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NUMERICAL MODELING OF TSUNAMI INUNDATION USING SUBGRID SCALE URBAN ROUGHNESS PARAMETERIZATION

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OUTLINE

- Introduction
- Numerical Method
- Validation of Urban Roughness Parameterization with Experiment
- Model Comparison
- Conclusions

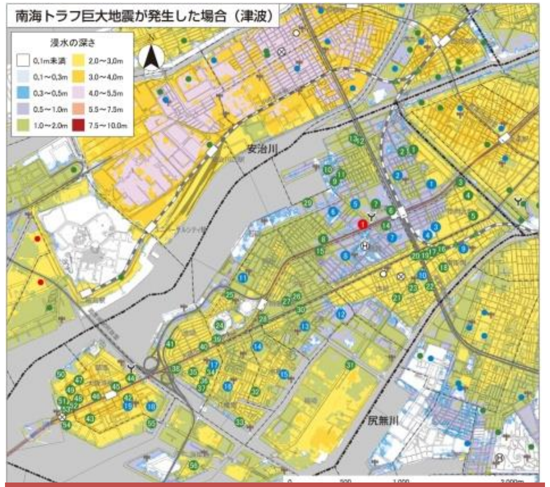
INTRODUCTION

Research Background

- Mega Tsunami hazard risk
  - •Urban city inundation of 2011 Tohoku Earthquake Tsunami → the first time a large tsunami inundated an urban city in modern times
  - •High occurrence probability of Nankai Trough Earthquake

The importance of hazard maps of tsunami inundation for urban areas in advance for tsunami hazard preparation (reduce fatalities and mitigate damage)

- Understanding tsunami inundation over coastal urban areas is necessary to make reasonable hazard maps,
- Current method for understanding tsunami inundation is insufficient
- The 2011 Tohoku tsunami showed complicated tsunami run-up behavior (diffraction, vortex generation , turbulence around structures)



TSUNAMI HAZARD MAP (OSAKA)

- Numerical model of tsunami inundaton
  - •An estimation method of tsunami hazard

Practical hazard map

Roughness modeling (Manning's coefficient) according to the land usage pattern is used instead of structures

Research Background

High resolution data for bathymetry and topography are necessary for detailed tsunami inundation modeling

Numerical model using structure resolving

Topography (less than O(10m)) is available

○ Pros	Direct consideration of the effect of structure
	High computational accuracy
× Cons	Difficulty in modeling
	Heavy computational cost

Example of high-resolution tsunami modeling

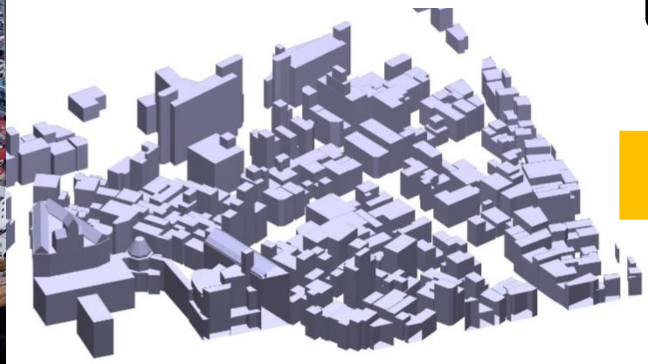
Kaiser et al. (2011)
Prasetyo (2017) Etc.

Improvement of medium resolution model in accuracy is important

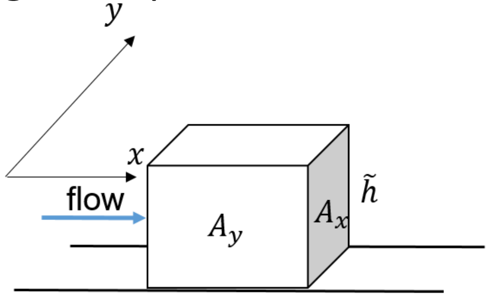
Objective

Develops and validates a numerical model of tsunami inundation using upscaled urban roughness parameterization and a Drag Force Model (DFM) to simulate the effect of structures as a drag force acting on flow

Upscaling high-resolution topography data



Urban roughness parameters



Medium resolution model considering subgrid scale topography

Δx is the upscaled mesh size, meaning the spatial resolution for the roughness parameters

High-resolution topography

(Δx = O(1m-10m))

upscale

Low/medium resolution topography

(Δx = O(50m-100m))

Accuracy : ◎ Comp. cost: △

Accuracy : △→○ Comp. cost : ◎

NUMERICAL METHOD

Outline of Numerical model

which has been used to simulate tsunami propagation from offshore to inland areas in Japan and other countries

Tsunami model：TUNAMI-N2 (Goto et al.,1997)

2D-Nonlinear Shallow Water Equations

- Continuity (mass conservation)

$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

- η : water level
- h : still water depth
- D : total water depth
- M, N : flow discharge flux
- n : Manning’s coefficient
- τ_b : bottom friction force

- Momentum conservation

$$\frac{\partial M}{\partial t} \quad \cdots \quad \frac{\partial \eta}{\partial x} \quad \frac{\tau_{bx}}{\rho}$$

$$\frac{\partial N}{\partial t} \quad \cdots \quad gD\frac{\partial \eta}{\partial y} - \frac{\tau_{by}}{\rho}$$

$$\frac{gn^2 M\sqrt{M^2 + N^2}}{D^{\frac{7}{3}}}$$

Urban roughness parameterization

Three different bottom boundary conditions are considered for NSWE

A) Drag Force Model（DFM）
B) Composite Equivalent Roughness Model(CERM)
C) Structure Resolving Model(SRM)
D) Uniform Roughness Model(URM)

Urban roughness parameterization A

(A) DFM (Target of this study)

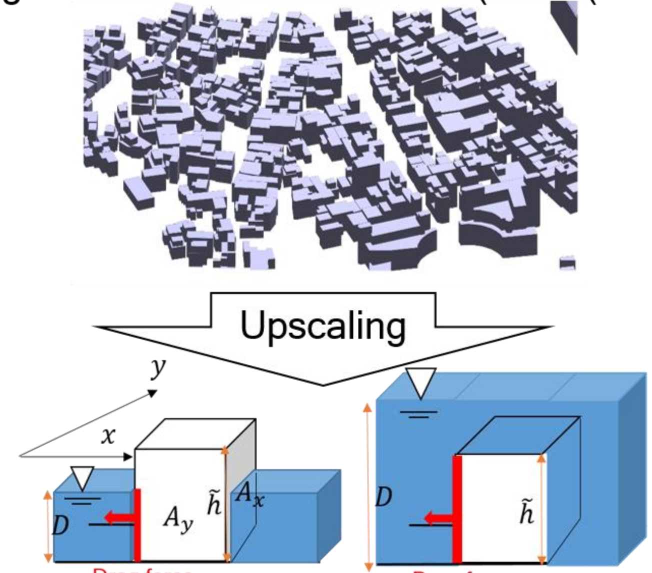
- Effect of structures are considered as drag forces

Upscaled by high-resolution topography

$$\frac{F_{Dx}d}{\rho} = \frac{1}{2} C_D \frac{A_x}{dxdyD} u|u|d \ (x\text{–direction})$$

$$\frac{F_{Dy}d}{\rho} = \frac{1}{2} C_D \frac{A_y}{dxdyD} v|v|d \ (y\text{–direction})$$

High-resolution structure data (Δx=O(1cm))



(a) Case for $D < \tilde{h}$ (partially submerged)

(b) Case for $D \geq \tilde{h}$ (fully submerged)

Cross-sectional view

- Case division
  - (a) Partial inundation $(D < \tilde{h})$ $d = D$
  - (b) Full inundation $(D \geq \tilde{h})$ $d = \tilde{h}$

A_x and A_y : projected area of structure,
d : water depth of the area which drag force acts on,
$\tilde{h}$: characteristic height of structure

Urban roughness parameterization B

（B） CERM（Aburaya and Imamura, 2002）

Divide the force acting on the water into bottom friction and resistance forces ⇒composite equivalent roughness

