Simulation of Tsunami Force in the Presence of Beachside Structures

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Background & Objective

- To deal with massive tsunamis (“level 2” tsunamis; e.g., 2011 Tohoku earthquake tsunami)
  - Construction of shore protection facilities for tsunamis at relatively high frequencies (“level 1” tsunamis)
  - Concept of disaster mitigation using multifaceted countermeasures is also essential

  ⇒ One of such concepts: Beachside rigid structures

  - Expected to be effective for disaster mitigation (e.g., possible to reduce tsunami force on rear buildings)

Objective

- To demonstrate the computational capability of our numerical model (FS3M) to simulate tsunami run-up and force
- To evaluate the influence of rigid structures on tsunami force on a rear building

What is FS3M?

3-D coupled ***F***luid-***S***tructure-***S***ediment-***S***eabed interaction ***M***odel (FS3M; Nakamura and Mizutani, 2014)

LES-based Navier-Stokes Solver (LES)

To compute incompressible viscous air-water multi-phase flow
(including seepage flow in porous media)

Volume-of-Fluid Module (VOF Module)

For air-water interface tracking
Based on multi-interface advection and reconstruction solver (MARS; Kunugi, 2000)

Immersed-Boundary Module (IB Module)

For fluid-structure interaction
Based on body-force type of immersed-boundary (IB) method (Kajishima and Takiguchi, 2002)

Sediment Transport Module (ST Module)

To compute seabed profile evolution due to bed load and suspended load, and the distribution of suspended sediment concentration

Finite Element Module (FE Module)

For coupled soil-water analysis
Based on finite element method computing the *u*-*p* approximation of the Biot equation

Fluid Dynamics Model (LES + VOF module)

- Large-eddy simulation (LES) model based on the dynamic two-parameter mixed model (DTM; Horiuti, 1997)
- Governing equations

Continuity equation

$$\frac{\partial\left(m\overline{v_j}\right)}{\partial x_j}=q^*$$

Navier-Stokes equation

- Turbulent stress based on the DTM
- Surface tension force based on the continuum surface force (CSF) model
- Laminar and turbulent resistance forces in porous media (Mizutani et al., 1996)

$$\left\{m+C_A\left(1-m\right)\right\}\frac{\partial\overline{v_i}}{\partial t}+\frac{\partial\left(m\overline{v_i}\;\overline{v_j}\right)}{\partial x_j}$$
$$=-\frac{m}{\hat{\rho}}\frac{\partial\overline{p}}{\partial x_i}+mg_i+\frac{m}{\hat{\rho}}\left(f_i^s+\overline{R_i}+\overline{f_i^{ob}}\right)+\frac{1}{\hat{\rho}}\frac{\partial}{\partial x_j}\left(2m\hat{\mu}\overline{D_{ij}}\right)+\frac{\partial}{\partial x_j}\left(-m\tau_{ij}^a\right)+\overline{Q_i}+m\overline{\beta_i}$$

Advection equation of the VOF function

$$m\frac{\partial F}{\partial t}+\frac{\partial\left(m\overline{v_j}F\right)}{\partial x_j}=Fq^*$$

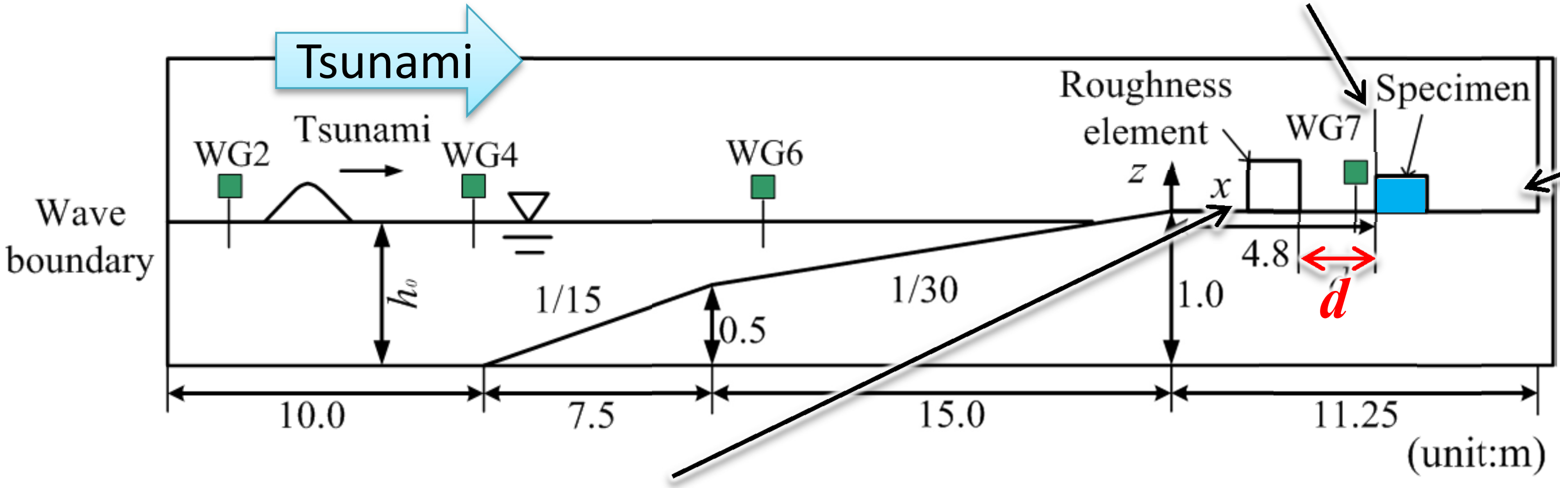
Computational Conditions

- For validity, FS3M was applied to a large-scale hydraulic experiment (scale: 1/25) conducted at Oregon State University

Computational domain (cross-sectional view)

A single leading-elevation tsunami was generated

As a building of interest, a specimen (0.60 x 0.60 x 0.40 m) was installed

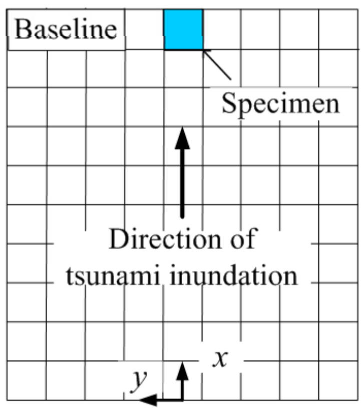


Crashed rock beach for wave dissipation was not installed because of no detailed information

