Digital wave flume using multi-fidelity approaches

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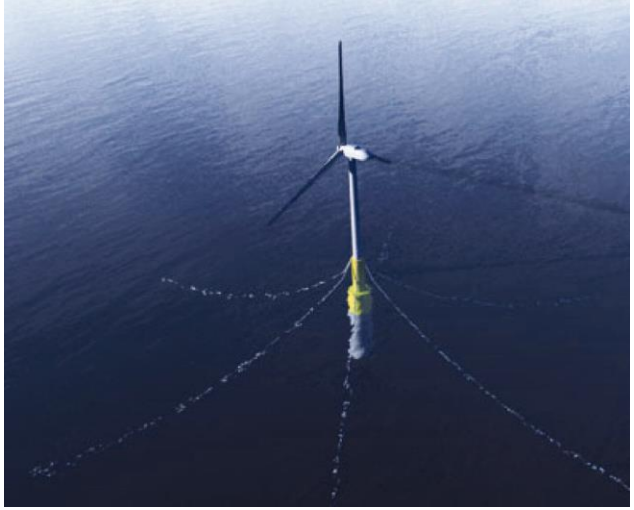
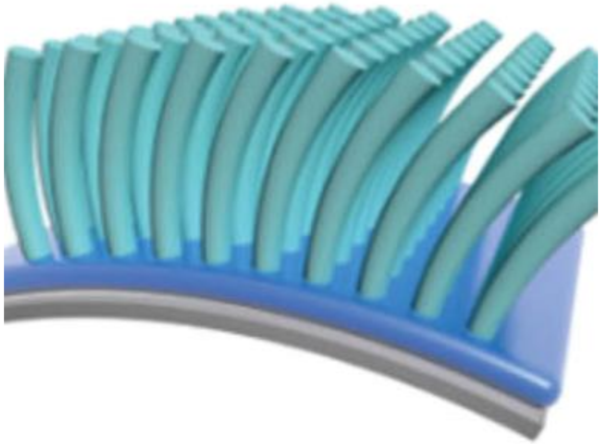
Research Motivation

Fg.1. Tsunami phenomenon[1]

Fg.2. Hurricane[2]



Fg.3. Floating wind turbine [3]



Fg.4. Ocean wave energy harvest[4]

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[1] Crossing swells, consisting of near-cnoidal wave trains. Photo taken from Phares des Baleines (Whale Lighthouse) at the western point of Île de Ré (Isle of Rhé), France, in the Atlantic Ocean.

[2] Hurricane Paulette, in 2020, is an example of a sheared tropical cyclone, with deep convection slightly removed from the center of the system

[3] Wang, C.M., Utsunomiya, T., Wee, S.C. and Choo, Y.S., 2010. Research on floating wind turbines: a literature survey. *The IES Journal Part A: Civil & Structural Engineering*, *3*(4), pp.267-277.

[4] Huang, B., Wang, P., Wang, L., Yang, S. and Wu, D., 2020. Recent advances in ocean wave energy harvesting by triboelectric nanogenerator: An overview. *Nanotechnology Reviews*, *9*(1), pp.716-735.

Smoothed Particle Hydrodynamics (SPH)[1]

Mesh-based Method

Meshless Method

- Computational points: Nodes ----- > **Particles**
- Each particle is associated with **field variables** such as mass, momentum, velocity, position, energy, etc**.**
- Particles are described through **Lagrangian** derivatives – Rate of change along with the trajectory

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[1] Gingold, R. A., & Monaghan, J. J. (1977). Smoothed particle hydrodynamics: Theory and application to non-spherical stars. *Monthly Notices of the Royal Astronomical Society*, *181*(3), 375–389

Smoothed Particle Hydrodynamics

- Each **particle** has an associated **weight** determined by a **kernel function**, which describes the **contribution of the neighboring particles** to the physical quantities (such as pressure or velocity)