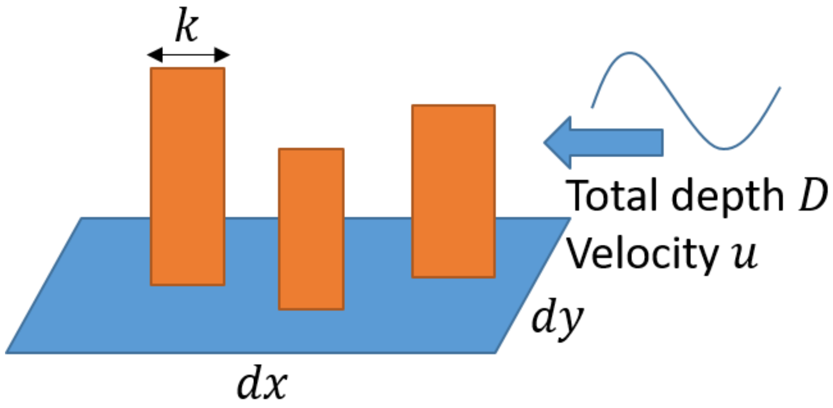
$$R_1 = \rho g D \frac{n^2 u^2}{D^{\frac{4}{3}}} dxdy \left(1 - \frac{\theta}{100}\right)$$

$$R_2 = \frac{1}{2} C_D \rho u^2 (kD) \frac{\theta}{100} \frac{dxdy}{k^2}$$

$$n_{eq} = \sqrt{n^2 + \frac{C_D}{2gk} \frac{\theta}{100 - \theta} D^{\frac{4}{3}}}$$

R_1 and R_2 corresponds to τ_b in NSWE

ρ : fluid density, g : gravitational acceleration, θ : occupancy ratio of structures, k : width of structure, C_D : drag coefficient , n : Manning's coefficient for bottom friction



Urban roughness parameterization C and D

（C） Structure Resolving Model (SRM)

The numerical simulation using the original topography with a fine grid (Δx=1 cm);

(D) Uniform Roughness Model(URM)

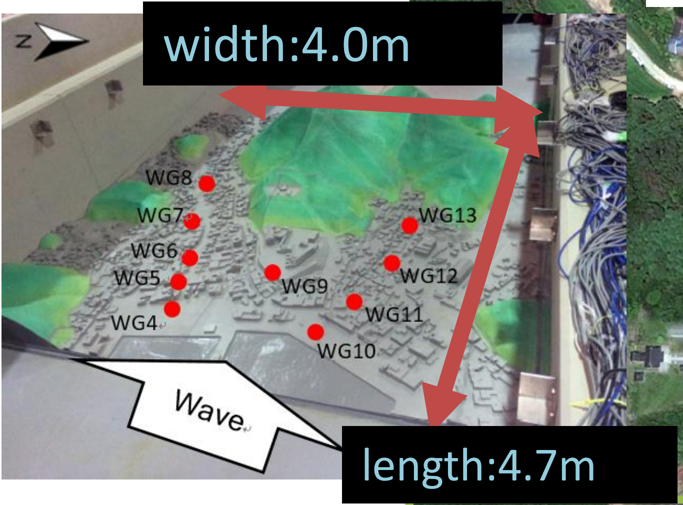
The numerical simulation using this structure-free to-topography with a constant Manning roughness coefficient;

VALIDATION OF URBAN ROUGHNESS PARAMETERIZATION WITH EXPERIMENT

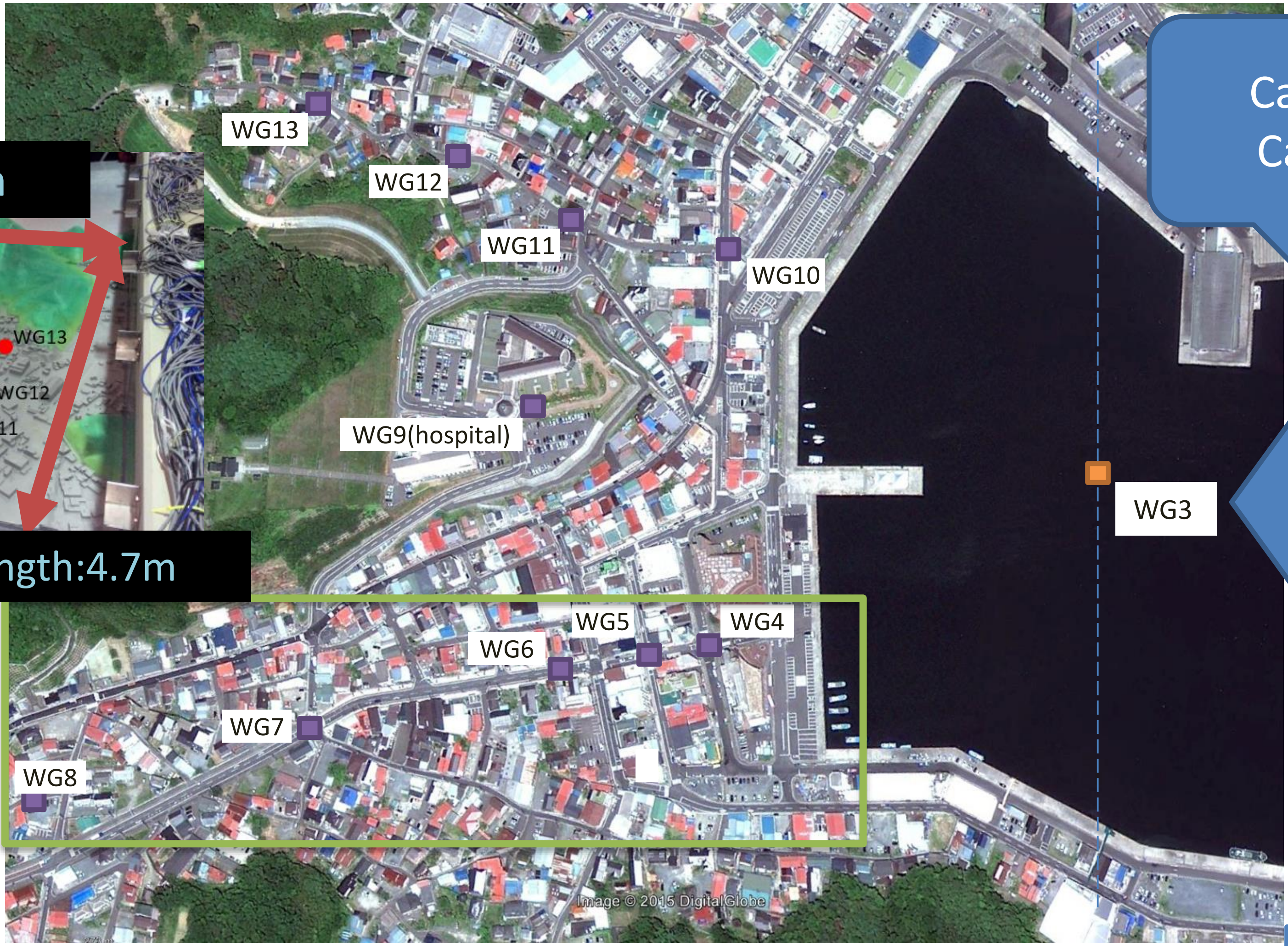
Experiment using 1/250 physical model

13 wave gauges were installed along the streets

North



1/250
Physical model



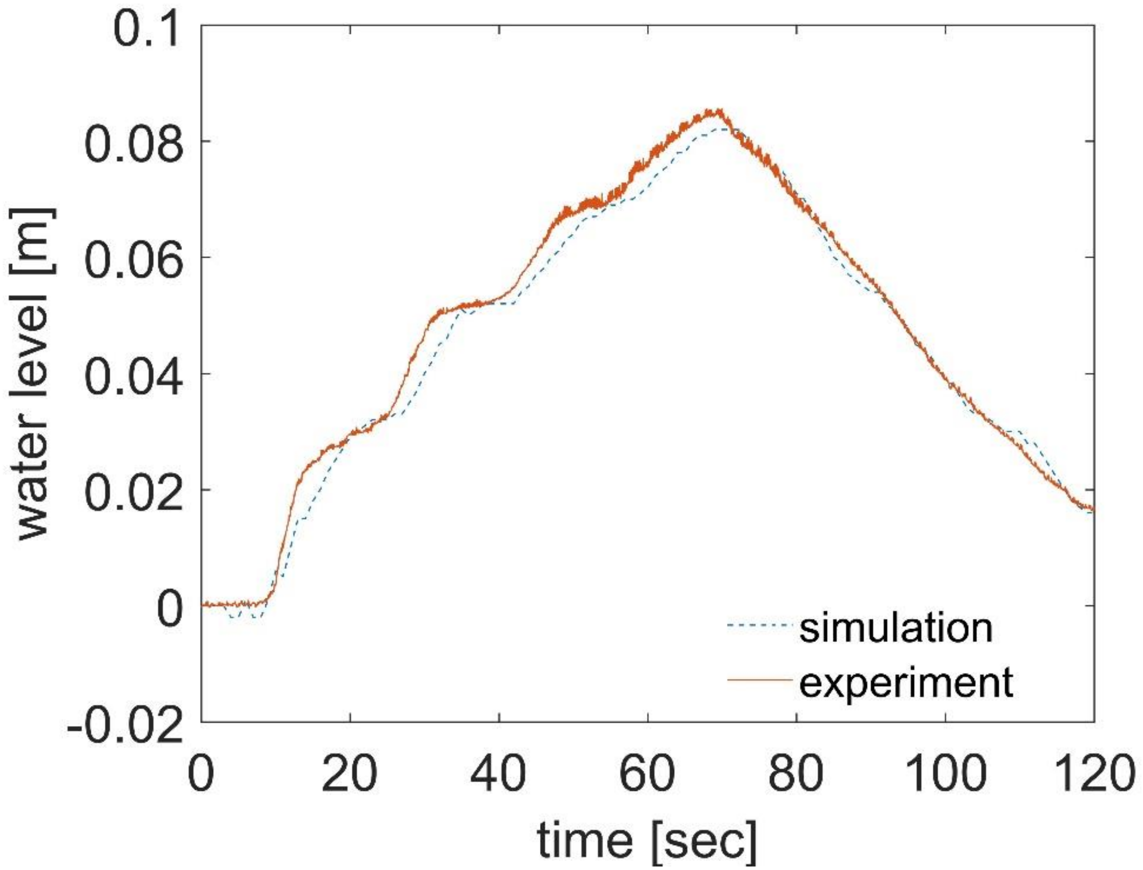
Case1) hydraulic bore
Case2) **solitary wave**