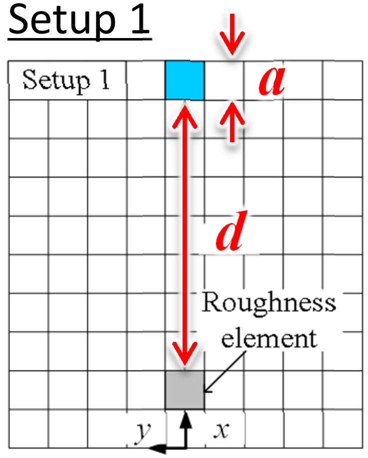
Macro-roughness cubic elements (a = 0.6 m) were installed at a distance of d offshore from the specimen

Their arrangement was changed to 58 patterns, including nine patterns in the experiment

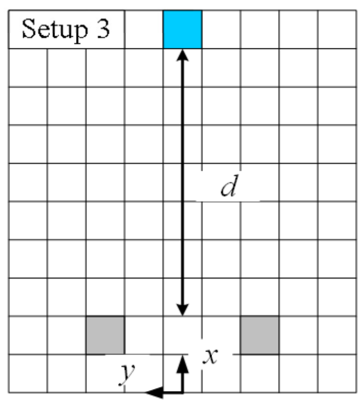
Baseline



Setup 1



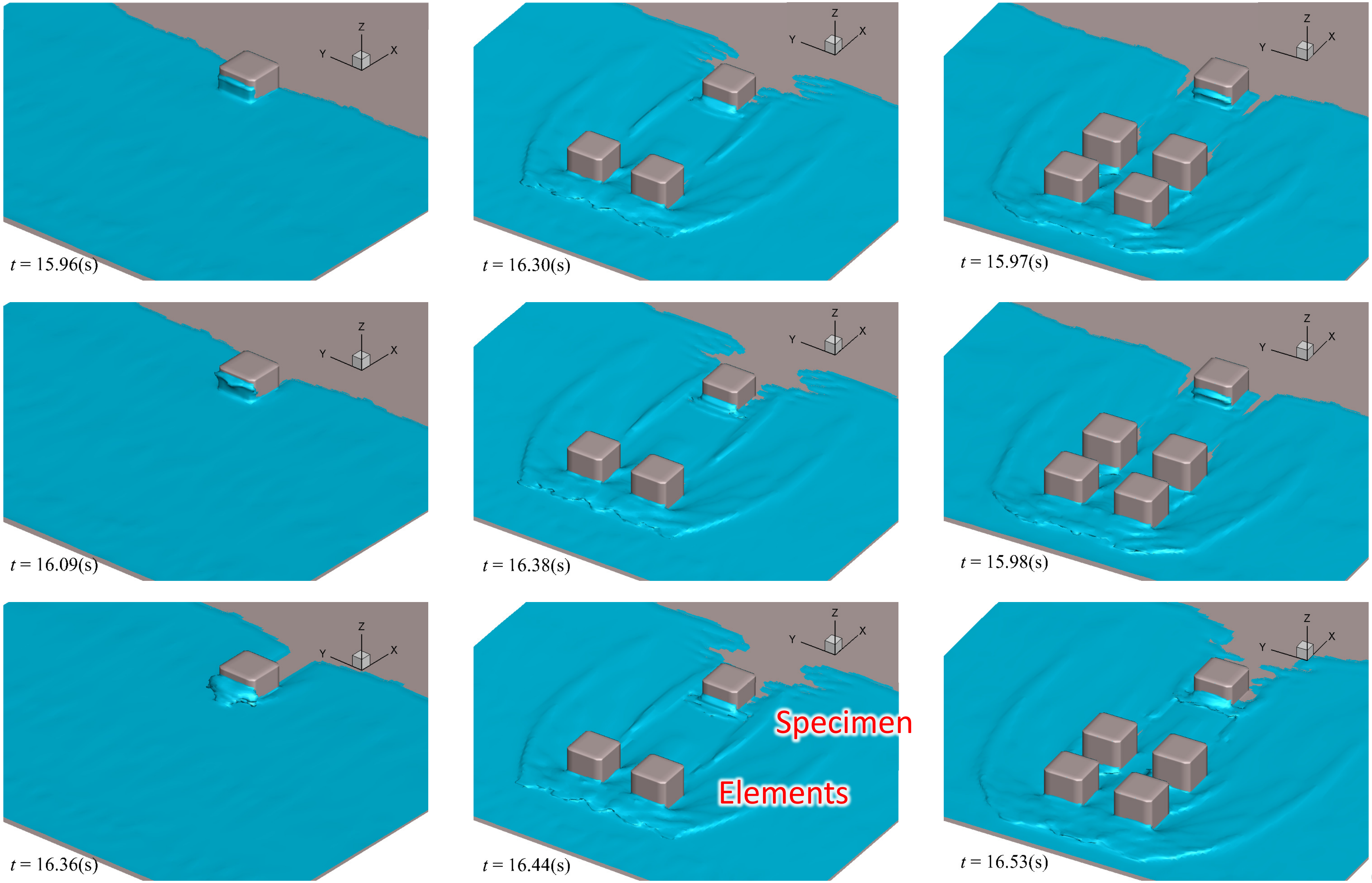
Setup 3



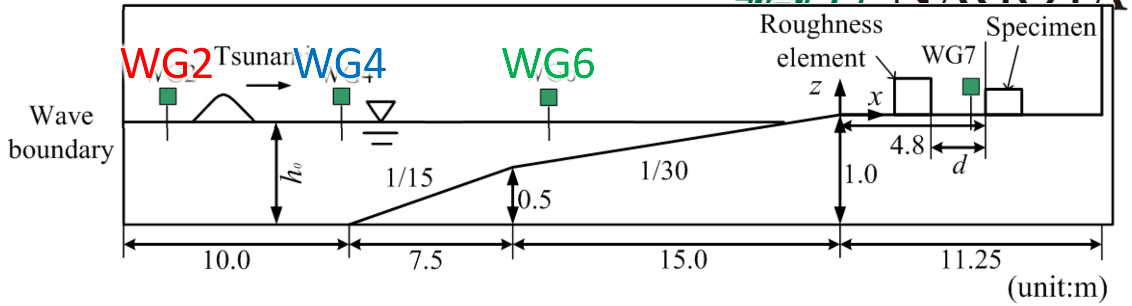
Deformation of Run-Up Tsunami

- Flow field around the elements and specimen

Baseline (no elements) | Setup 2, d/a = 4 | Setup 4, d/a = 4

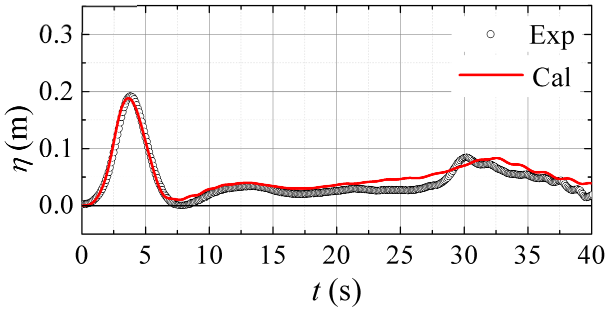