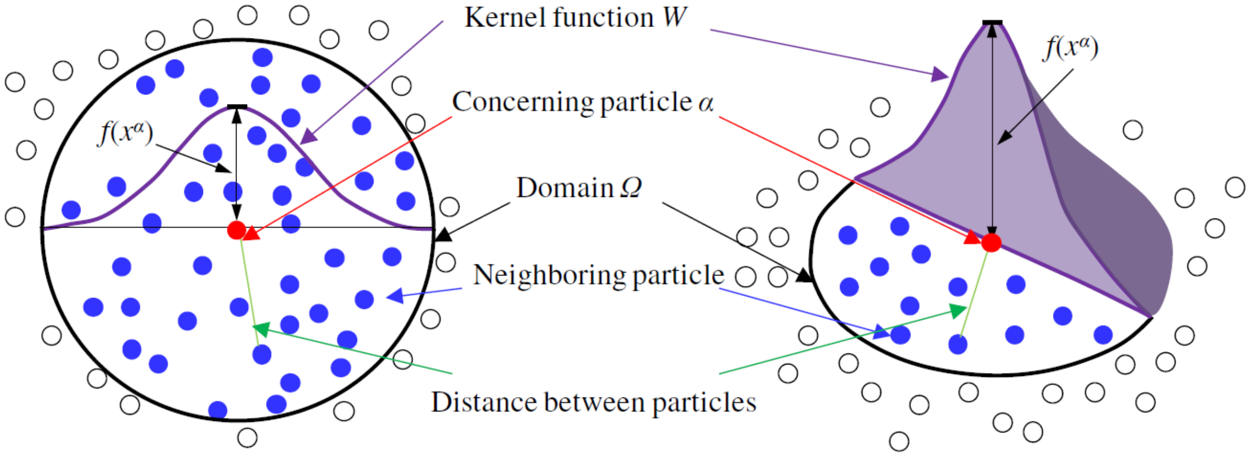

Fig. The concept of Smoothed Particle Hydrodynamics[1]

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[1] Dai, Z., Wang, F., Huang, Y., Song, K., & Iio, A. (2016). SPH-based numerical modeling for the post-failure behavior of the landslides triggered by the 2016 Kumamoto earthquake. *Geoenvironmental Disasters*, *3*(1)

Experimental Setup

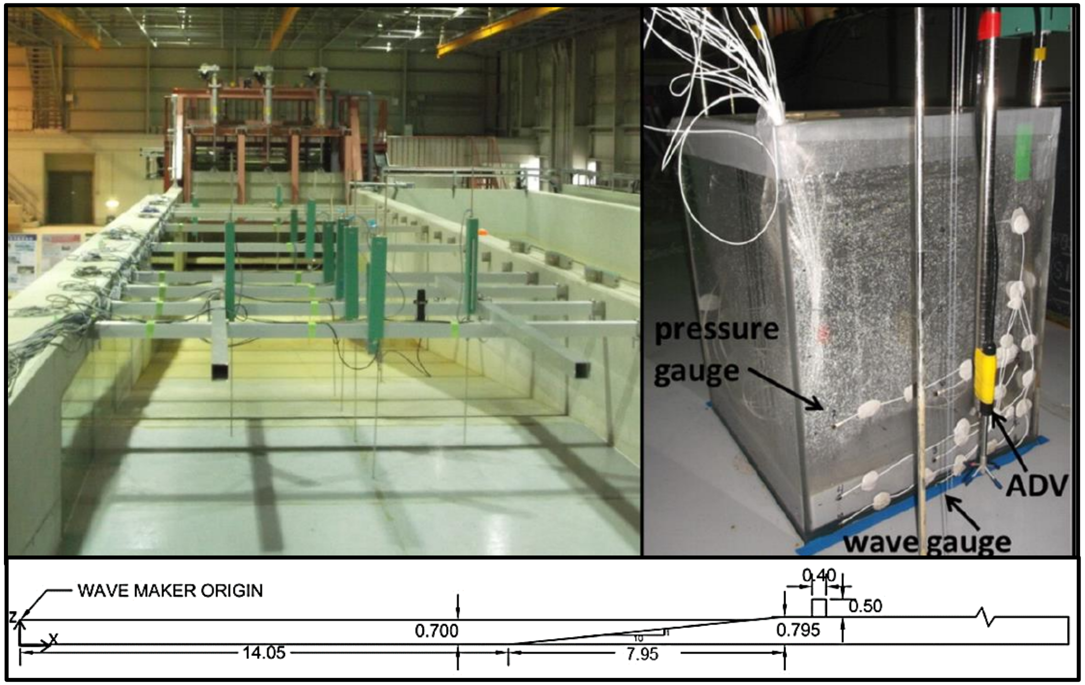

Fig. Left: resistance wave gauges and acoustic velocimeters positioned in hydraulic wave flume. Right: instrumented specimen and front side pressure gauges, wave gauge, and acoustic doppler velocimeters. Bottom: Profile views of experimental flume[1]