wave

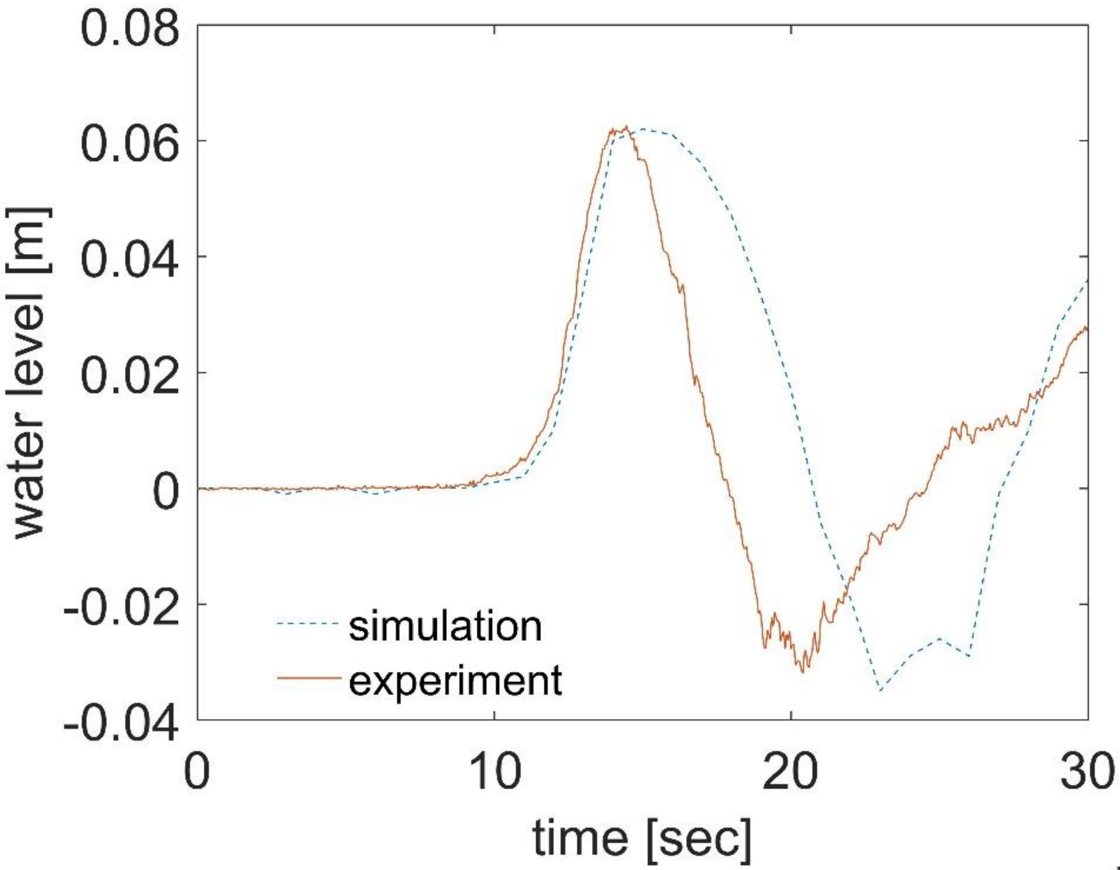
Figure : Wave gauge locations

Prasetyo, 2017
(Kyoto U. Ph.D. thesis)

Incident waves (water level at WG3)

