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The State of the Art and Science of Coastal Engineering

Numerical Simulation of Three-Dimensional Flow Around Harbor due to Tsunami Using FAVOR Method and WENO Scheme

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INTRODUCTION (1)

Topography Change due to Tsunami

Serious Damage to Harbor Functions

- Damage to the harbor facilities by scouring
- Use restriction of ships by sediment deposition...

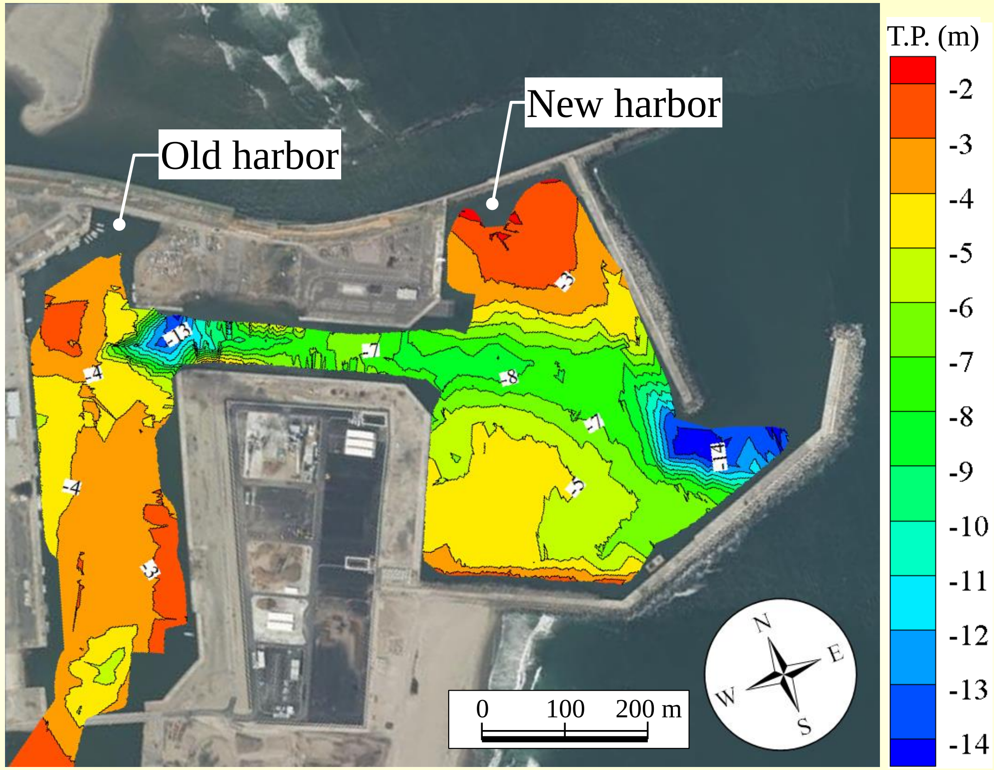
⇨ **It is extremely important for disaster prevention to predict the topography change due to tsunami quantitatively.**

Convectional Prediction Method of Topography Change

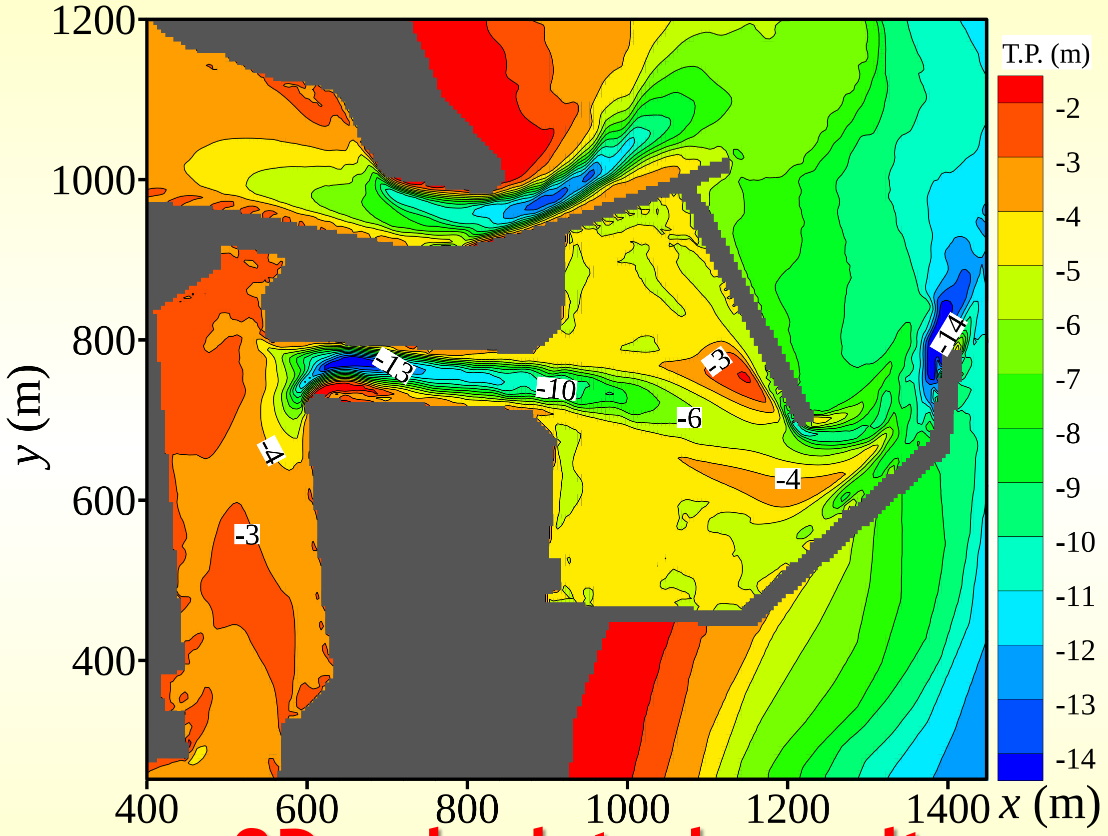
- 2D nonlinear long-wave model for tsunami propagation
- 2D models are practical and very useful for the calculation of large-area.

INTRODUCTION (2)

Example of Topography Change by 2D Model



Bathymetric survey



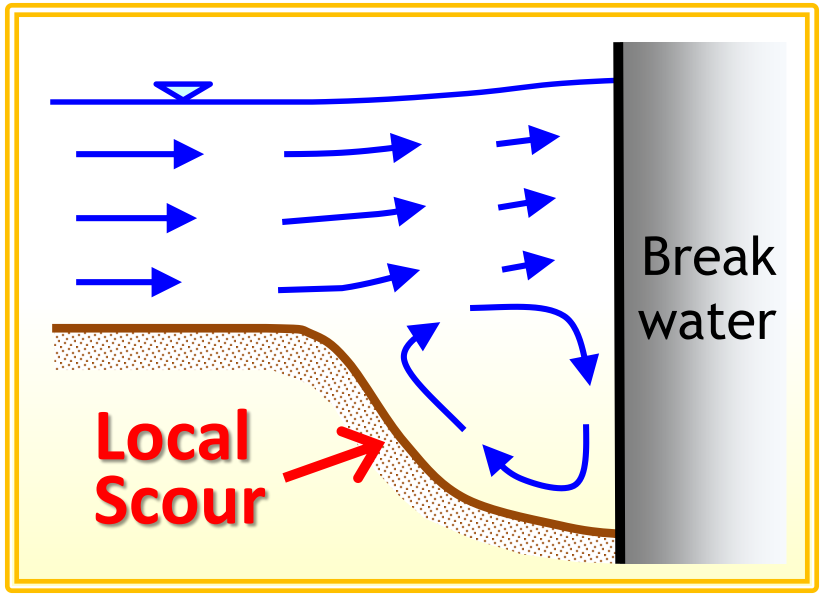
2D calculated result

◎ Erosion in the channel is reproduced well.