Comparison

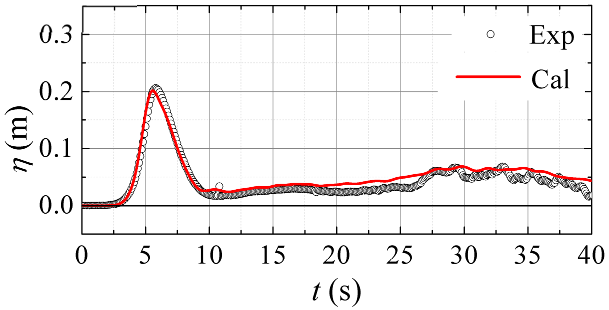


- Water surface elevation η (Setup 4, d/a = 1)

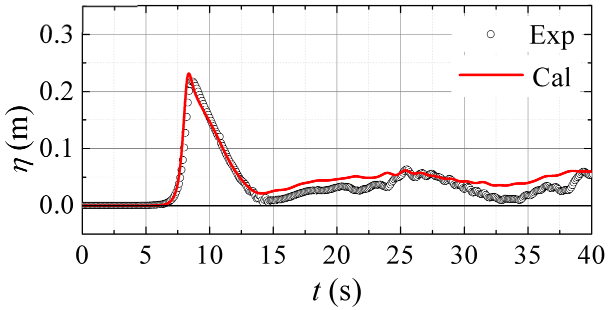
WG2



WG4

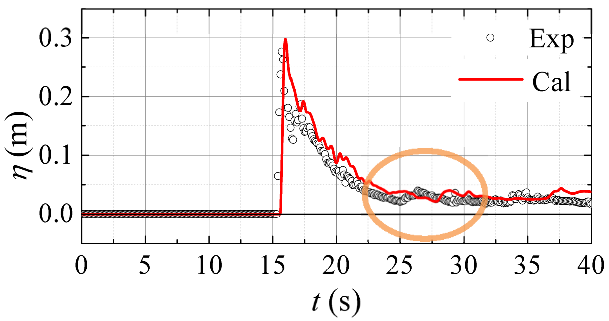


WG6

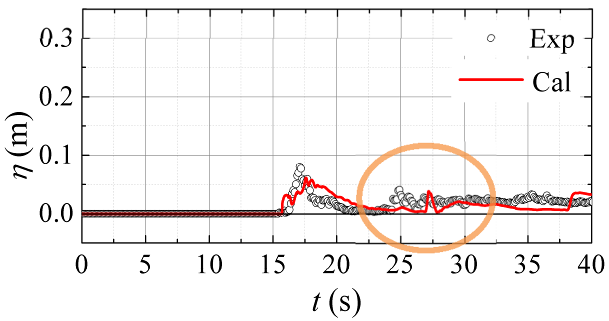


- Inundation depth η (Setup 4, d/a = 1)

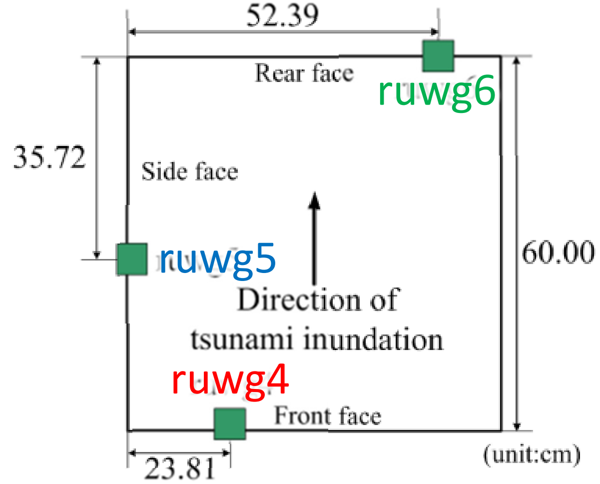
Front of the specimen (ruwg4)



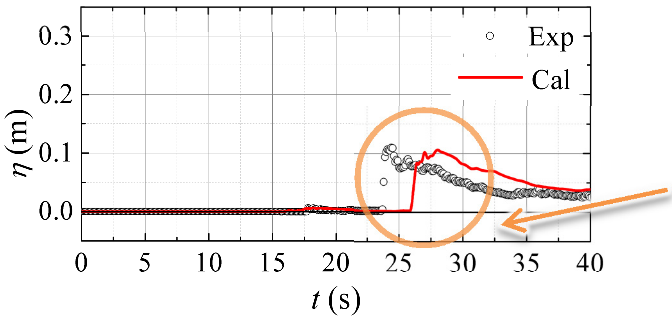
Side of the specimen (ruwg5)



Top view of the specimen

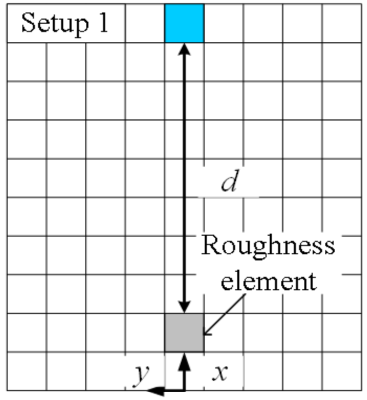


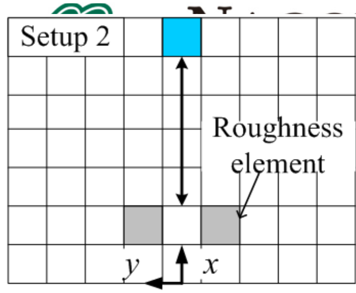
Back of the specimen (ruwg6)