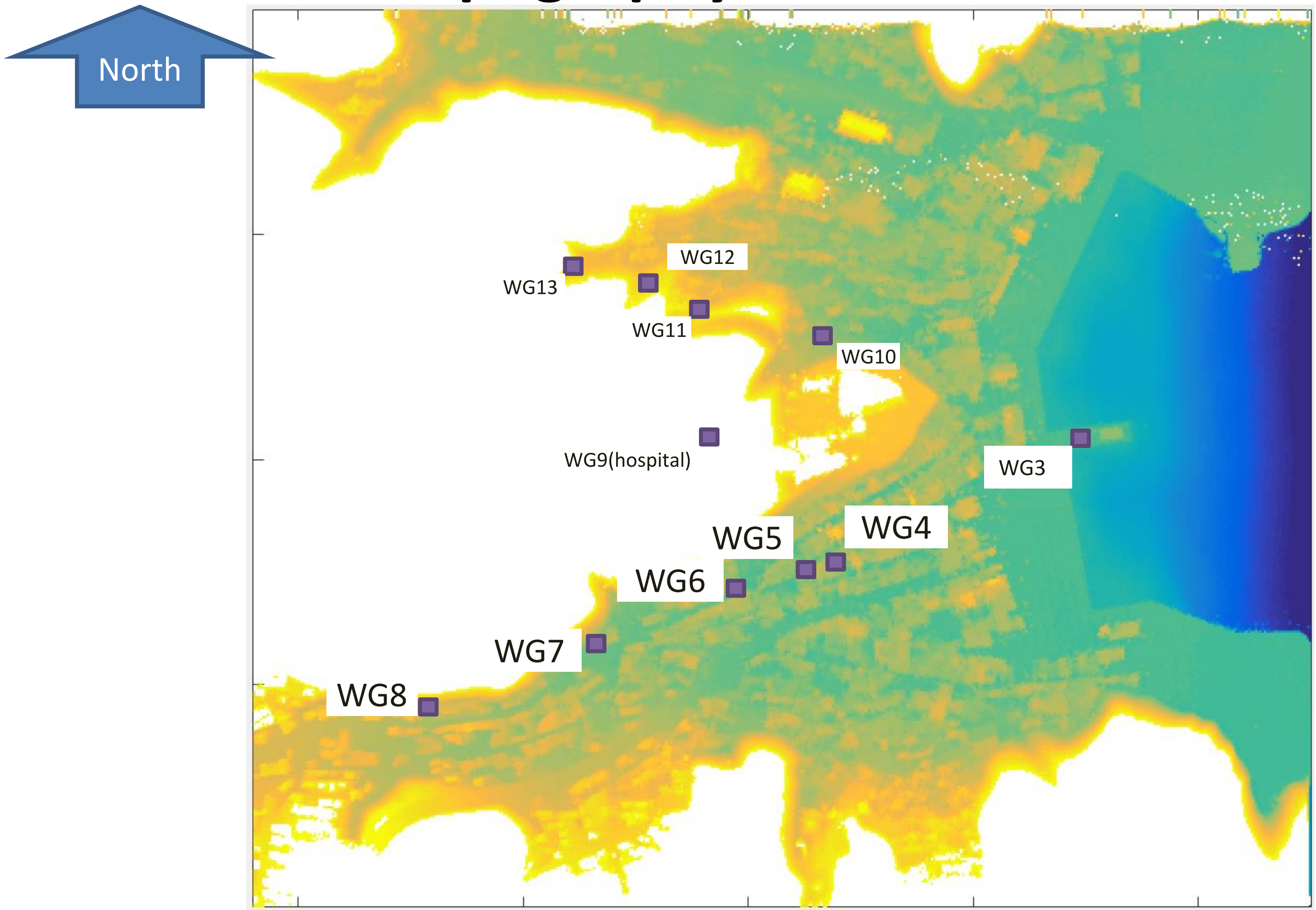


bore



solitary wave

Topography for simulation

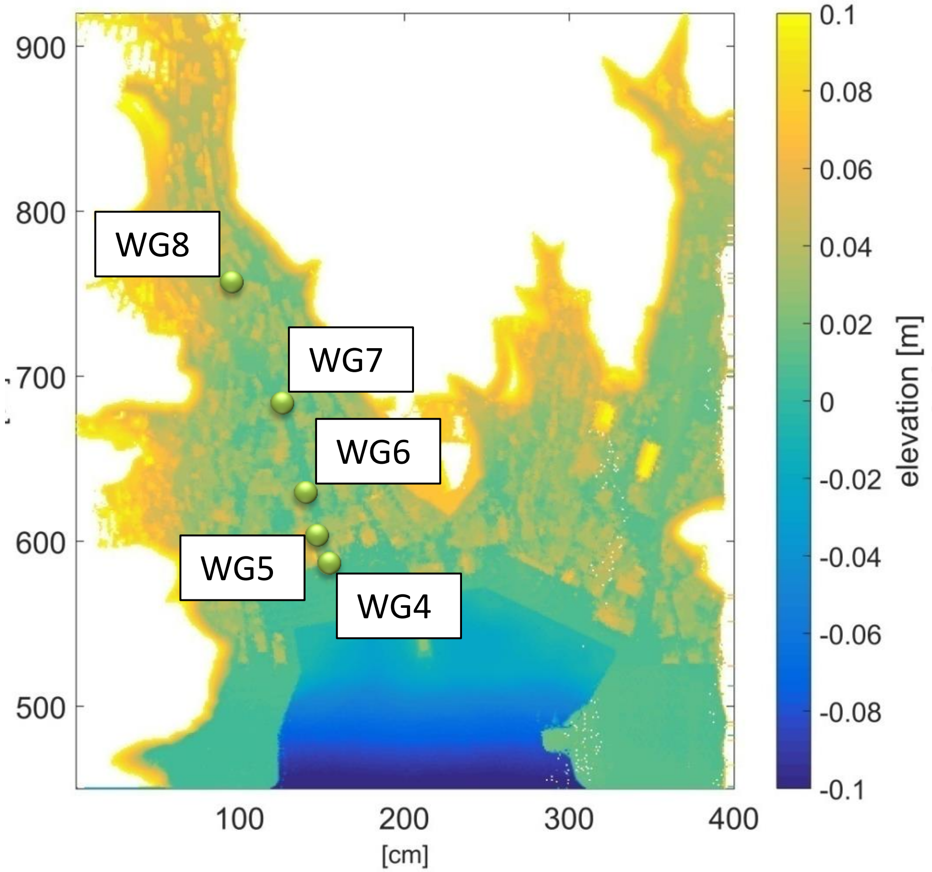


Original topography (laser scanned)

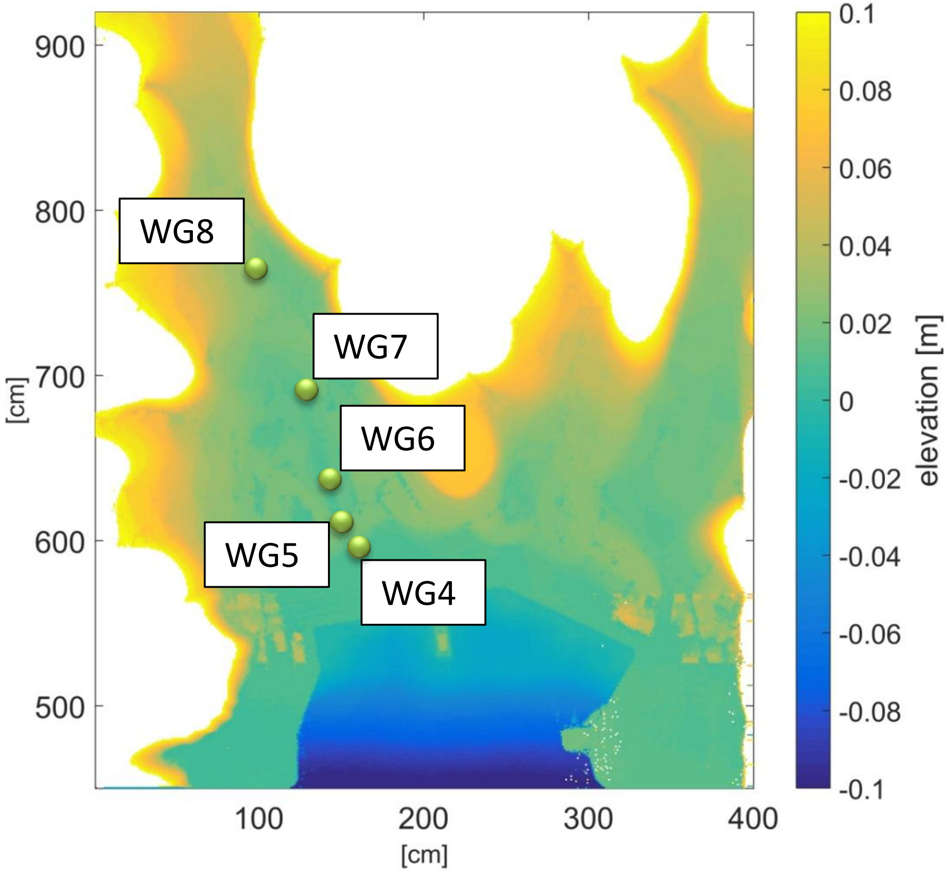
for
(C) SRM

Topography for simulation

Structure Resolving topo (SR)



Bare-Earth topo (BE)



Structure Resolving topo
- (C) SRM

Bare Earth
- (D) URM

Bare Earth＋Urban Roughness
- (A) DFM
- (B) CERM

Bottom roughness condition

MODEL	URBAN AREA	OTHERS	TOPOGRAPHY	STRUCTURE
(A)DFM	0.025	0.025	BE	Drag force
(B)CERM	n_{eq}	0.025	BE	Manning
(C)SRM	0.025	0.025	SR	Topography
(D)URM	0.025	0.025	BE	None

Drag force coefficient

$$C_D = a\exp(\lambda b Re) + 0.25$$

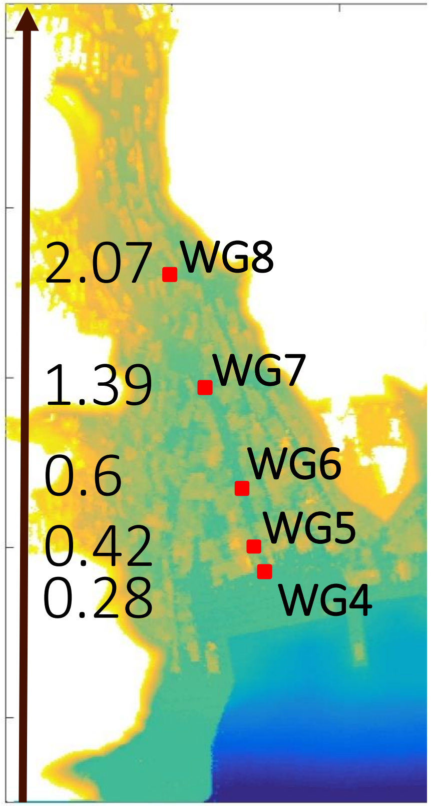
- $C_D = 3.0$, $C_D = 0.5$, $C_D = f(Re)$