⇨ **Local scour at the tip of breakwater is not reproduced.**

INTRODUCTION (3)

Flow in front of a Breakwater



3D flow field is generated around a harbor when tsunami strikes.

A full three-dimensional (3D) flow model is needed to predict the topography change accurately.

First-Order Upwind Scheme

The prediction accuracy decreases due to the numerical diffusion if the calculation mesh is coarse.

In order to avoid the decrease of prediction accuracy...

Application of high-order schemes is effective.

INTRODUCTION (4)

Fifth-order WENO scheme

(**W**eighted **E**ssentially **N**on-**O**scillatory scheme)

⇨ This scheme can calculate discontinuous flows stably and high accuracy.

FAVOR method

(**F**ractional **A**rea/**V**olume **O**bstacle **R**epresentation method)

⇨ This method can impose boundary conditions smoothly at complicated boundaries in the Cartesian coordinate system.

Purpose

Development of a 3D tsunami flow model using the FAVOR method and the WENO scheme in order to predict a flow field around a harbor accurately.

NUMERICAL MODEL (1)

Governing Equations introduced with FAVOR method

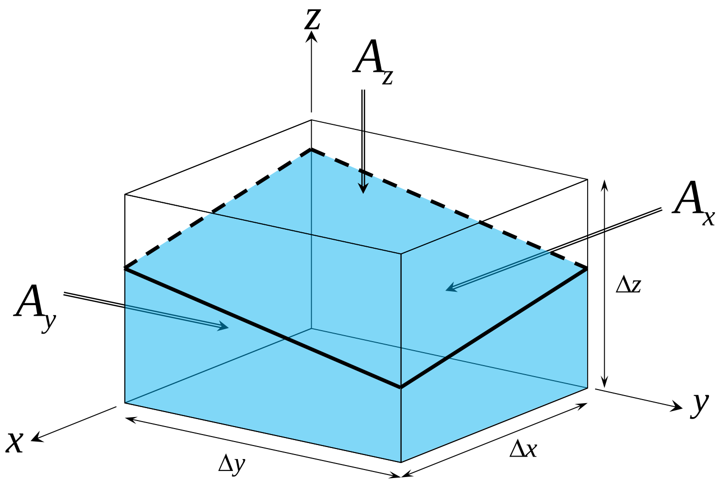
Continuity equation

$$\frac{\partial}{\partial x_j}\left\{A_{(j)}u_j\right\}=0$$

Momentum equation

$$\frac{\partial u_i}{\partial t}+\frac{1}{V}\left\{\frac{\partial A_{(j)}u_ju_i}{\partial x_j}\right\}=-g\delta_{3i}-\frac{1}{\rho}\frac{\partial P}{\partial x_i}+\frac{1}{V}\frac{\partial}{\partial x_j}\left\{A_{(j)}\left(\nu+\nu_t\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right\}$$

where, i, j = 1,2,3; $(x_1, x_2, x_3) = (x, y, z)$; u_i = velocity in x_i direction; V = fractional volume rate; $A_{(i)}$ = fractional area rate in x_i direction $[(A_{(1)}, A_{(2)}, A_{(3)}) = (A_x, A_y, A_z)]$; g = gravitational acceleration; δ = Kronecker's delta; ρ = fluid density; $P = p + 2/3k$; p = pressure; ν = kinematic viscosity of fluid



***k*-equation**

$$\frac{\partial k}{\partial t}+\frac{1}{V}\left\{\frac{\partial A_{(j)}u_jk}{\partial x_j}\right\}=\frac{1}{V}\frac{\partial}{\partial x_j}\left\{A_{(j)}\nu_k\frac{\partial k}{\partial x_j}\right\}+\nu_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\varepsilon$$

***ε*-equation**

$$\frac{\partial \varepsilon}{\partial t}+\frac{1}{V}\left\{\frac{\partial A_{(j)}u_j\varepsilon}{\partial x_j}\right\}=\frac{1}{V}\frac{\partial}{\partial x_j}\left\{A_{(j)}\nu_\varepsilon\frac{\partial \varepsilon}{\partial x_j}\right\}+C_1\frac{\varepsilon}{k}\nu_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-C_2\frac{\varepsilon^2}{k}$$