- Hybrid Tsunami Open Flume in Ujigawa (HyTOFU) Laboratory, Kyoto University
- 45 m long, 4 m wide, and 2 m deep wave flume, slope 1:10
- A single specimen (building) instrumented with pressure gauges was placed on flat platform
- Solitary waves was generated using wave piston
- Free surface elevation was measured in 10 different locations using resistance-type Wave Gauges

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[1] Tomiczek, T., Prasetyo, A., Mori, N., Yasuda, T., & Kennedy, A. (2016). Physical modelling of tsunami onshore propagation, peak pressures, and shielding effects in an urban building array. *Coastal Engineering*, *117*, 97–112.

Numerical Setup

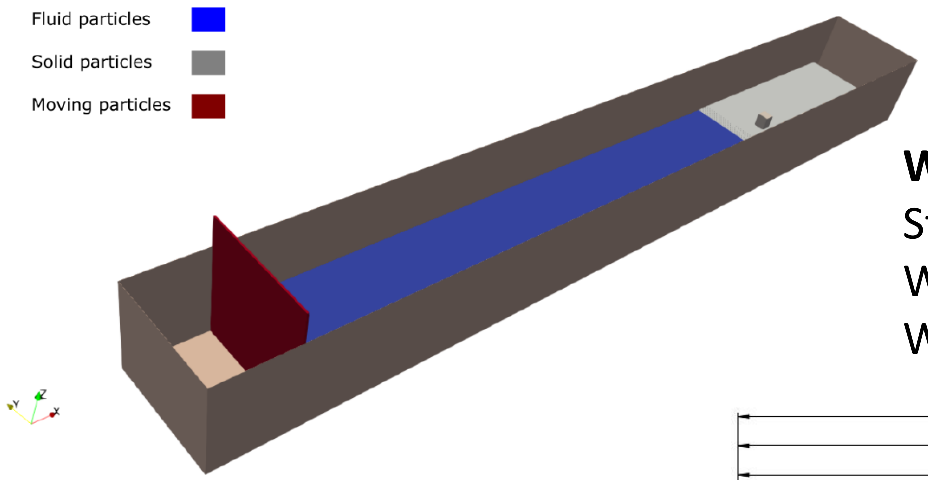

Fig. 5. HyTOFU DualSPHysics setup

Wave parameters

Still water depth - 0.7m

Wave type - Solitary wave

Wave height - 0.4m

🟥 Rigid fixed structure

● Wave gauge

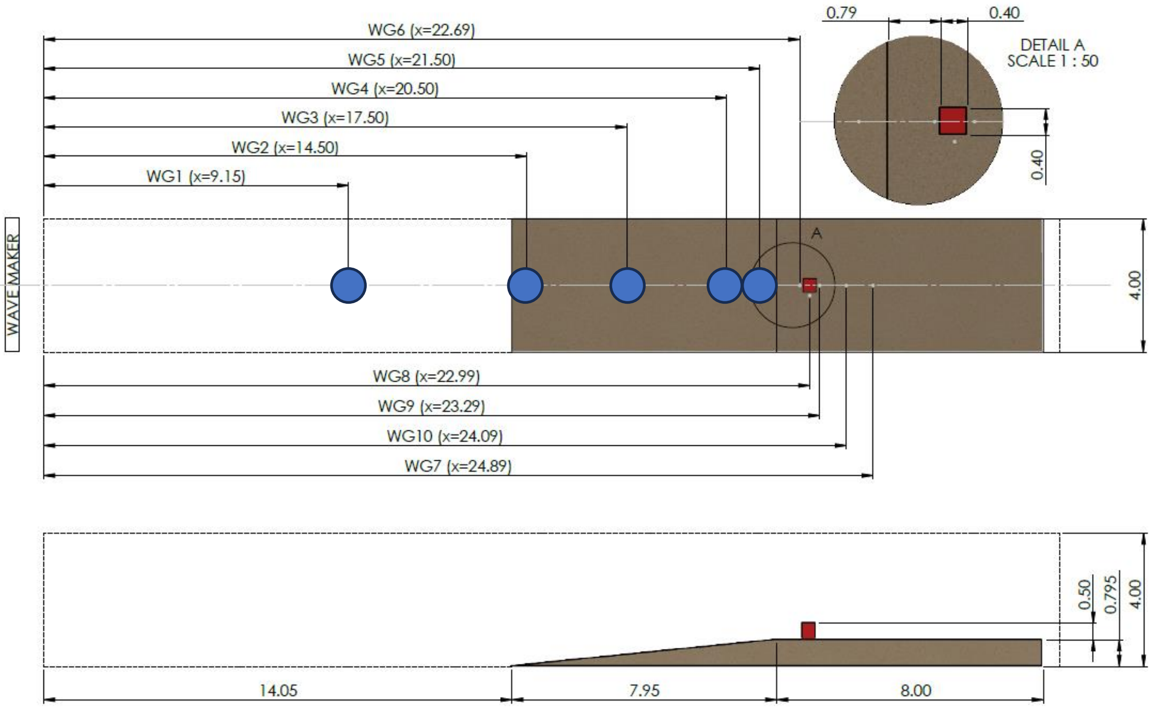

Fig. HyTOFU set up with the location of the wave gauges

Dynamic boundary conditions[1]

- domain → particles
- Grey particles – solid particles (walls, building)
- Red particles – moving particles (piston wavemaker)
- Blue particles – fluid particles (water)

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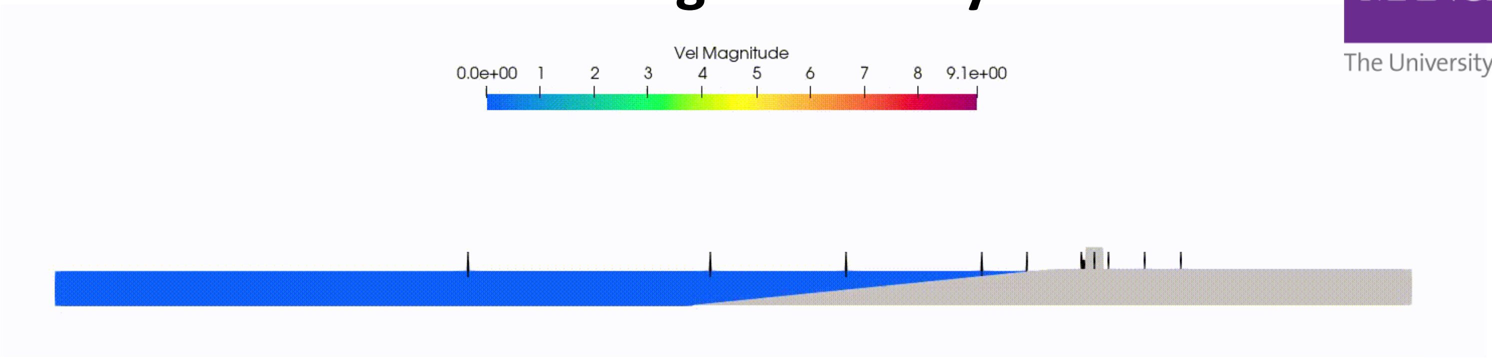
[1] Crespo, A. J. C., Domínguez, J. M., Rogers, B. D., Gómez-Gesteira, M., Longshaw, S., Canelas, R., Vacondio, R., Barreiro, A., & García-Feal, O. (2015). DualSPHysics: Open-source parallel CFD solver based on Smoothed Particle Hydrodynamics (SPH). *Computer Physics Communications*, *187*