- Good agreement with experimental data
- Difference in the phase of the reflected wave because no absorbing beach was installed

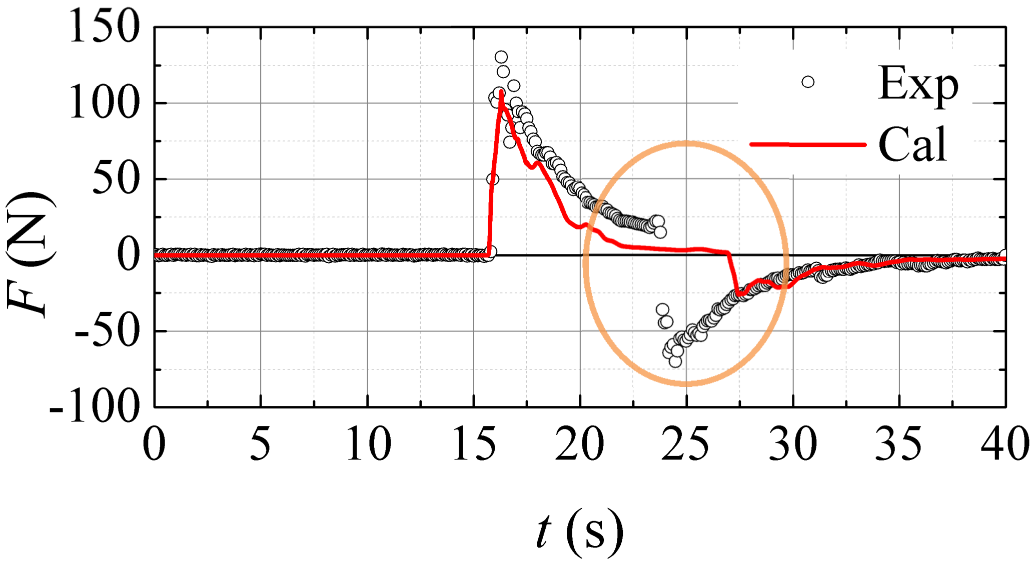
Comparison



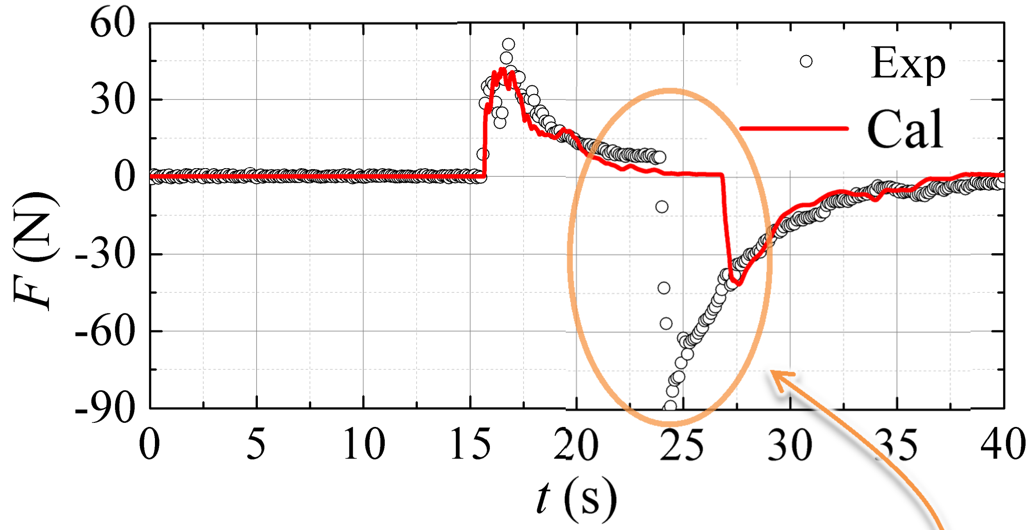


- Tsunami force F in the direction of tsunami propagation

Setup 1, d/a = 7



Setup 2, d/a = 4

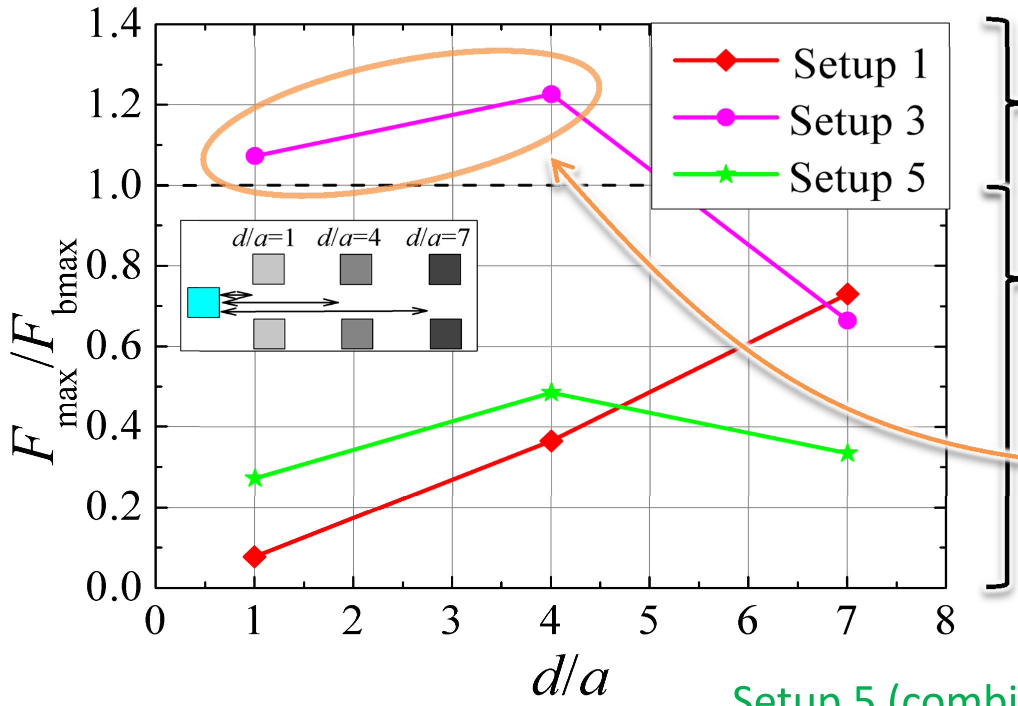


- Landward force (F > 0) can be predicted reasonably well
- Similar with η, there is a difference in the seaward force (F < 0) because of the difference in the reflected wave