$$\nu_t=C_\mu\left(k^2/\varepsilon\right)$$

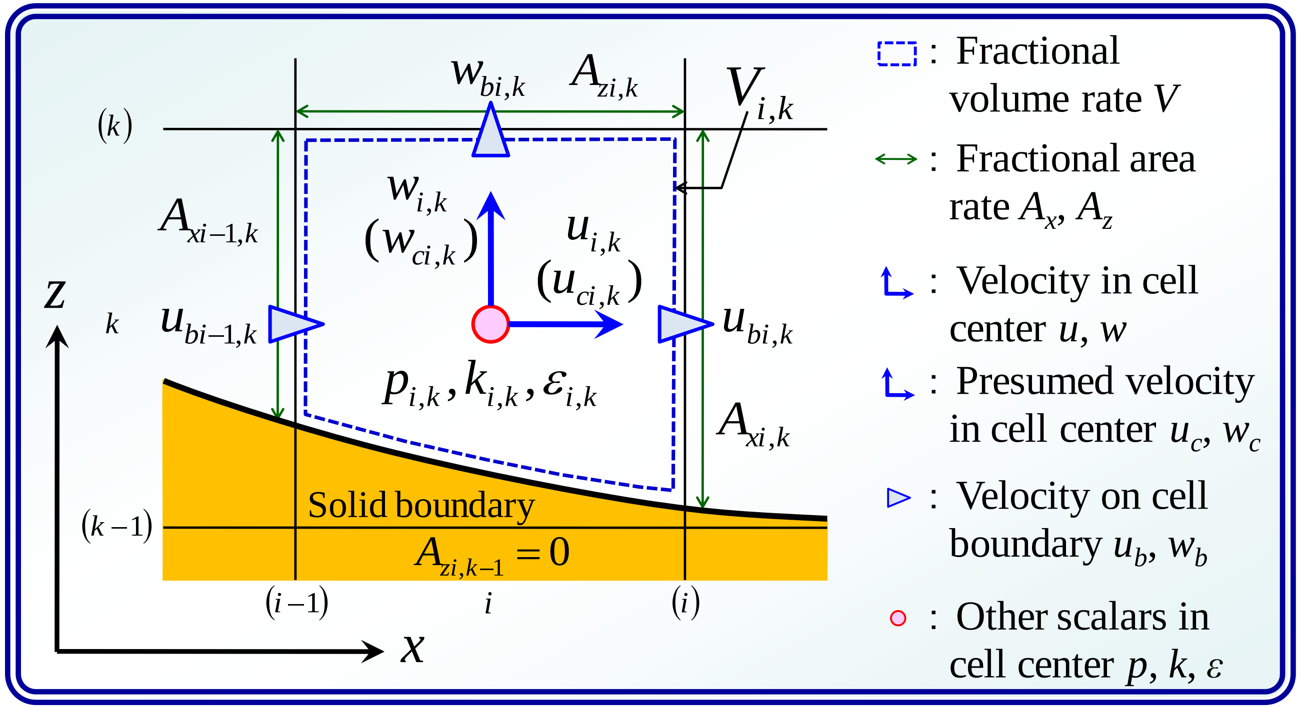
$$\nu_k=\nu+\nu_t/\sigma_k$$

$$\nu_\varepsilon=\nu+\nu_t/\sigma_\varepsilon$$

C_μ = 0.09 , σ_k = 1.00 , σ_ε = 1.30 , C_1 = 1.44 , C_2 = 1.92

NUMERICAL MODEL (2)

Numerical scheme



◎ Adaptation of Collocated grid

⇨ Since a control volume can be represented by one grid, introduction of the FAVOR method is easy.

Discretization method

⇨ Momentum equation : { WENO scheme for convection terms / Adams-Bashforth method for time integration

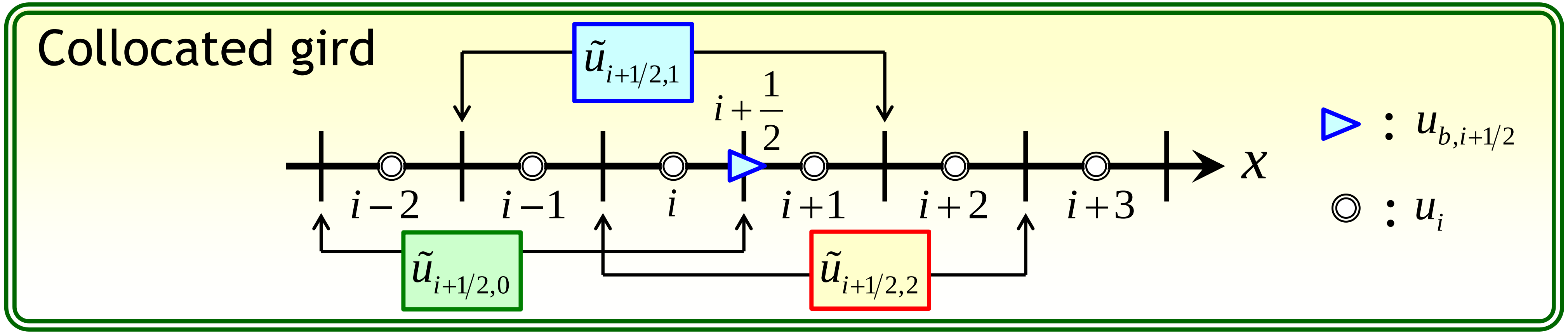
⇨ Pressure : HSMAC method on collocated grid arrangement

⇨ Turbulent model : Hybrid scheme for advective term

NUMERICAL MODEL (3)

Discretization of Convection Terms by WENO scheme

$$\frac{1}{V}\frac{\partial\left(A_x uu\right)}{\partial x}=\frac{A_{x,i+1/2}u_{b,i+1/2}\tilde{u}_{i+1/2}-A_{x,i-1/2}u_{b,i-1/2}\tilde{u}_{i-1/2}}{V_i\cdot\Delta x}+O\left(\Delta x^5\right)$$



If ($u_{b,i+1/2}\geq 0$) then

$$\tilde{u}_{i+1/2,0}=\frac{1}{3}u_{i-2}-\frac{7}{6}u_{i-1}+\frac{11}{6}u_i$$

$$\tilde{u}_{i+1/2,1}=-\frac{1}{6}u_{i-1}+\frac{5}{6}u_i+\frac{1}{3}u_{i+1}$$

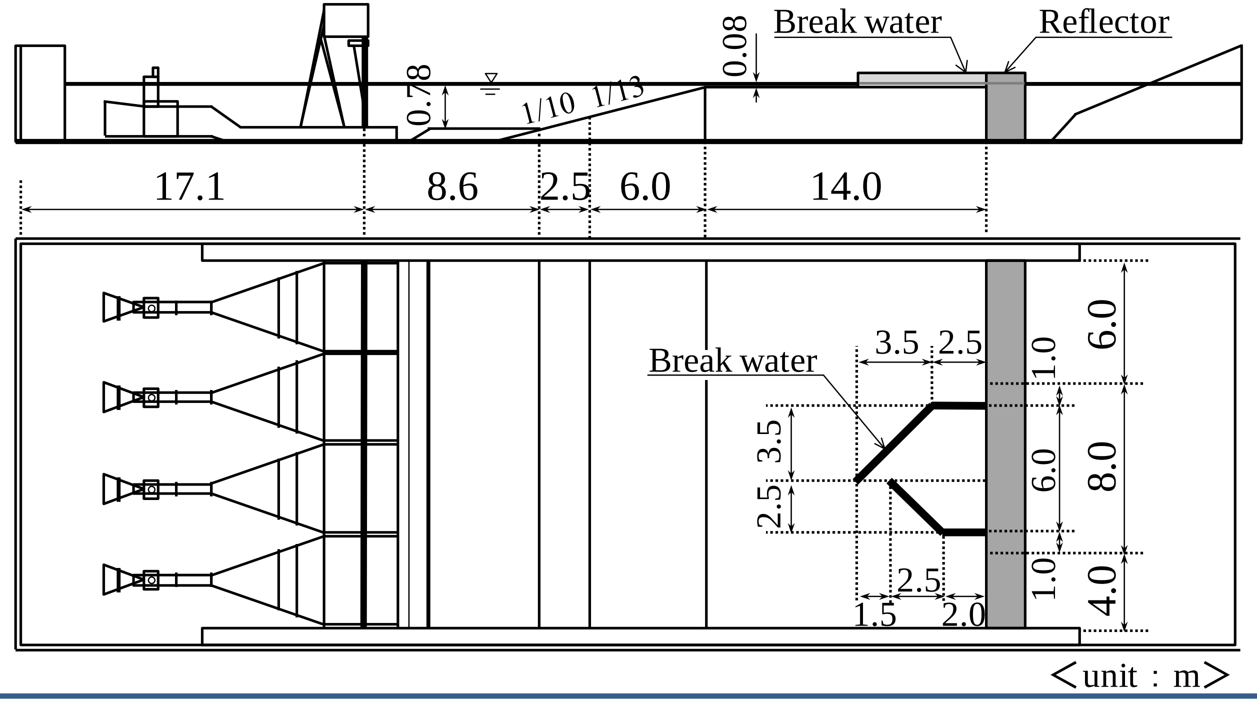
$$\tilde{u}_{i+1/2,2}=\frac{1}{3}u_i+\frac{5}{6}u_{i+1}-\frac{1}{6}u_{i+2}$$

$$\tilde{u}_{i+1/2}=\sum_{s=0}^{2}\omega_s\tilde{u}_{i+1/2,s}$$

where, ω_s = weighted values associated with each stencil

EXPERIMENTAL CONDITIONS

Laboratory Experiment (Fujii et al. 2009)