Based on experiment by Wieselsberger, 1921

Target range of Re is 500 to 10000

Sensitive analysis of C_D for DFM

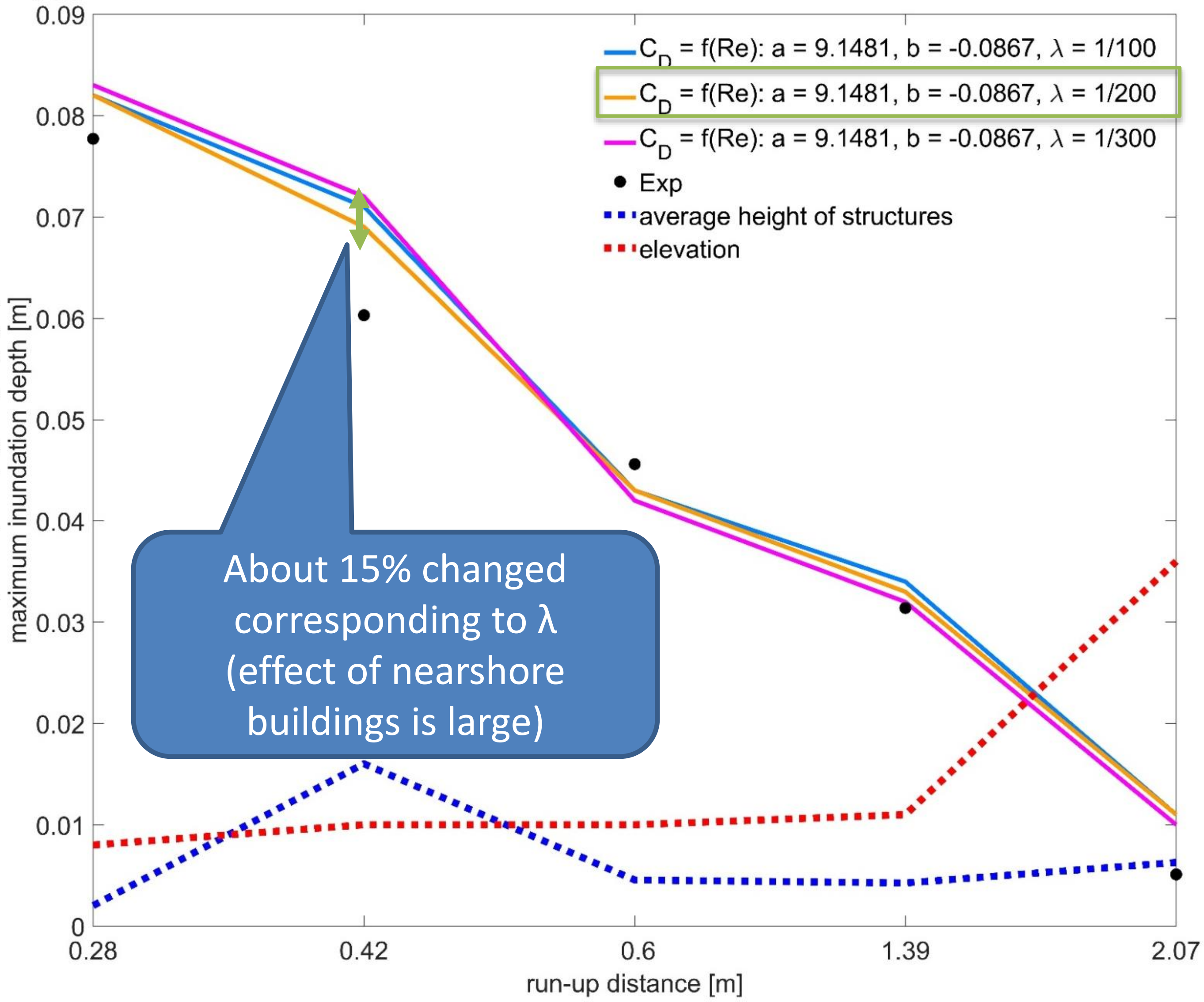
Run-up distance[m]



Wave

Incident wave:
Solitary wave

Maximum inundated depth (at each WG)



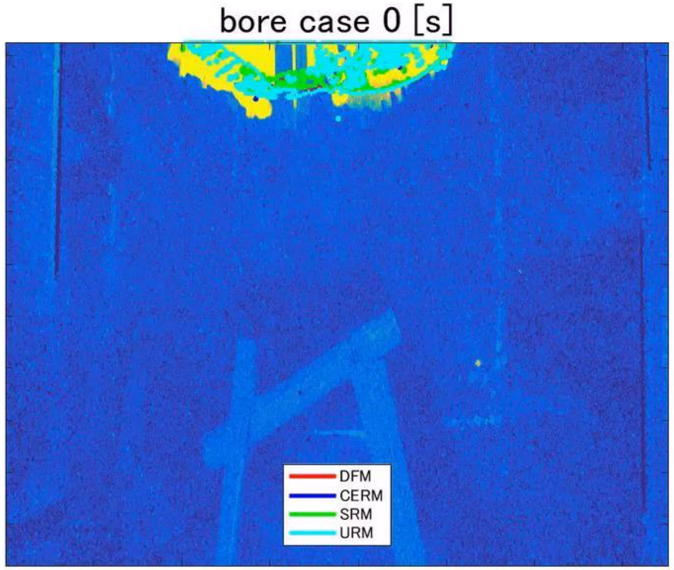
MODEL COMPARISON

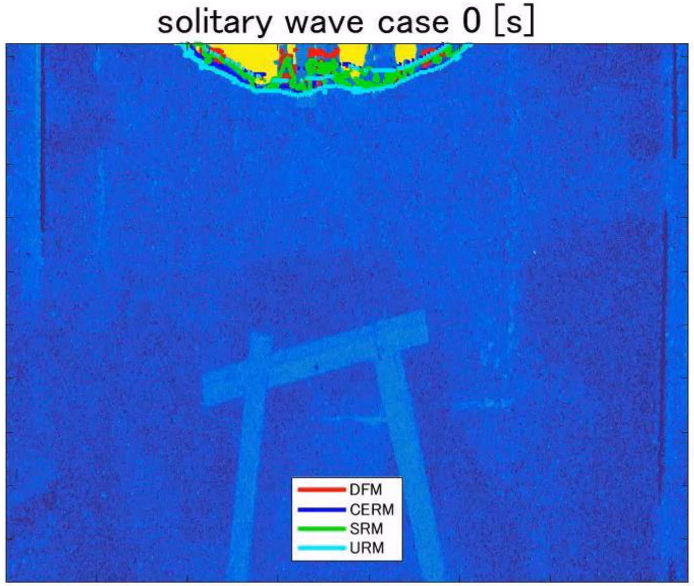
Time series of inundated area

Bore

Flow direction

Solitary wave





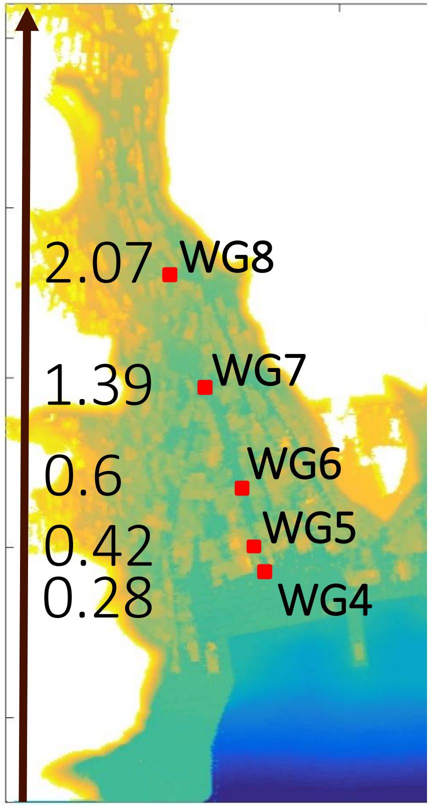
legend
DFM
CERM
SRM
URM

Yellow colored area: experiment

Inundation speed:
bore case: exp>URM>DFM>CERM>SRM
soliton case: URM>exp>SRM>DFM>CERM