Computational capability of FS3M is demonstrated in terms of η and F

Influence of Elements

- Reduction rate of the maximum tsunami force F_{max} against the no-element baseline case F_{bmax}

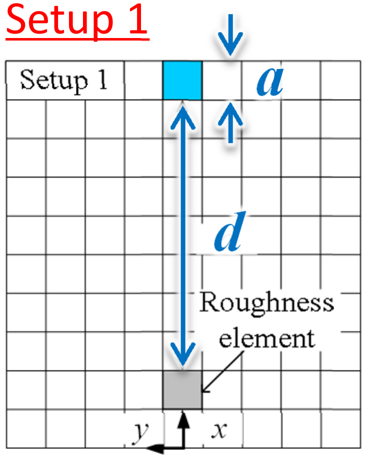


} F_{max} is increased (negative effect)

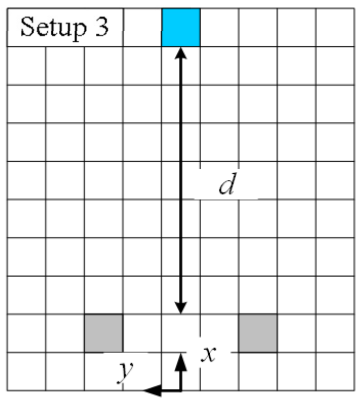
} Effective to reduce F_{max} (positive effect)

- For d/a = 1 and 4, Setup 3 has a negative effect on F_{max}

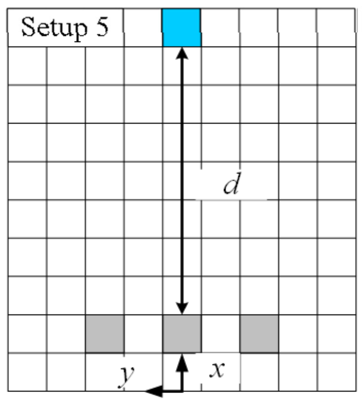
Setup 1

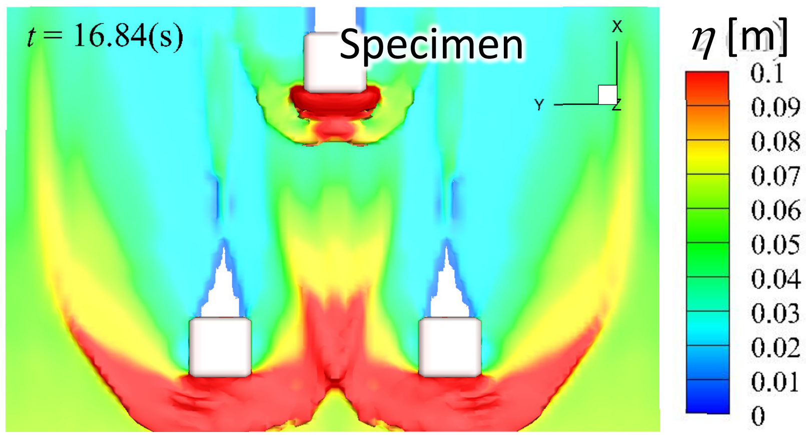


Setup 3



Setup 5 (combination of Setups 1 & 3)

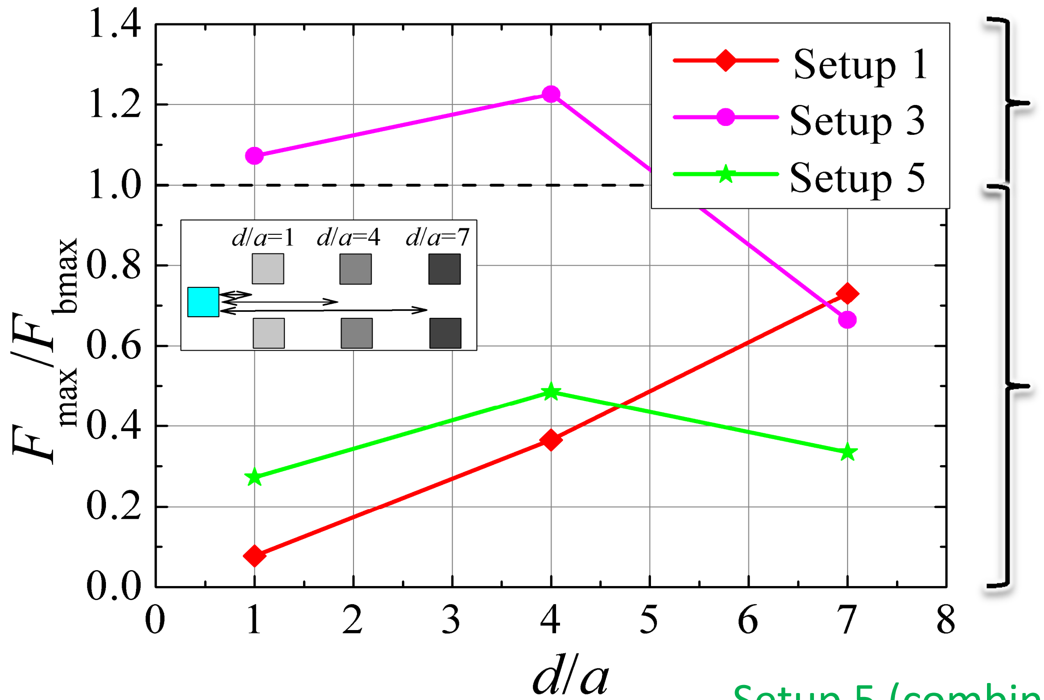




(Setup 3, d/a = 4)