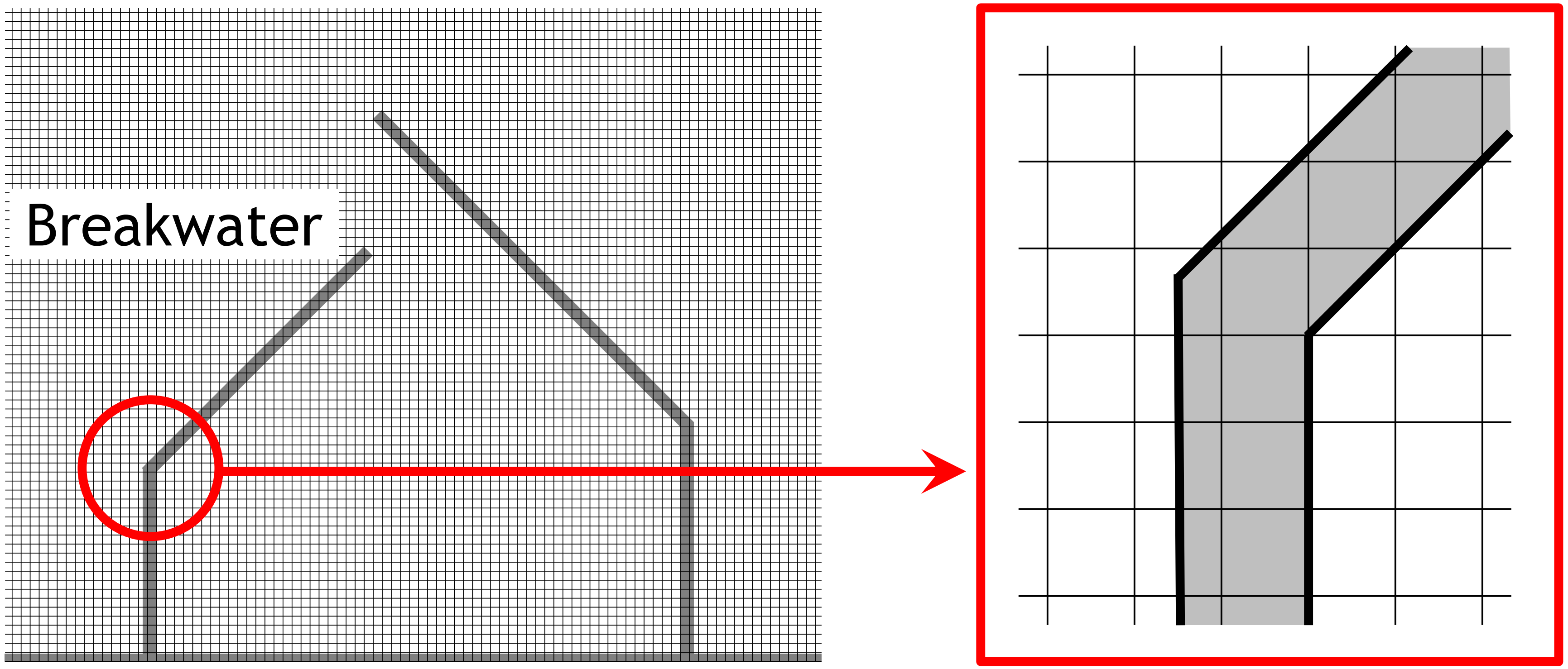
◎ Experimental Conditions

Thickness of breakwater	0.15 m
Initial flow depth h	0.08 m
Tsunami conditions	30 sec, 0.06 m

Fujii, N., Ikeno, M., Sakakiyama, T., Matsuyama, M., Takao, M., Mukohara, T., Hydraulic experiment on flow and topography change in harbor due to tsunami and its numerical simulation. *J. Japan Society of Civil Eng.*, B2-65 (1), 291-295 (in Japanese with English abstract) (2009).

