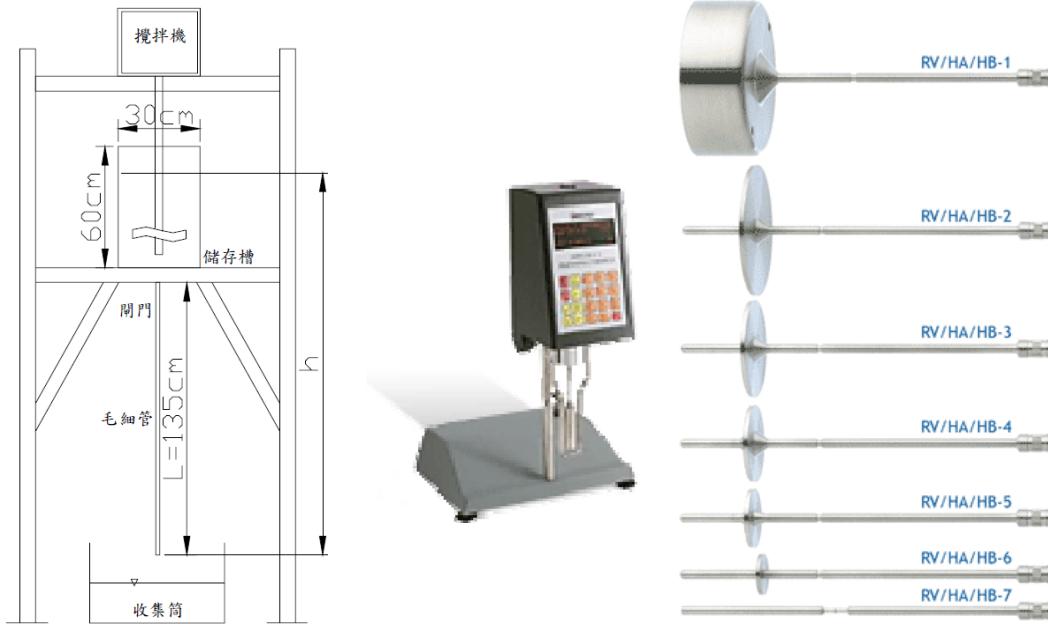
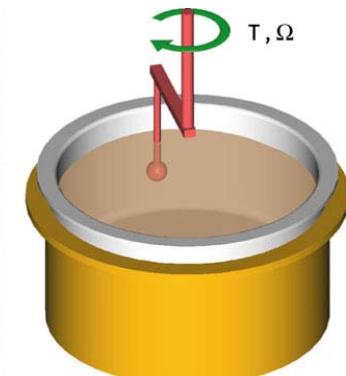


FIG. 1. Rheograms for Three Data Sets: Govier et al. (1957); Savage and McKeown (1983); and Bagnold (1954)



Julien 及 Lan (1991) 提出此消散係數  $\mu_c$  可用<sup>+</sup>

$$\mu_c = \rho_m l_m^2 + a_1 \rho_s \lambda^2 d_s^2 \quad (3-32)$$

來表示，其中<sup>+</sup>

$\rho_m$ ：含泥沙流體之密度<sup>+</sup>

$l_m$ ：含泥沙流體之 Prandtl 混和長度係數，趙(2004)提到 Julien et al.(1991)  
假設  $l_m = 0.4$  倍土石流動深度<sup>+</sup>

$a_1$ ：為一經驗常數，Bagnold 之建議為 0.001<sup>+</sup>

$\rho_s$ ：泥沙顆粒之密度<sup>+</sup>

$d_s$ ：顆粒之粒徑<sup>+</sup>

$\lambda$  由 O'Brien 等人(1993) 引用 Bagnold(1954)定義如下：<sup>+</sup>

$$\lambda = \left[ \left( \frac{C_*}{C_v} \right)^{1/3} - 1 \right]^{-1} \quad (3-33)$$