Influence of Elements

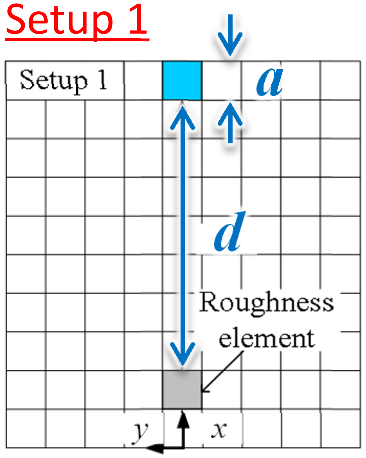
- Reduction rate of the maximum tsunami force F_{max} against the no-element baseline case F_{bmax}



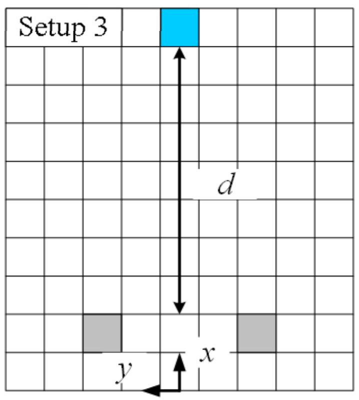
F_{max} is increased (negative effect)

Effective to reduce F_{max} (positive effect)

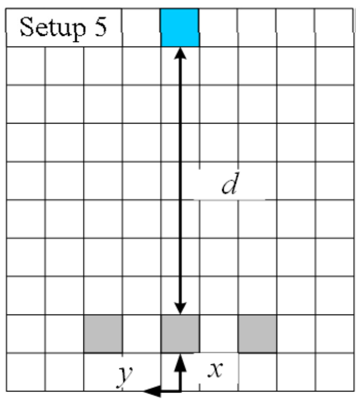
Setup 1



Setup 3



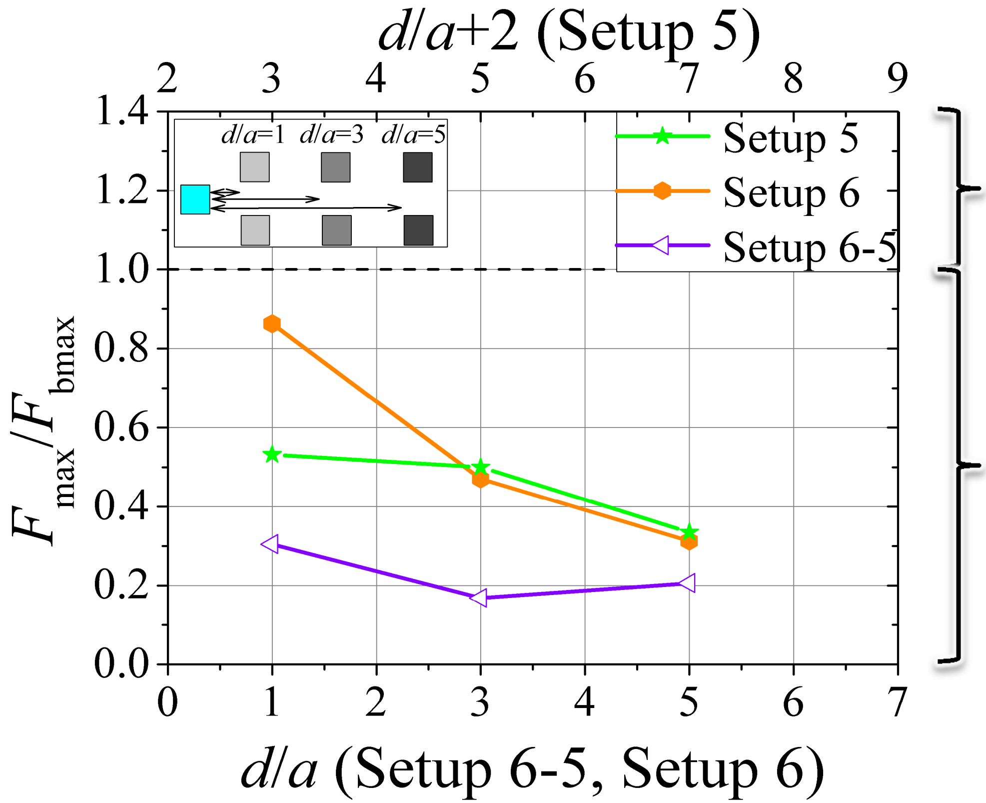
Setup 5 (combination of Setups 1 & 3)



- Setup 5 roughly has the influence of both Setup 1 & Setup 3

Influence of Elements

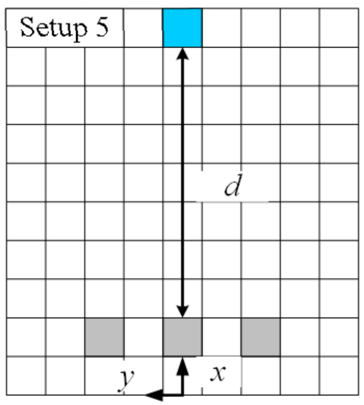
- For more complicated arrangement



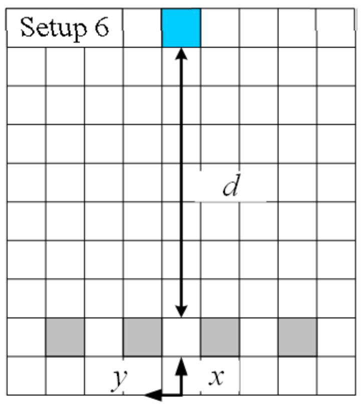
F_{max} is increased (negative effect)

Effective to reduce F_{max} (positive effect)