CALCULATION CONDITIONS

Calculation Mesh

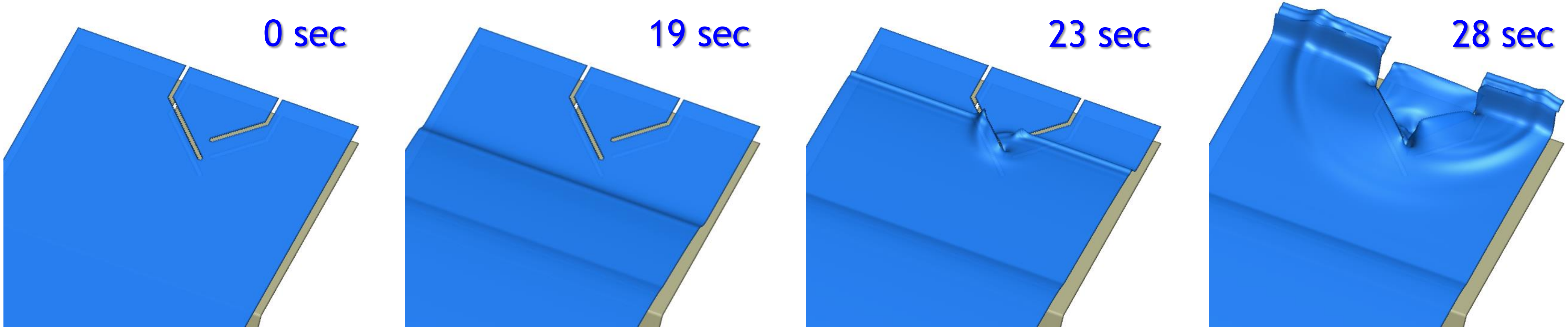


◎ Calculation Conditions

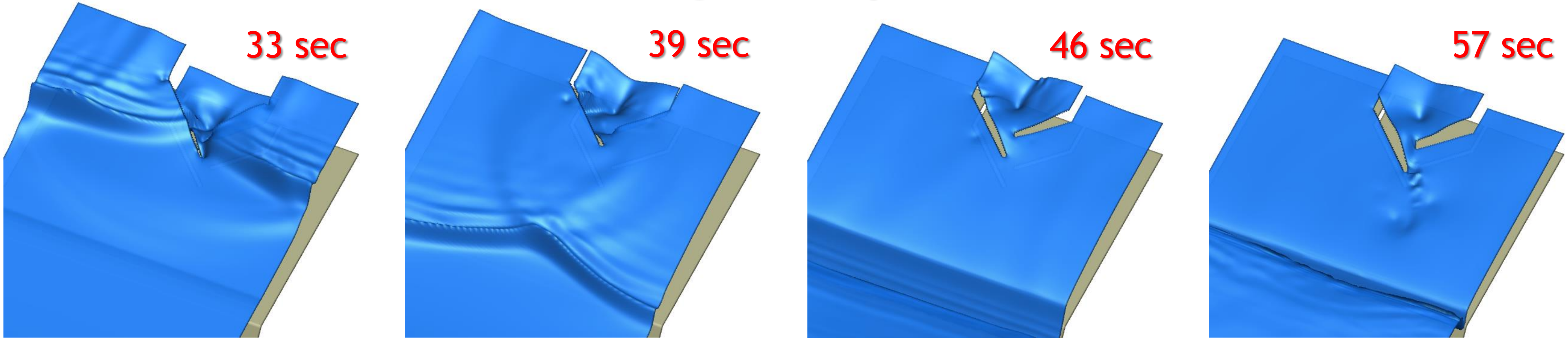
Δt (sec)	0.005	Δz (m)	0.02
Δx, Δy (m)	0.10	n (s/m$^{1/3}$)	0.012

RESULTS & DISCUSSIONS (1)

Bird’s-Eye View of Water Surface (Calculation)



Leading wave process



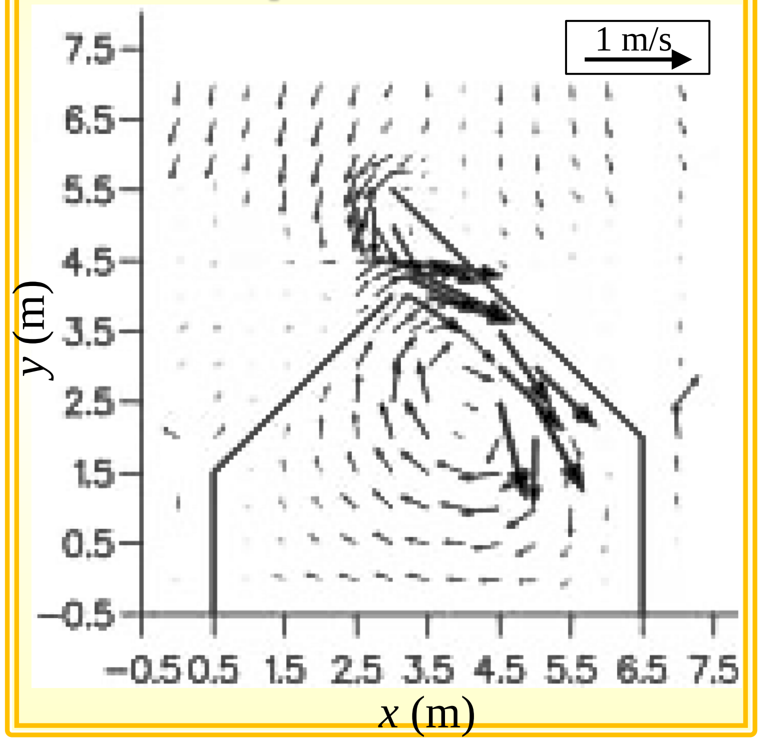
Backwash process

RESULTS & DISCUSSIONS (2)