$C_*$ ：最大體積濃度 ( $C_* \sim 0.615$ )<sup>+</sup>

$C_v$ ：體積濃度<sup>+</sup>

# Plug into our rheological model

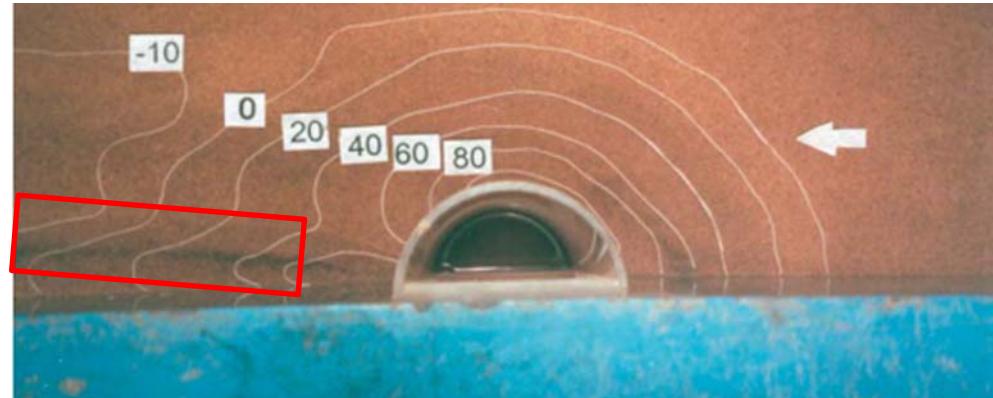
$$\tau = 2\mu(\bar{D})\bar{D}$$

剪應力 Shear stress      切變率 strain rate

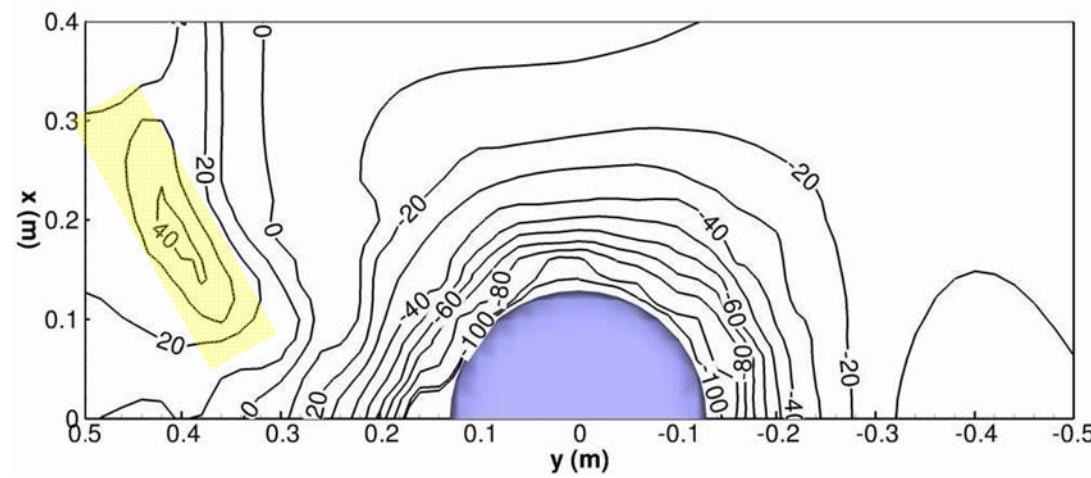
賓漢黏滯係數 Bingham viscosity      降伏應力 Yield stress (Bingham yield)      二次項 Quadratic term

$$\mu(\bar{D}) = \begin{cases} \mu_B + \frac{\tau_0}{\sqrt{\frac{1}{2}\bar{D} \cdot \bar{D}}} + \frac{1}{2}\mu_c \cdot \bar{D} & , \quad \frac{1}{2}\tau : \tau \geq \tau_0^2 \quad (\text{液態}) \\ \infty \text{ and } \bar{D} = 0 & , \quad \frac{1}{2}\tau : \tau < \tau_0^2 \quad (\text{固態}) \end{cases}$$

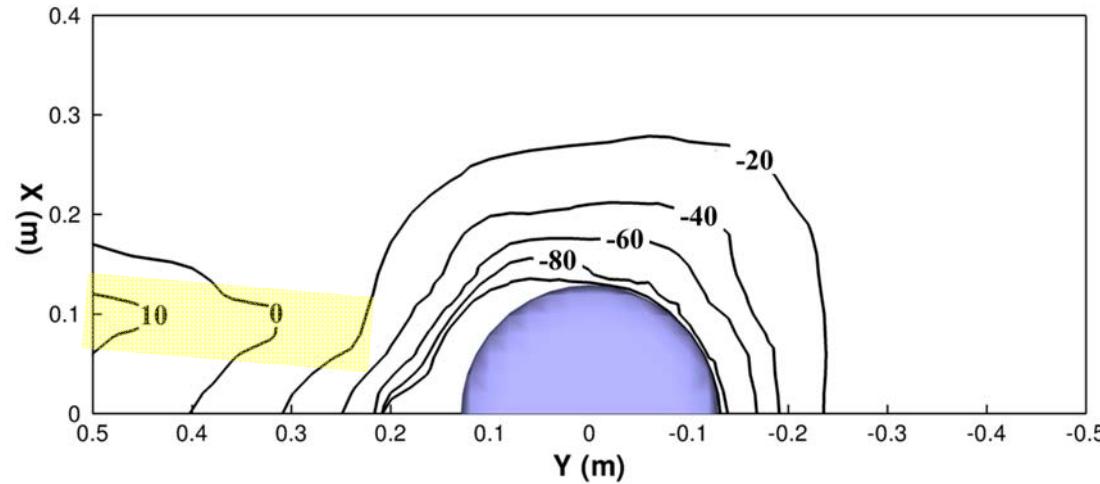
Snapshot of the experiment :