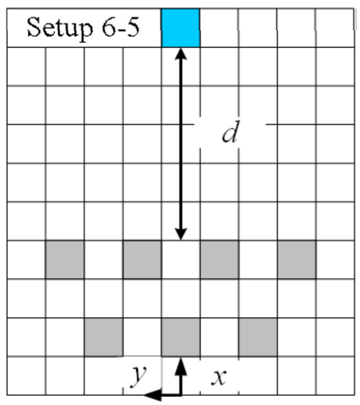
Setup 5



Setup 6

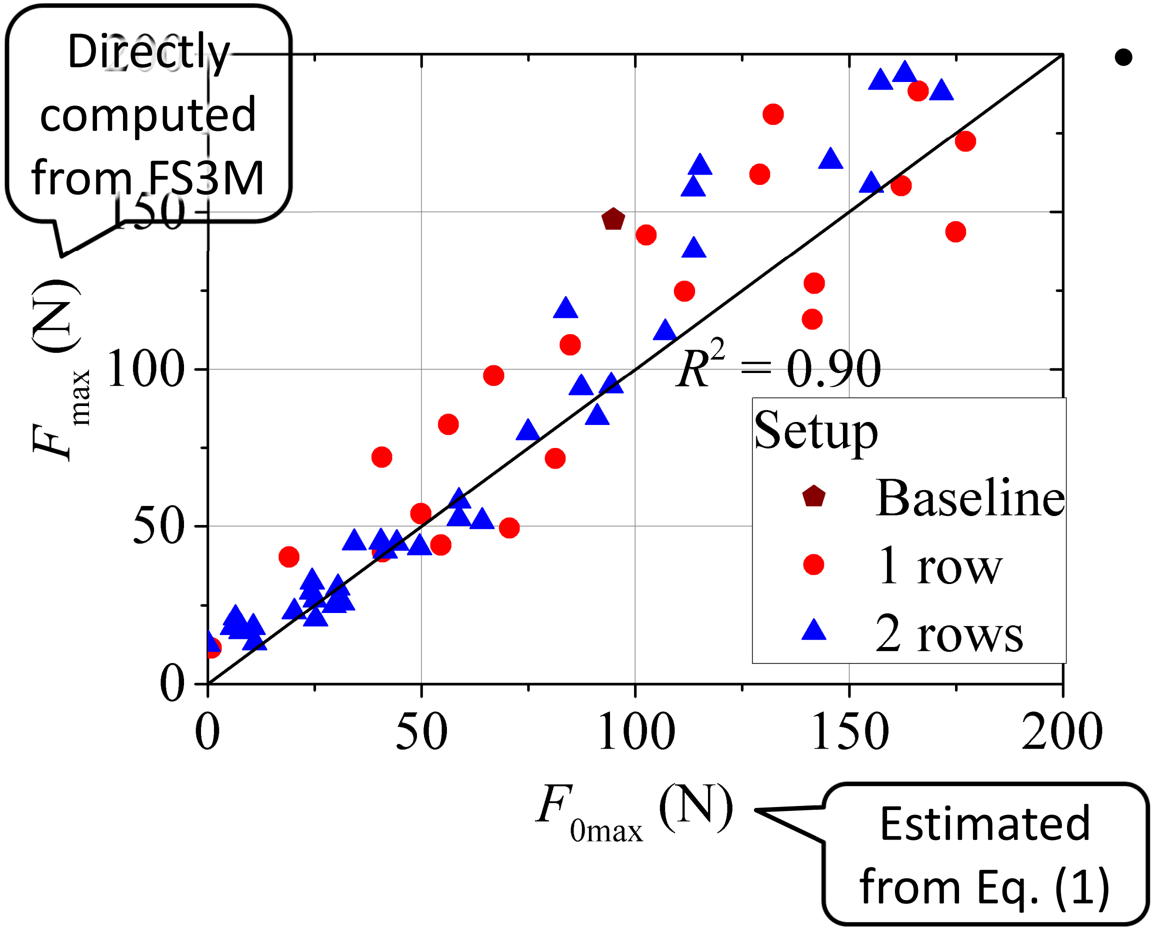


Setup 6-5 (Setups 5 & 6)



- Similar tendency can be observed
- F_{max}/F_{bmax} can be estimated from the combination of the influence of each element

Evaluation of Maximum Tsunami Force



- From the concepts of momentum conservation and drag force, Yeom et al. (2007) proposed

$$F_{0\max} = \frac{1}{2}\rho C_D a\left(\eta_0 u_0^2\right)_{\max} \quad \text{Eq. (1)}$$

C_D: Drag coefficient (= 2.0 here)

η_0, u_0: Inundation depth and bottom flow velocity without the specimen

ρ: Density of water

a: Width of the specimen

⇨ Maximum tsunami force $F_{\max}$ can be predicted reasonably well regardless of the number and arrangement of the elements

$$F_d = \frac{1}{2}\rho_s C_d B\left(hu^2\right)_{\max} \quad \text{(FEMA P646)}$$

$$F_{dx} = \frac{1}{2}\rho_s I_{tsu} C_d C_{cx} B\left(hu^2\right)$$

(ASCE 7-16)

Influence of Suspended Sediment

- Tsunamis consist of a mixture of water and sediment
- Necessary to consider the influence of suspended sediment (i.e., change in fluid density and viscosity)
- FS3M can deal with the change in fluid density and viscosity due to suspended sediment

Change in fluid density

$$\hat{\rho} = (1-C)\{F\rho_w + (1-F)\rho_a\} + C\rho_s$$

C: Concentration

F: VOF function

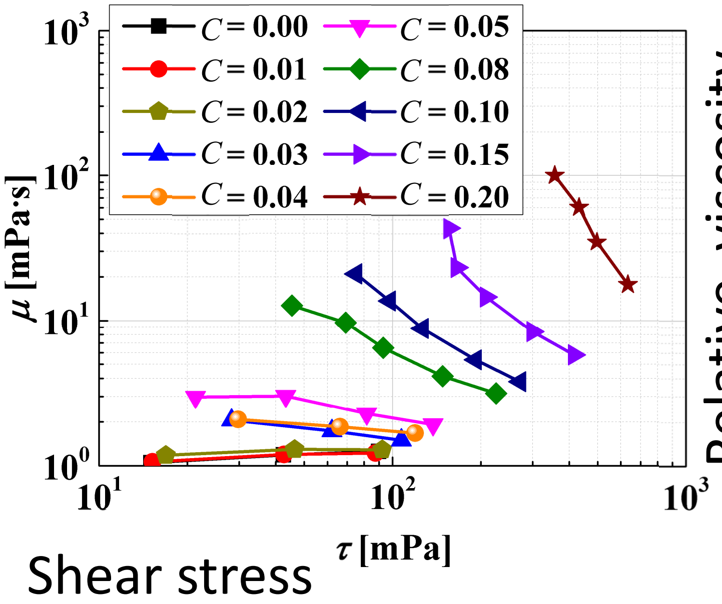
ρ_w, ρ_a, ρ_s: density of water, air, sediment particles