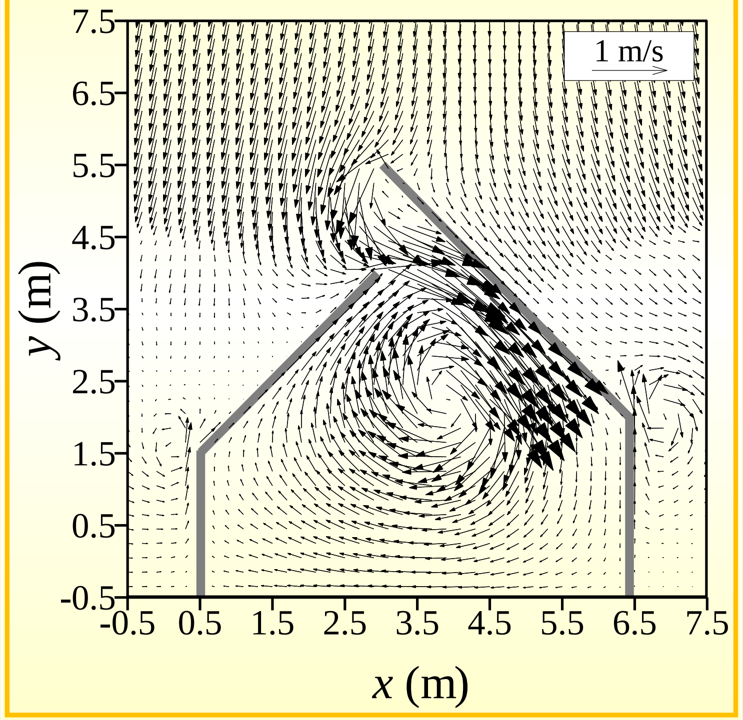
Comparisons of Flow Velocity Vectors

◎ Leading wave process of tsunami

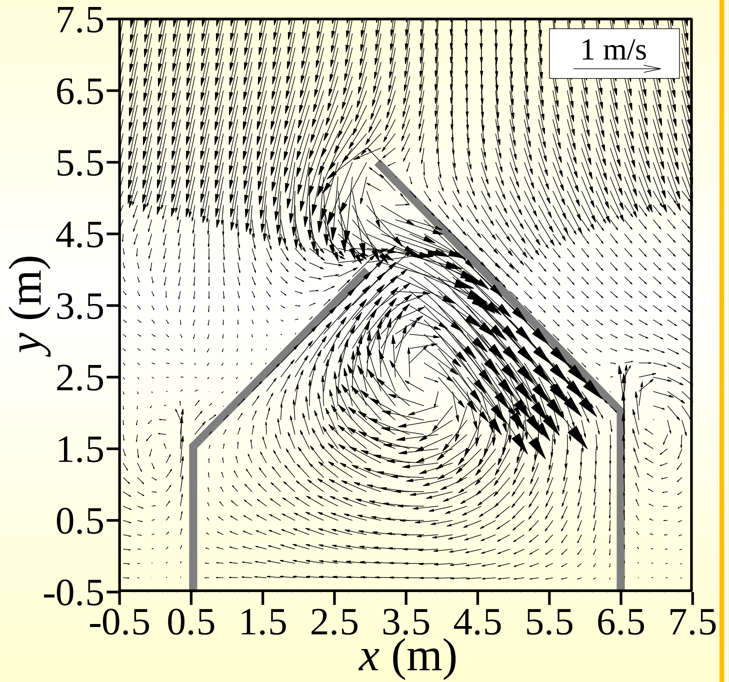
Experiment



WENO scheme



First-order scheme



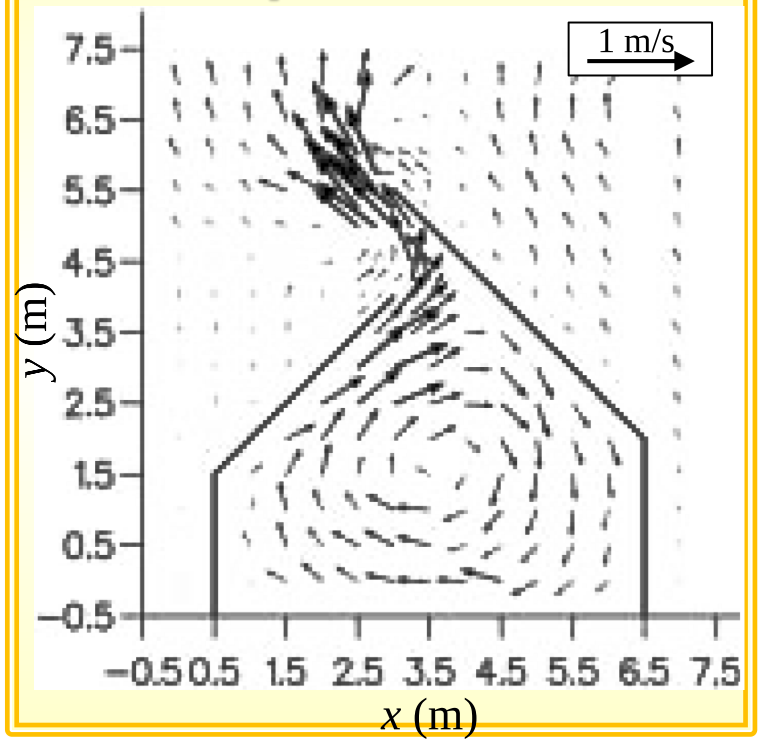
⇨ Calculated flows near breakwaters are reproduced smoothly along the breakwaters by introducing the FAVOR method.

RESULTS & DISCUSSIONS (3)