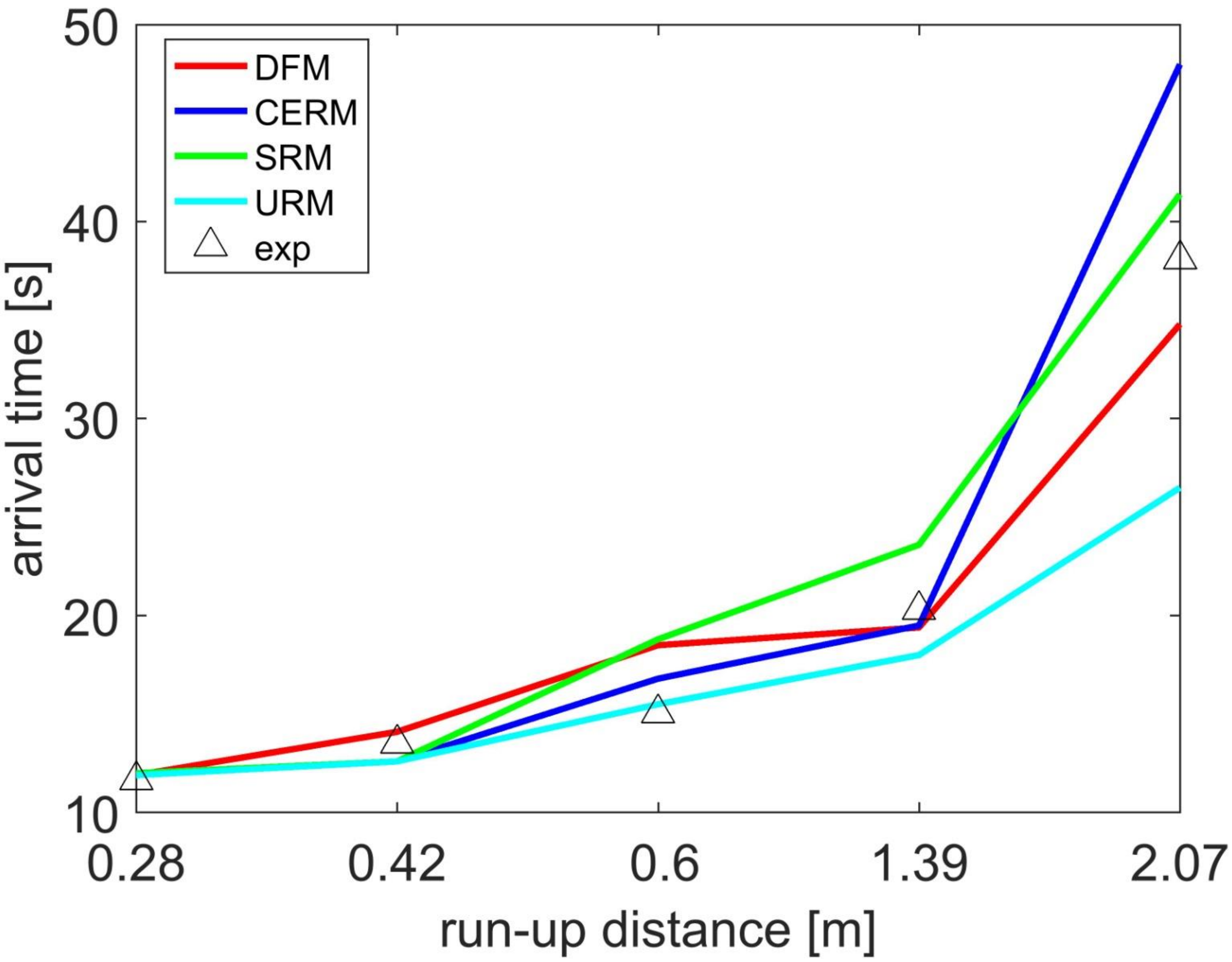
Model comparison (arrival time)

Run-up distance[m]



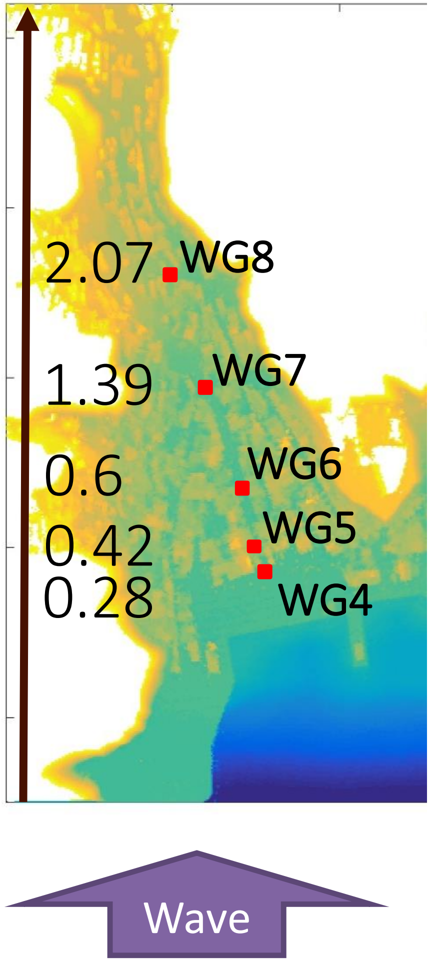
Incident wave:
bore

Arrival time (at each WG)

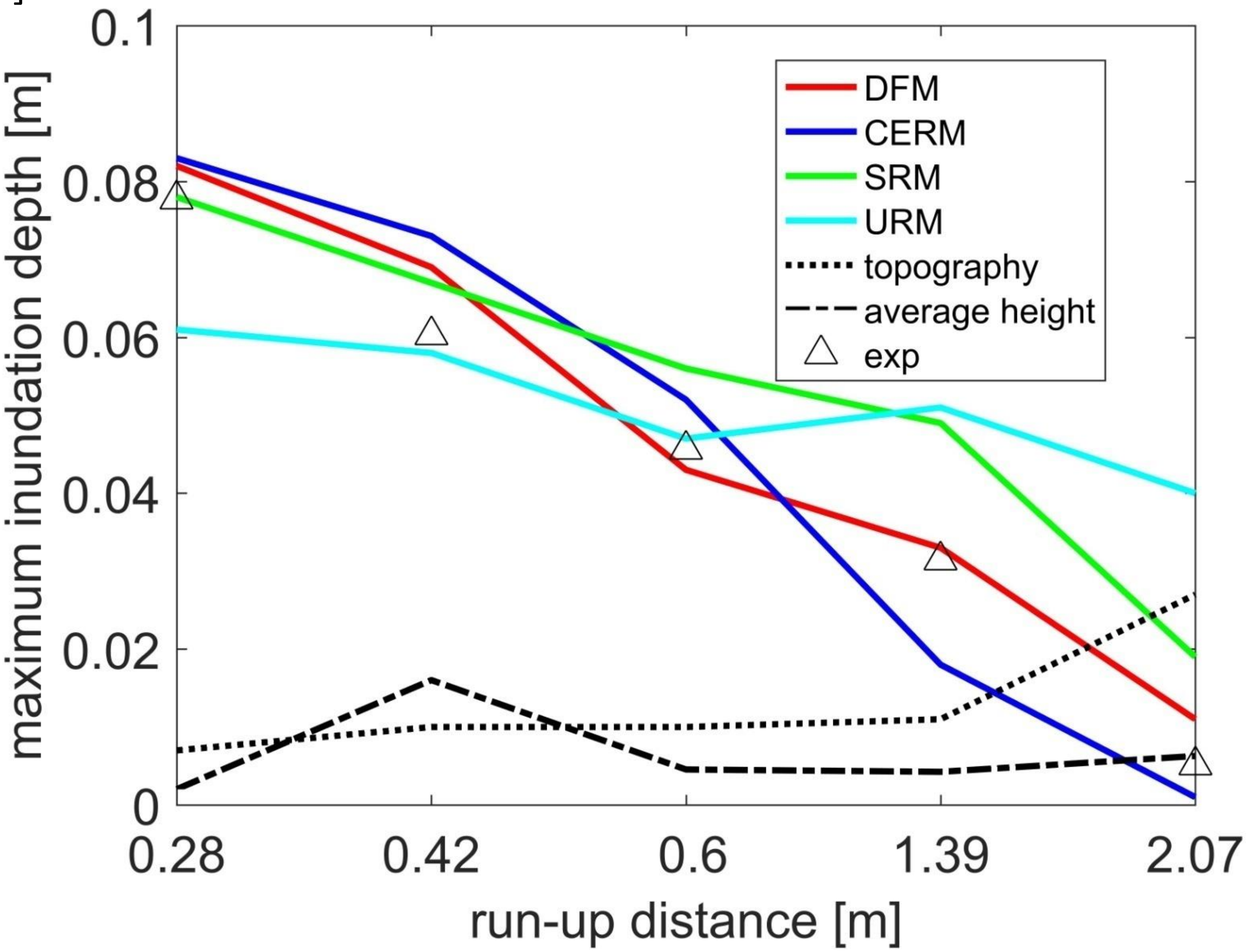


Model comparison (max. depth)

Run-up distance[m]