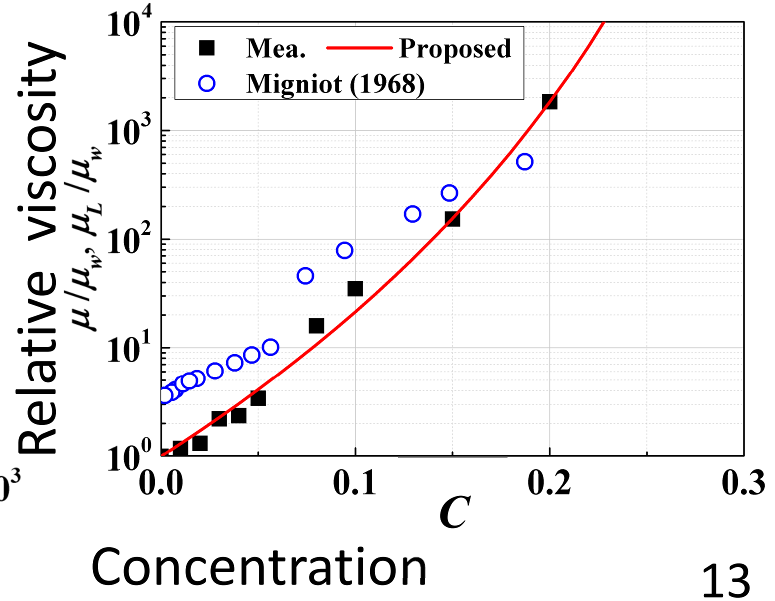
Change in fluid viscosity for kaolin clay

$$\hat{\mu} = F\mu + (1-F)\mu_a$$

$$\frac{\mu - 1}{\mu_L - 1} = \left[1 + \left(\frac{\tau}{80}\right)^2\right]^{-1}$$

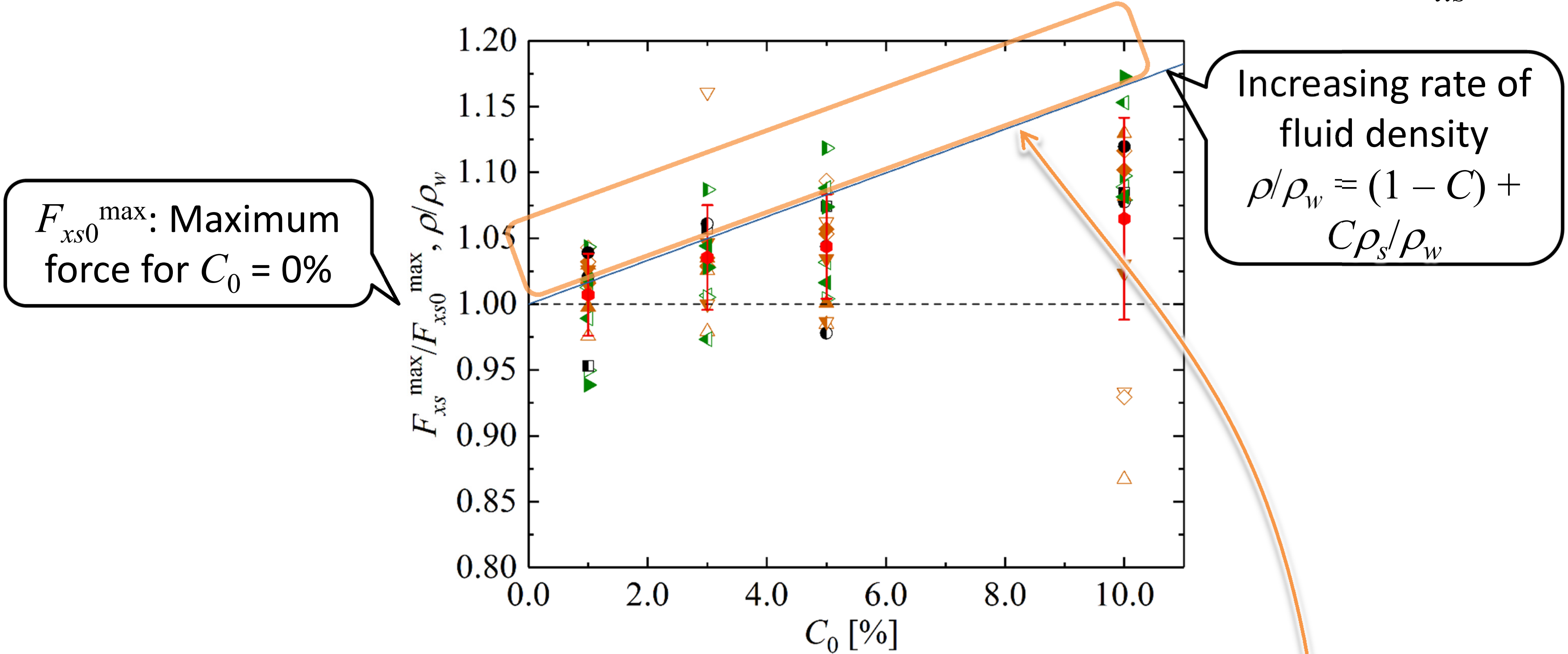
$$\mu_L = \mu_w\left(1 - \frac{C}{0.379}\right)^{-10.0}$$





Influence of Suspended Sediment

- Maximum tsunami force induced by quasi-steady pressure $F_{xs}^{\max}$



  - Maximum tsunami force $F_{xs}^{\max}$ increases with the suspended sediment concentration C_0
  - Increase in the maximum tsunami force $F_{xs}^{\max}/F_{xs0}^{\max}$ can exceed that in the fluid density ρ/ρ_w

⇨ Essential to consider the change in fluid viscosity as well

Summary

- The computational capability of FS3M to simulate tsunami run-up and force was demonstrated in terms of water surface elevation, inundation depth, and tsunami force
- The influence of macro-roughness elements can be estimated from the combination of the influence of each element
- The maximum tsunami force can be predicted reasonably well using the estimation equation regardless of the number and arrangement of the elements
- The increase in the maximum tsunami force can exceed that in the fluid density; thus, it would be essential to deal with tsunamis containing suspended sediment

Questions?

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