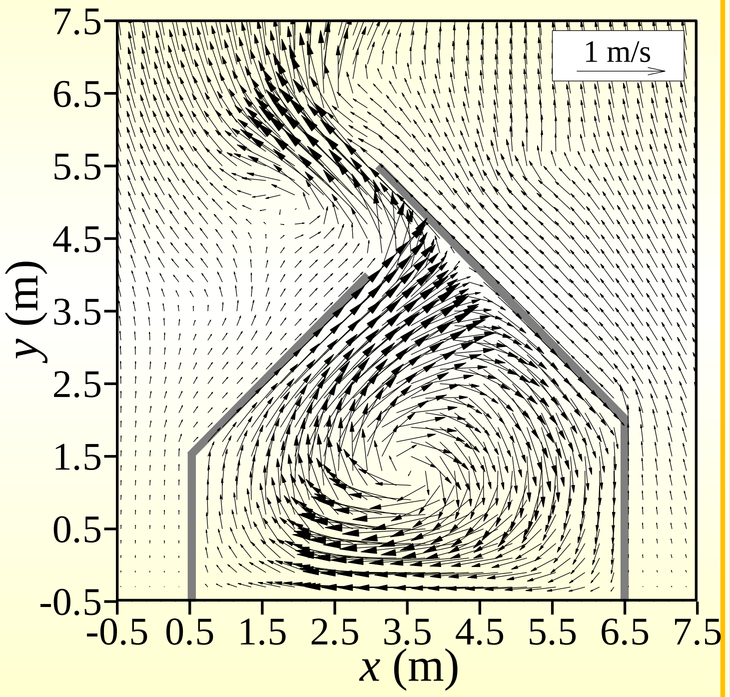
Comparisons of Flow Velocity Vectors

- Backwash process of tsunami

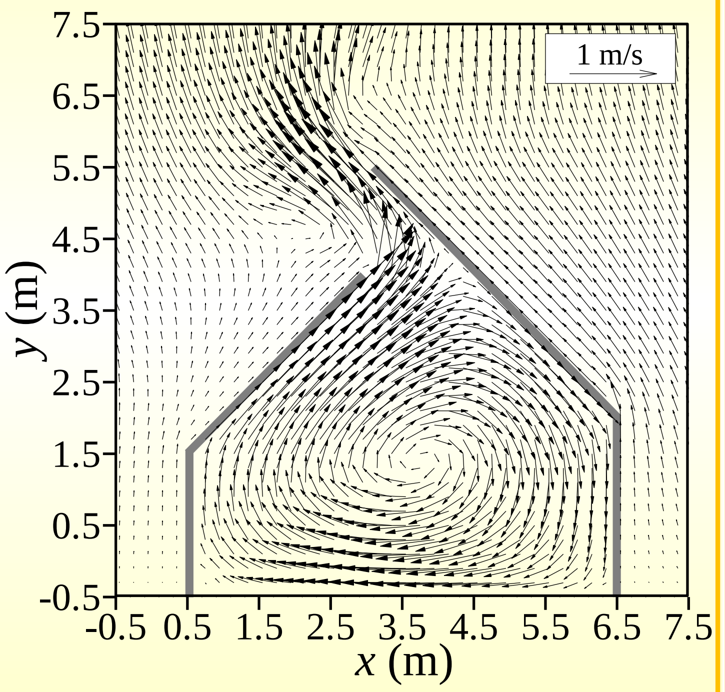
Experiment



WENO scheme



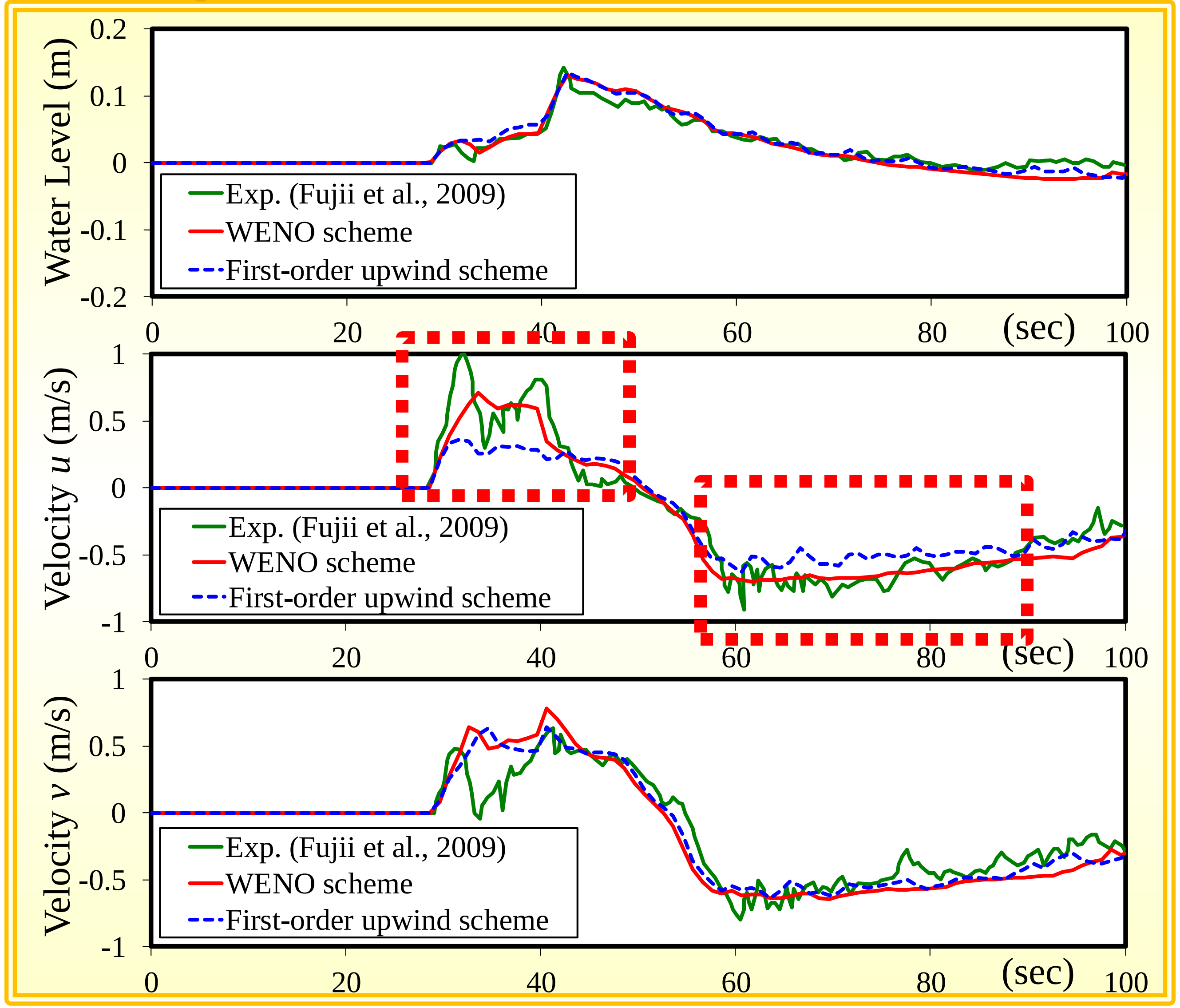
First-order scheme

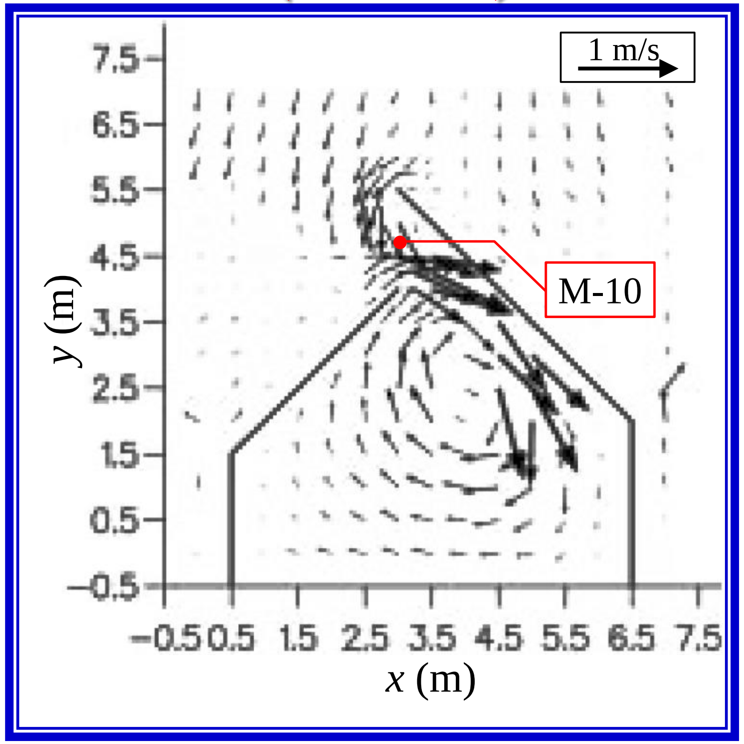


⇨ Flow spreading by numerical diffusion is reduced in the WENO scheme.

RESULTS & DISCUSSIONS (4)

Comparisons of Time Variation of Flow (M-10)

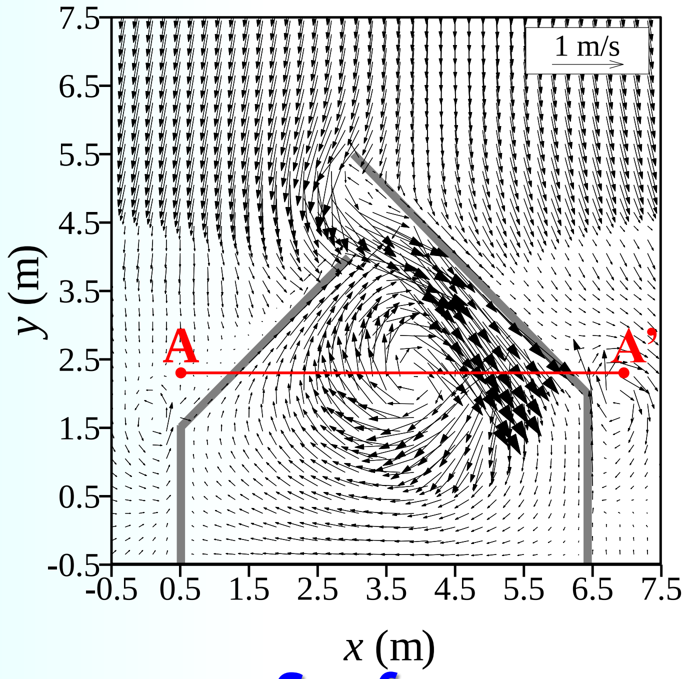




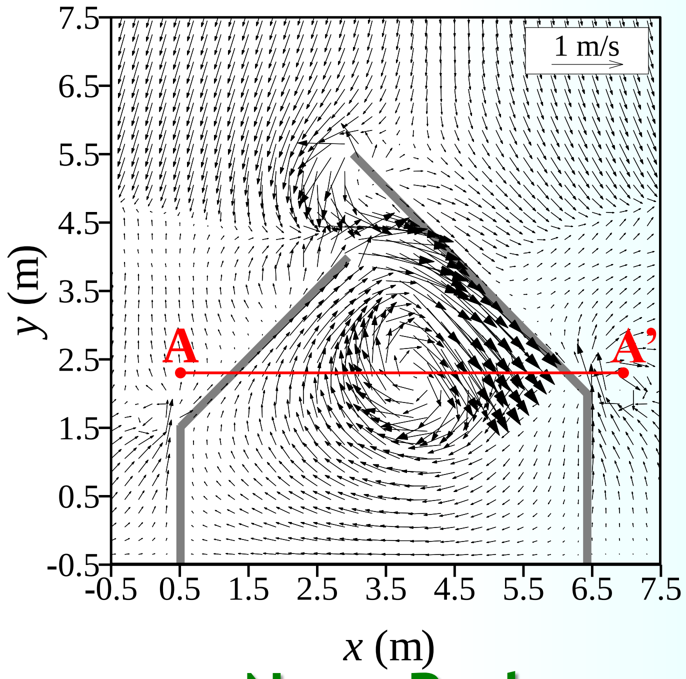
Regarding velocity ***u***, the calculated result by WENO scheme is good agreement with the experimental data.