Convergence study



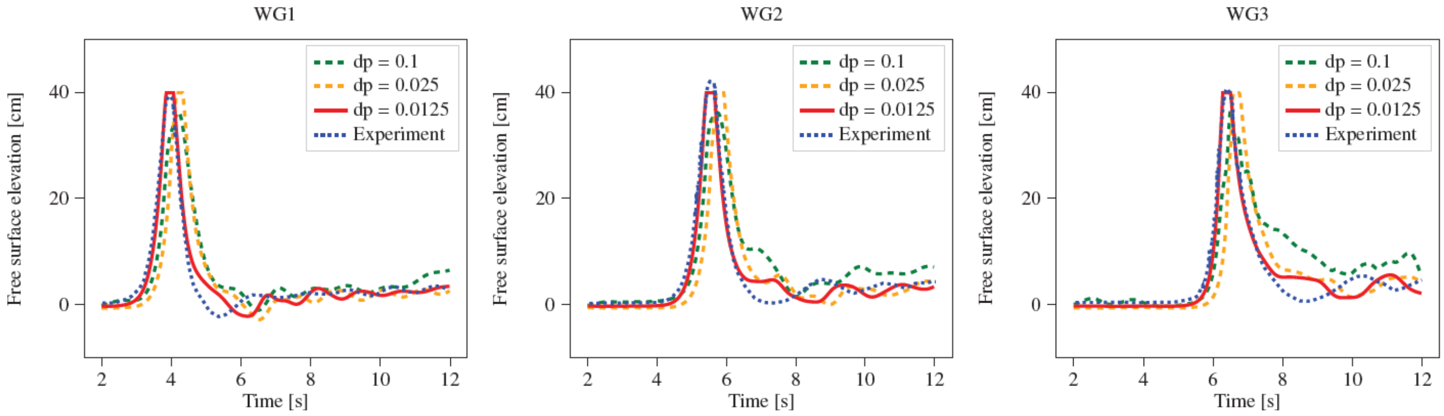


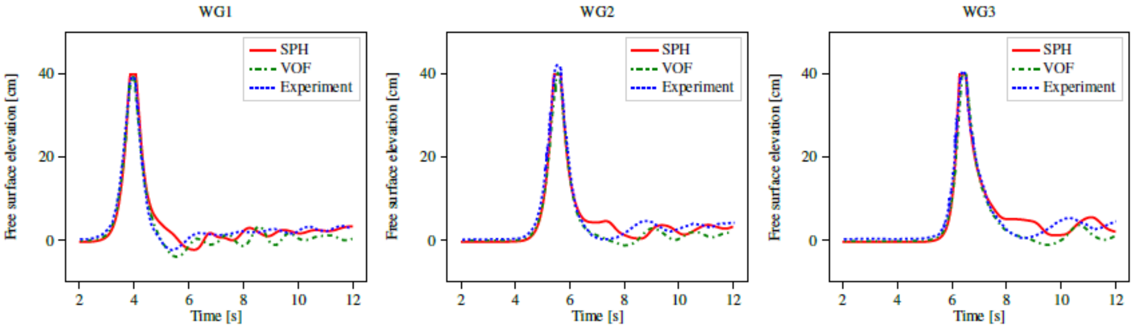
Fig. Convergence study associated with wave gauges 1, 2 and 3

- Initial interparticle distance (dp)
- Wave height (W) = 0.4 m

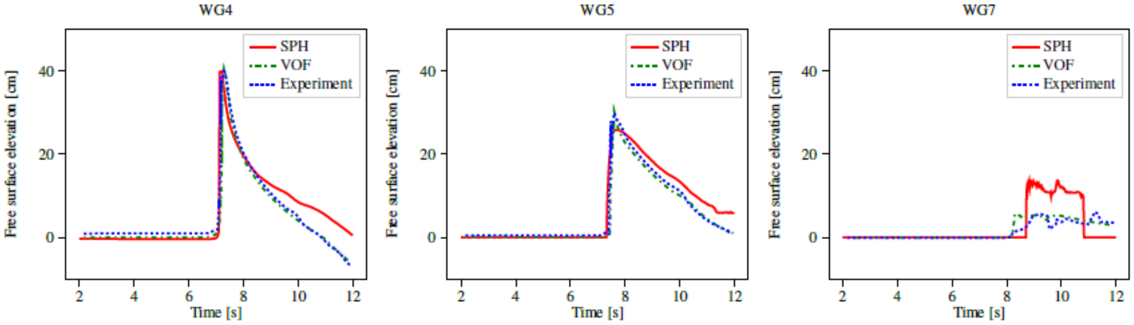
- **dp = 0.0125m showed superior agreement with experimental data**

dp	H/dp	Error in peak height	Error in wave arrival time	Compute time
0.1	4	8.87 %	-2.20 %	78.51s
0.025	16	1.96 %	-3.14 %	97854s
0.0125	32	1.86 %	1.57 %	110534s