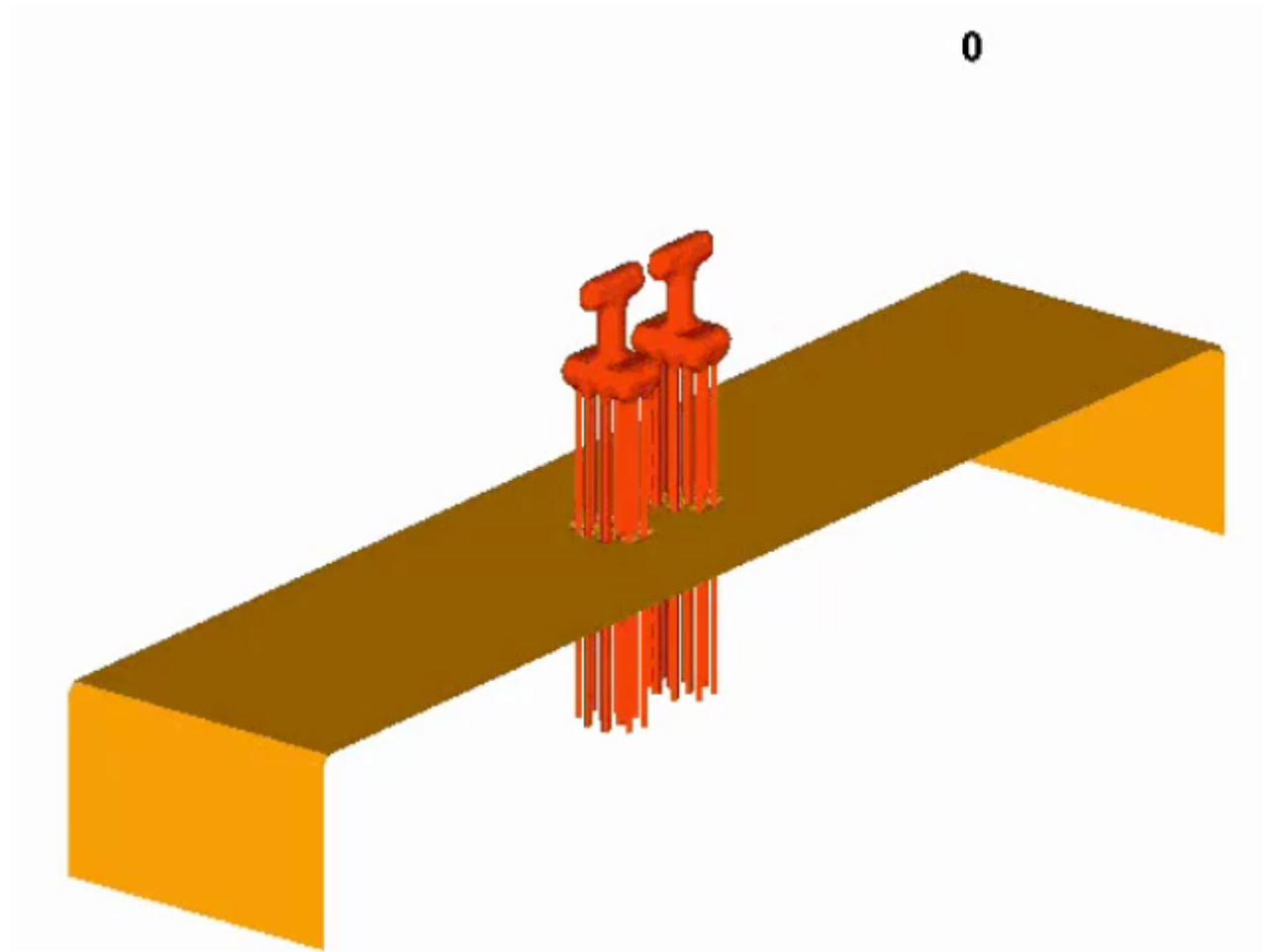
Numerical result without  
particle collision term :