RESULTS & DISCUSSIONS (6)

3D Flow at the Time of Leading Wave (Calculation)

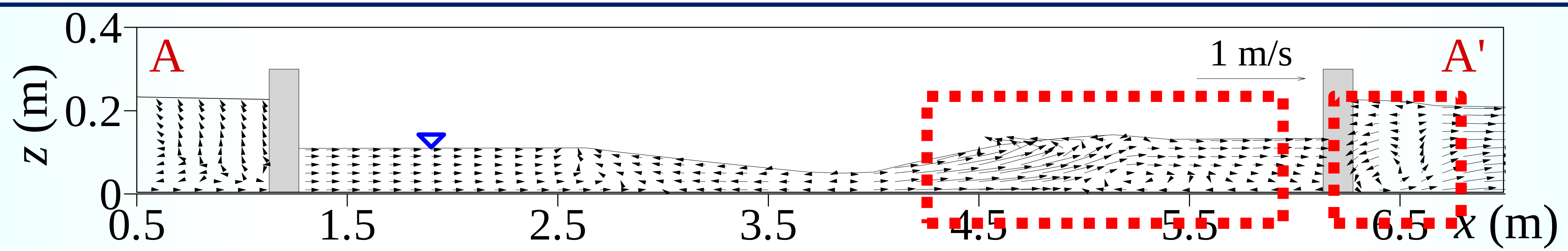


Surface



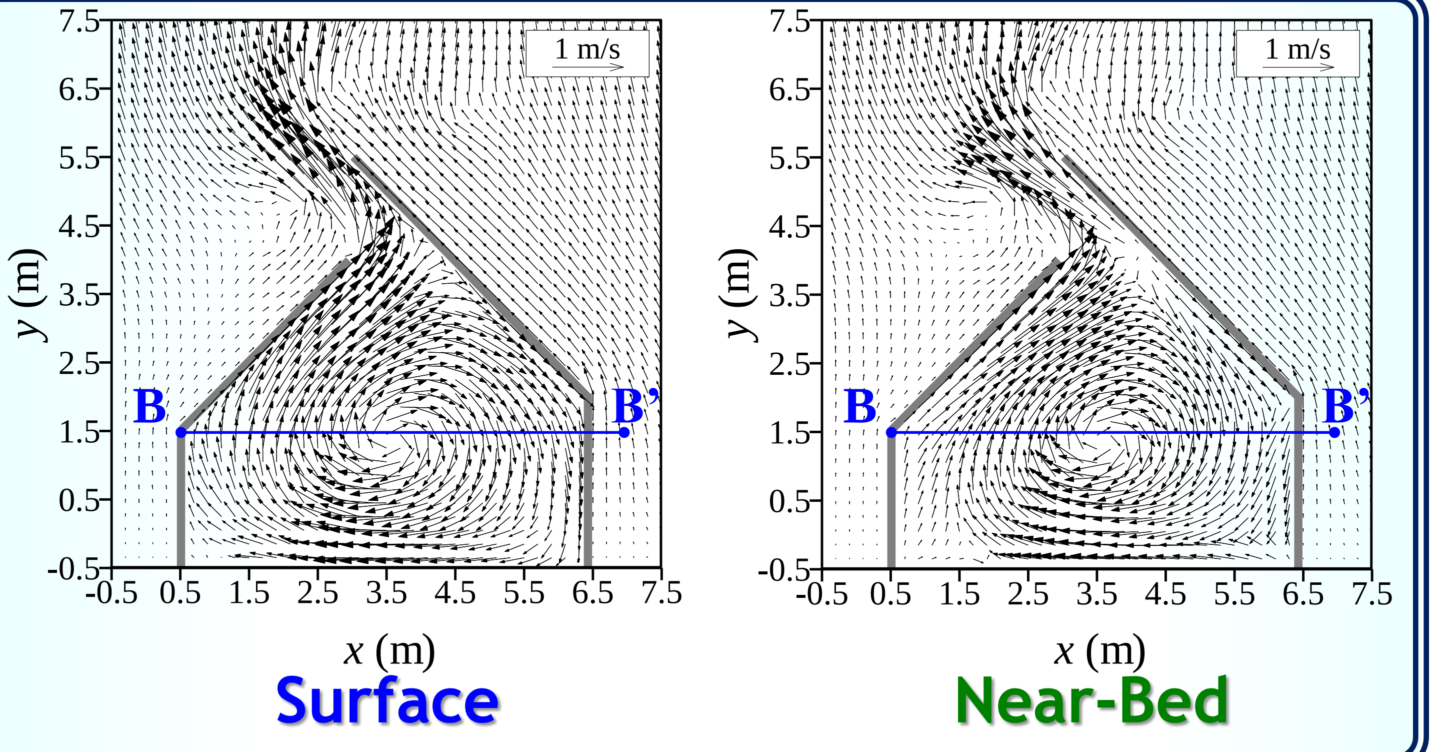
Near-Bed

- Scale of the circulating flow in the harbor differs between water surface and near-bed.
- Some vortex flows are generated in the harbor and near the breakwater.

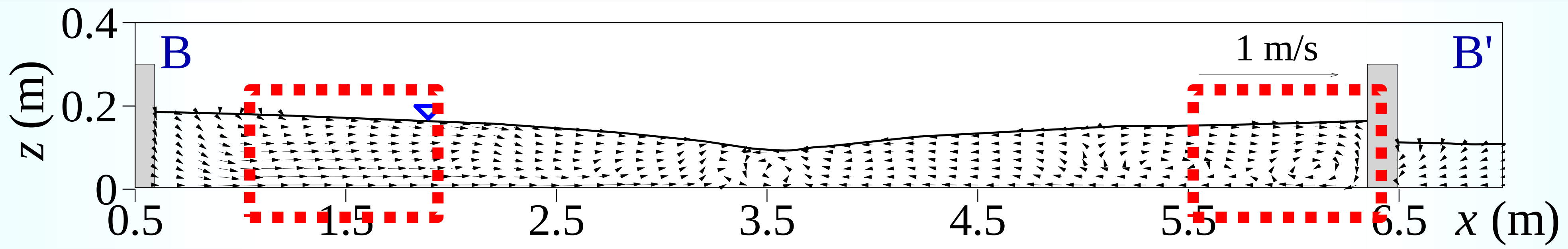


RESULTS & DISCUSSIONS (7)

3D Flow at the Time of Backwash (Calculation)



- Circulating flow flows toward the center of the vortex at near-bed more than water surface.
- Complex 3D flow field is generated around a harbor when tsunami strikes.



CONCLUSIONS

A 3D tsunami flow model using the FAVOR method and the WENO scheme was proposed in order to predict 3D flow filed around a harbor accurately.

- It was clarified that the proposed model can calculate flows around structures which are not along the coordinate smoothly by introducing the FAVOR method.
- By comparing between experimental and calculated results, the proposed numerical model was able to reproduce the flow field more accurately than the low-order scheme model.

In the future work, we will introduce a topography change model into this 3D flow model.

Thank you for your attention!