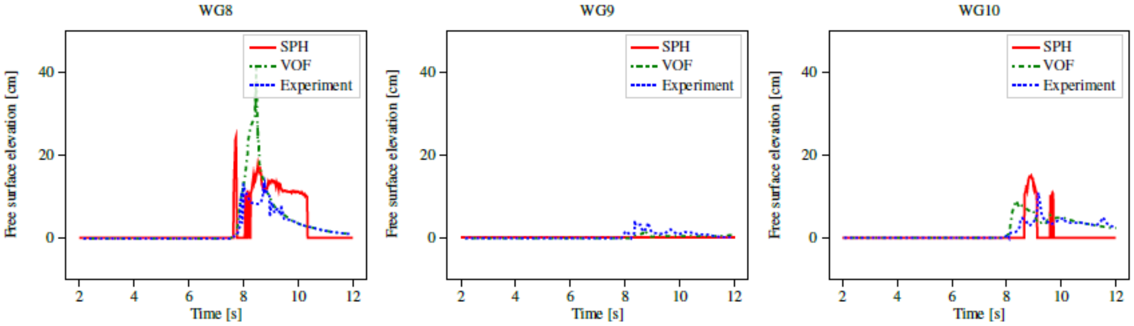
Smoothened Particle Hydrodynamics: Results