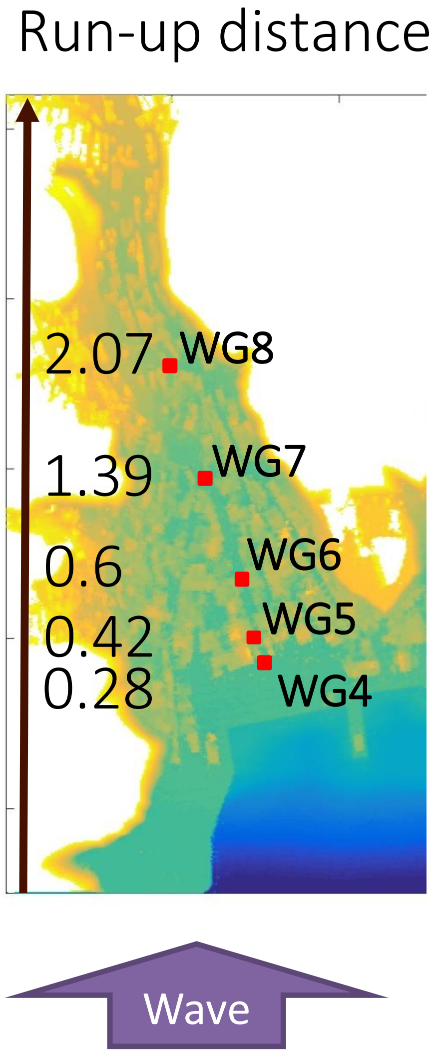


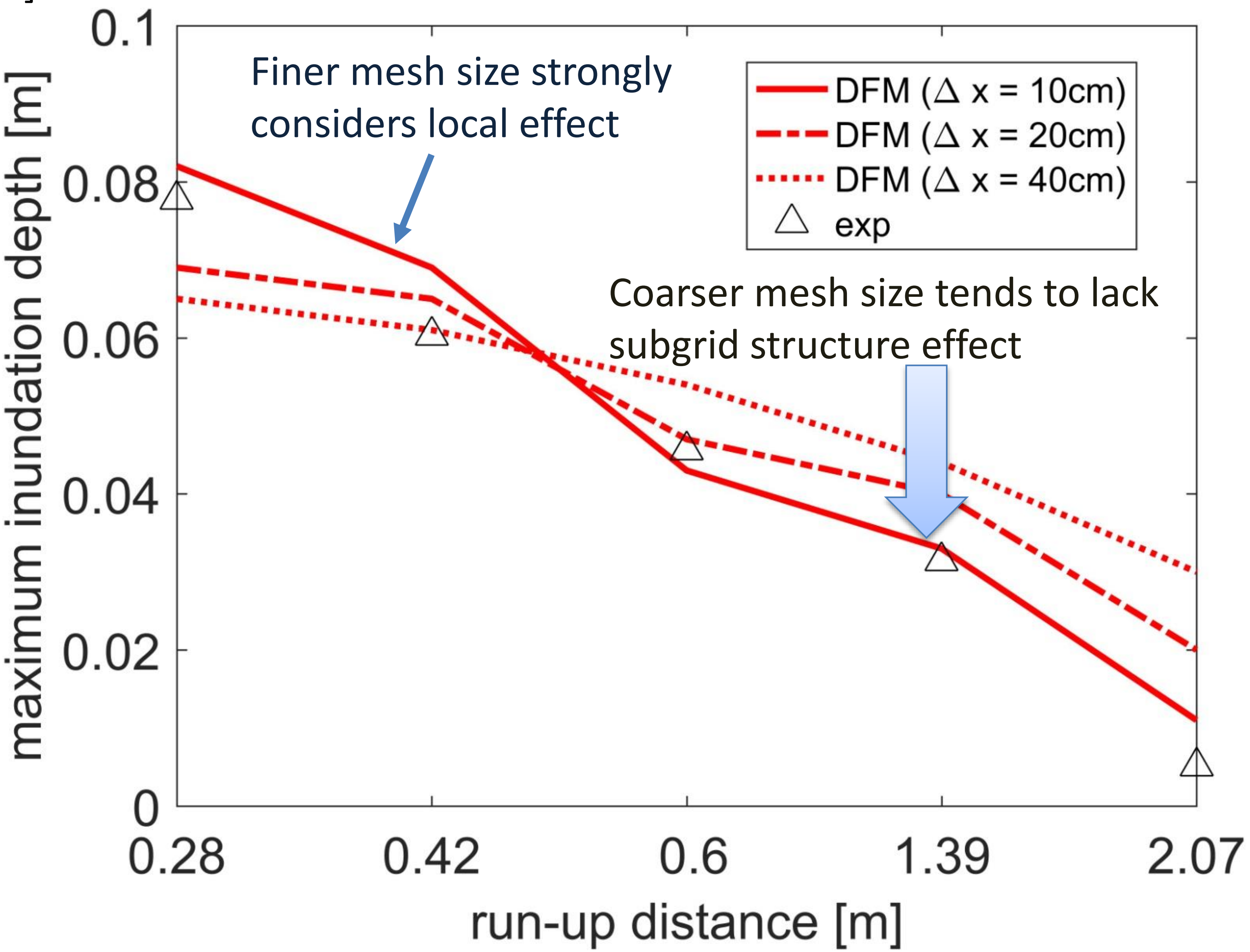
Maximum inundated depth (at each WG)



Incident wave :
solitary wave

Mesh size dependency (max. depth)





Incident wave :
solitary wave

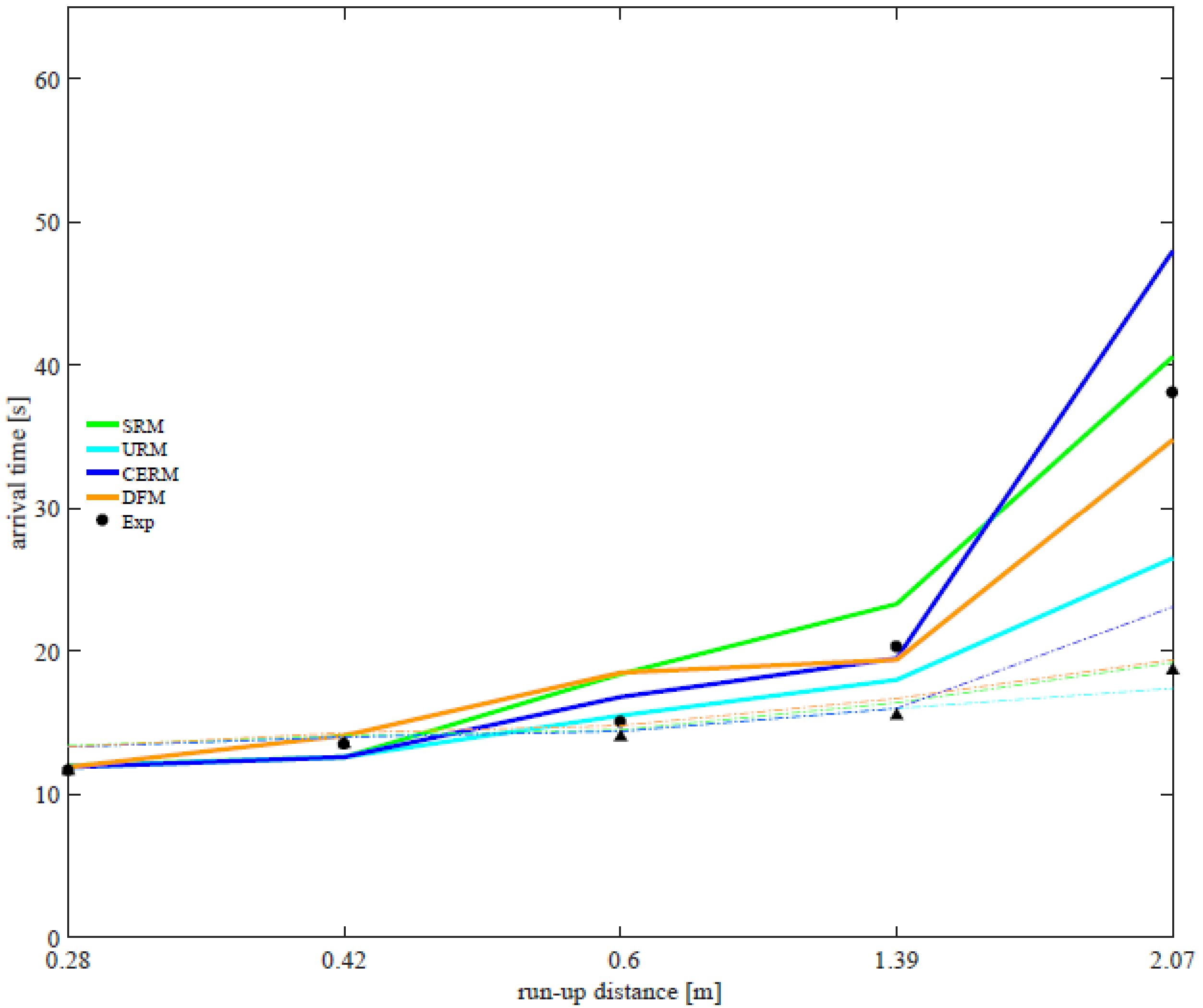
Main conclusions

- Validation of urban roughness parameterization
  +for DFM sensitivity analysis of C_D
  - DFM can express flow directionality and submergence of structures to some extent.
  - Accuracy of maximum inundation depth and arrival time by DFM is improved more than other models.
  - Mesh size dependency still remains.
- Further challenges
  - Determination of C_D
    - Artificial empirical relationship of C_D and Re considers the energy dissipation.
    - The target of Re needs to be determined for prototype scale.
  - Improvement of upscaling method
    - Spatial layout of subgrid scale structure is not considered.