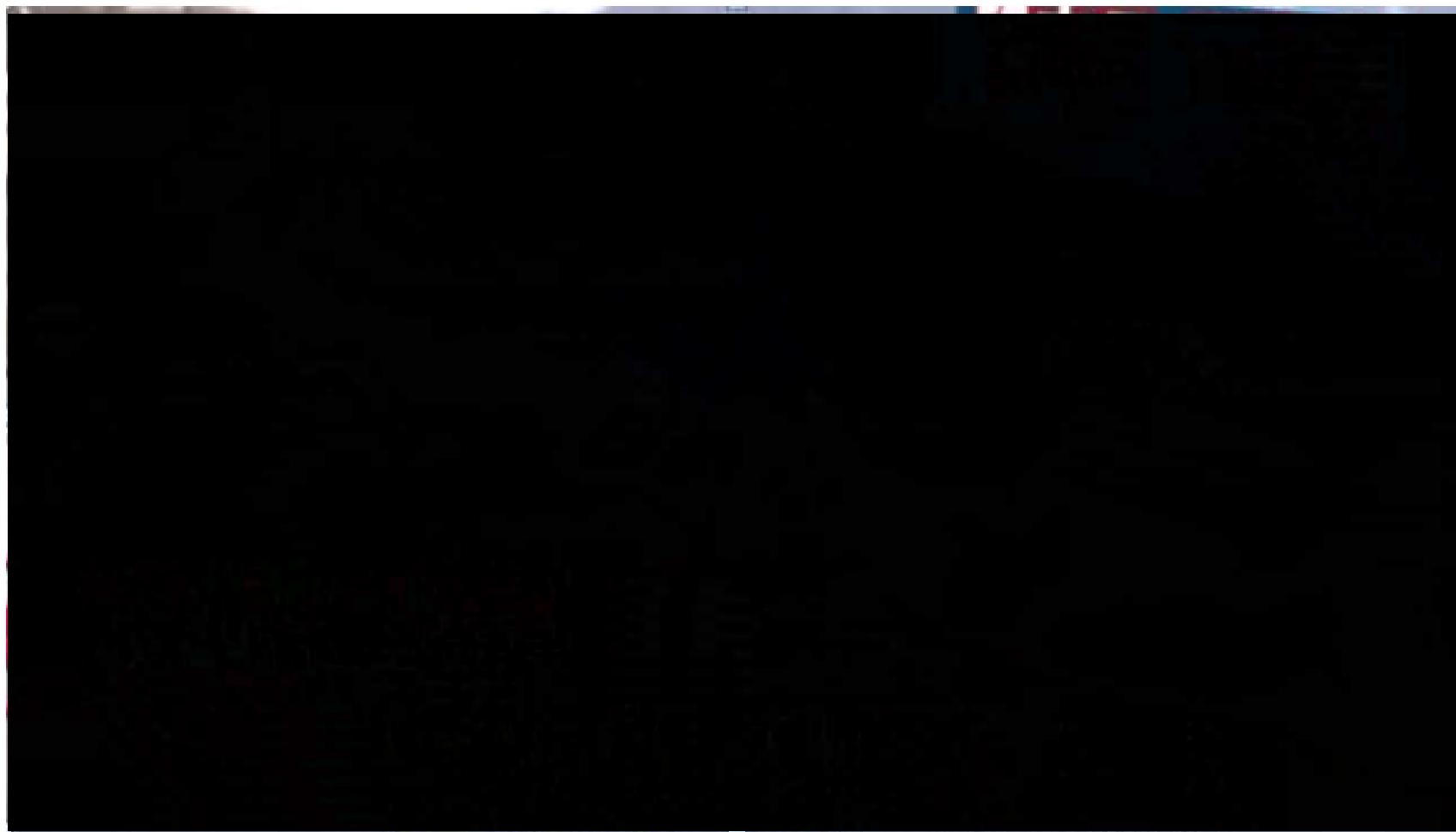
Numerical result with  
practical collision term :



0



# Dirty water?



# Conclusion

- Bingham constitutive model is able to describe mud and sediment motions.
- Combining with VOF model, we are able to simulate the complex local scour problem with only 3 property parameters.
- Very accurate results are presented.
- This model can be used on many practical problems, such as landslide, mudslide, local scour problems.
  
- Thanks for listening. Any questions for Prof. Wu?
- 吳祚任？