(a) Wave Gauge 1 (b) Wave Gauge 2 (c) Wave Gauge 3



(d) Wave Gauge 4 (e) Wave Gauge 5 (f) Wave Gauge 7

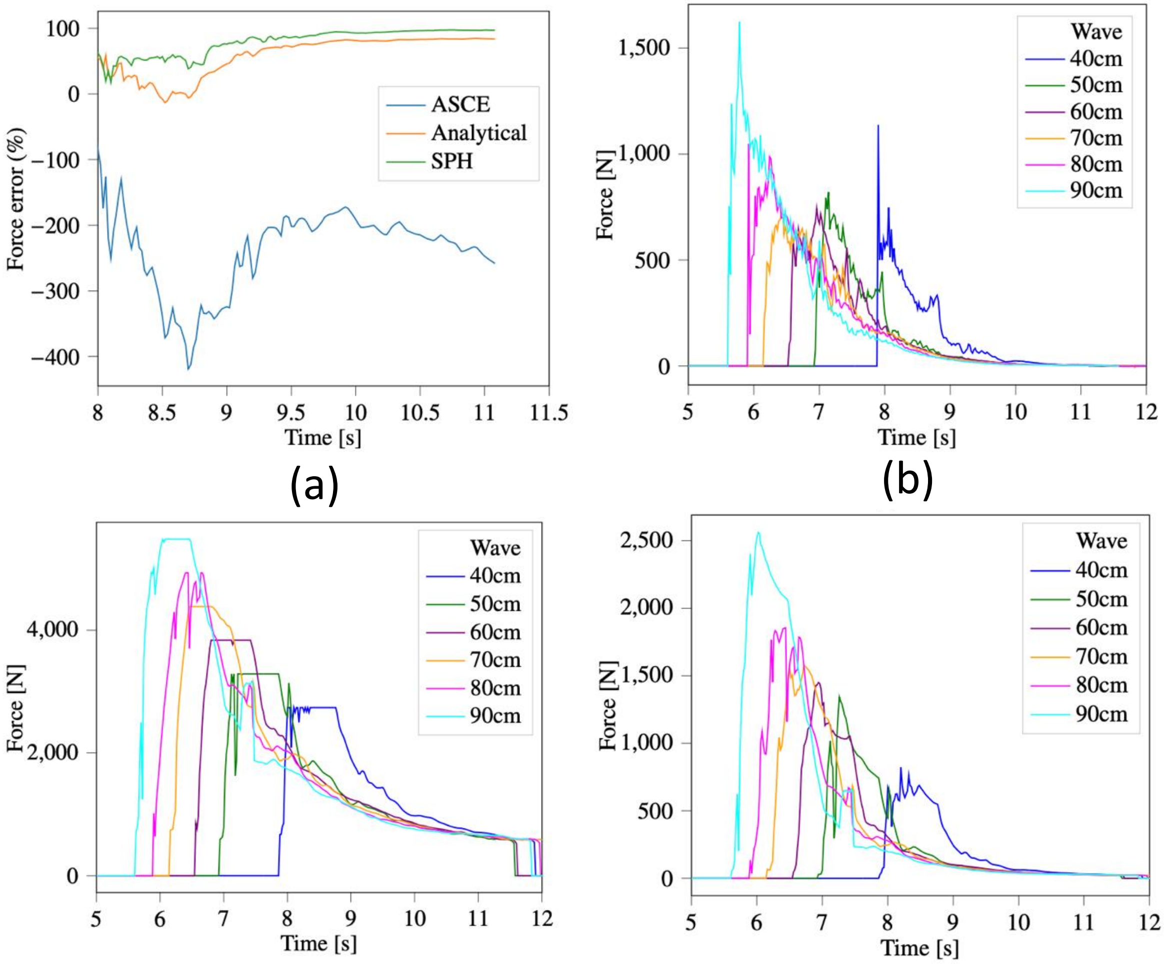


(g) Wave Gauge 8 (h) Wave Gauge 9 (i) Wave Gauge 10

Fig. 7. Comparison of free surface elevation data

- Free surface elevation agreement is observed in initial flat and sloping sections (WG1, WG2, WG3) and test section (WG4, WG5)
- Unable to validate accuracy of free surface elevation representation in front (WG6) and back (WG9) of the specimen due to limitations in data recording