Thank you for your attention

Appendix

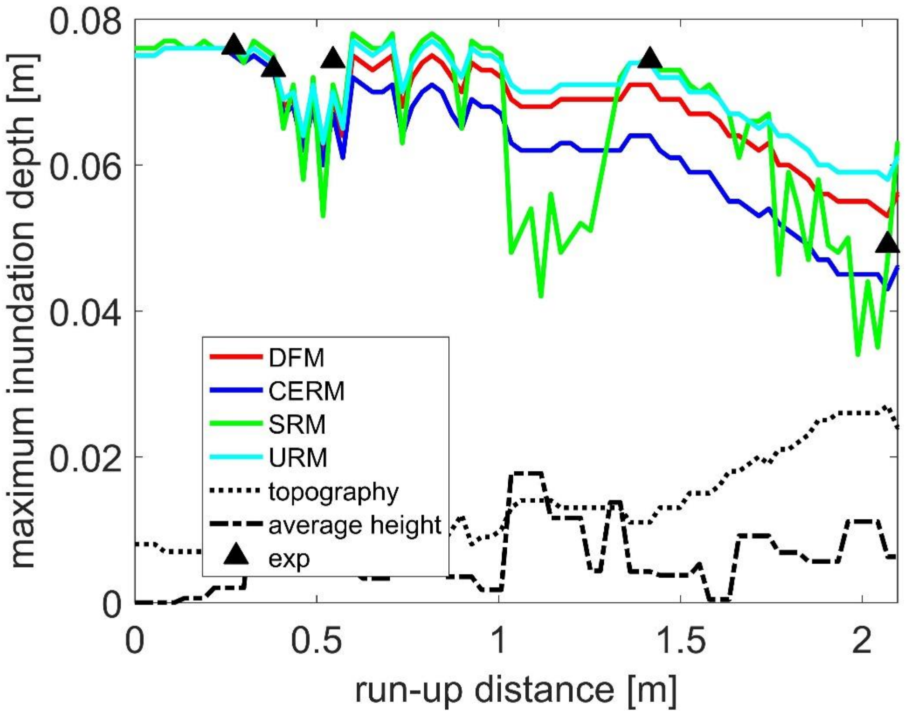
Comparison of each roughness parameterization in terms of arrival time from onshore to inland by DFM, CERM, SRM and URM.



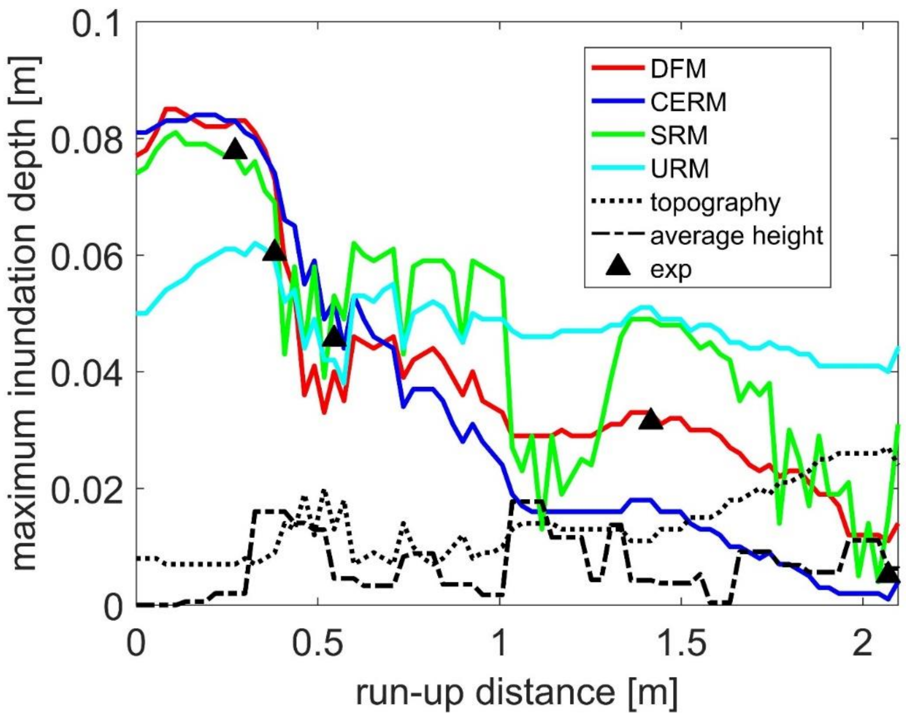
Solid lines for the hydraulic bore

Dashed lines for solitary wave

Detailed Results (max. depth)

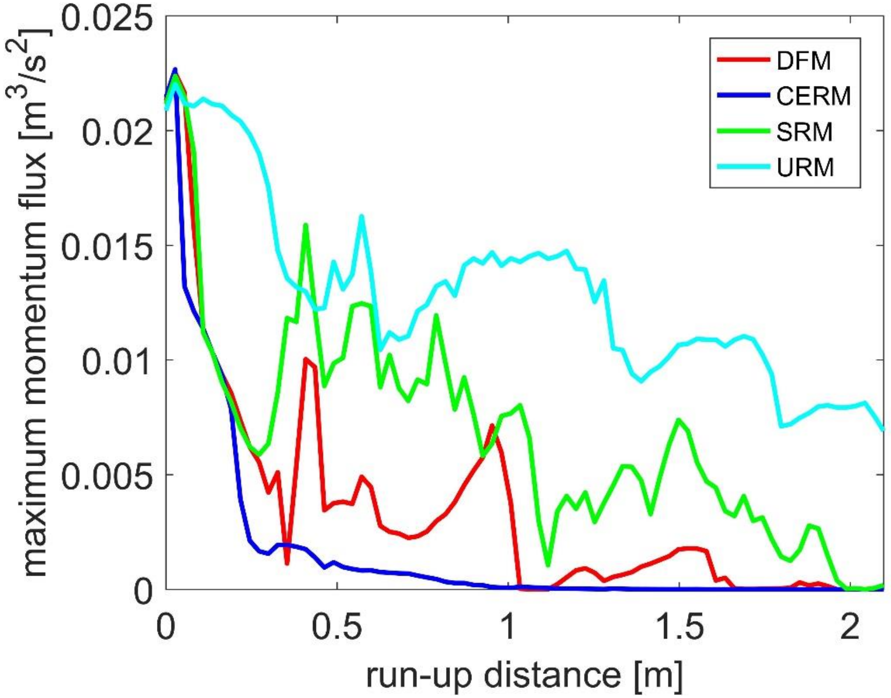


bore

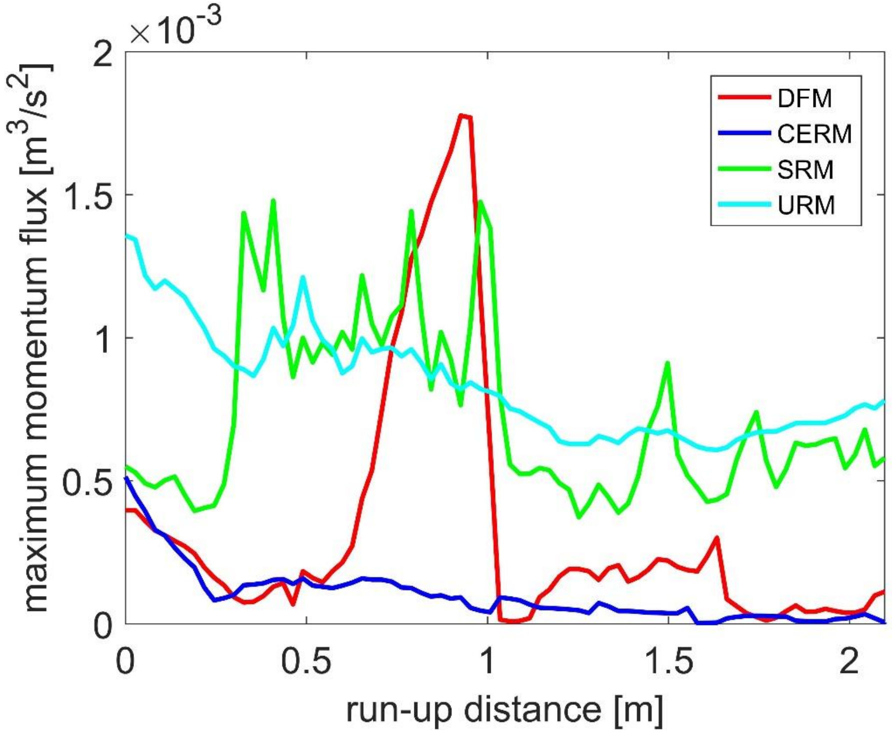


solitary wave

Detailed results (Momentum flux)



bore



solitary wave

Mesh size dependency