- Overall. wave arrival time and wave height show effective validation of the numerical model

Wave loading evaluation



(a)

(b)

(c)

(d)

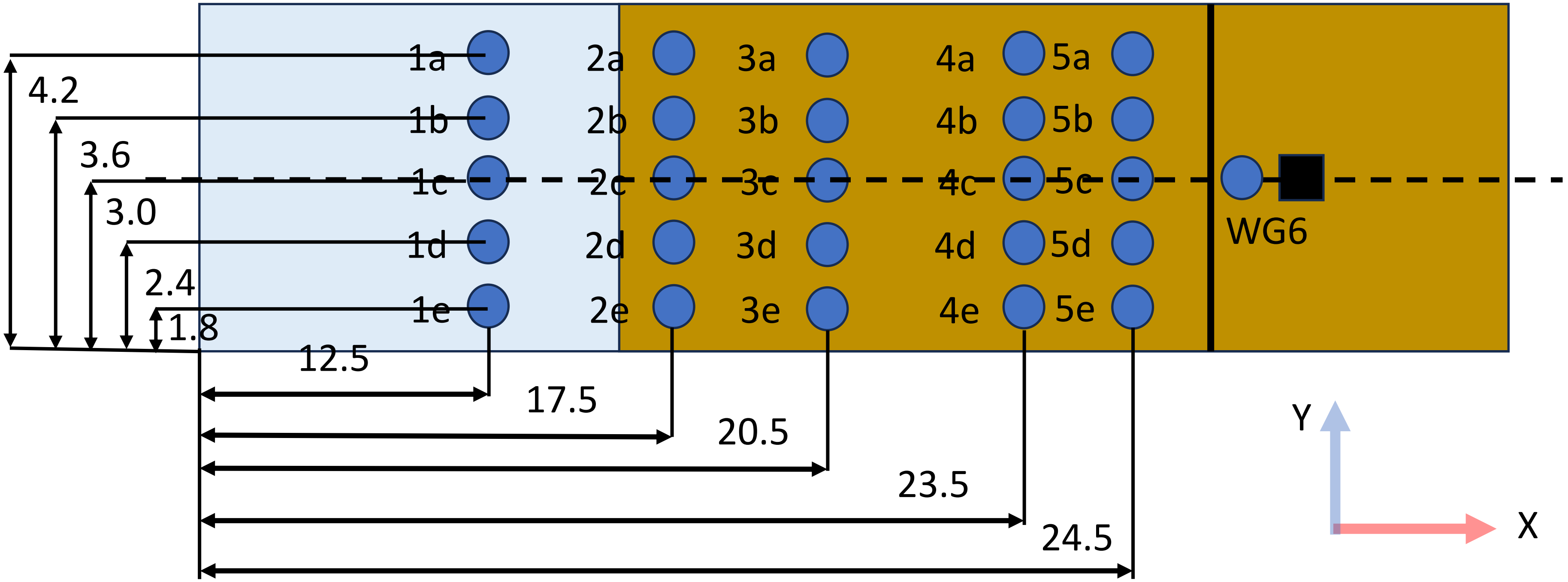
Fig. 8. Evaluation of wave loading with different initial wave heights

- Comparison of different methods for evaluation of structural response (a)
- Forces evaluated using different wave heights
  - SPH model (b)
  - ASCE (c)
  - Analytical (d)

Why maximum drag force does not consistently increase as initial wave height increase?

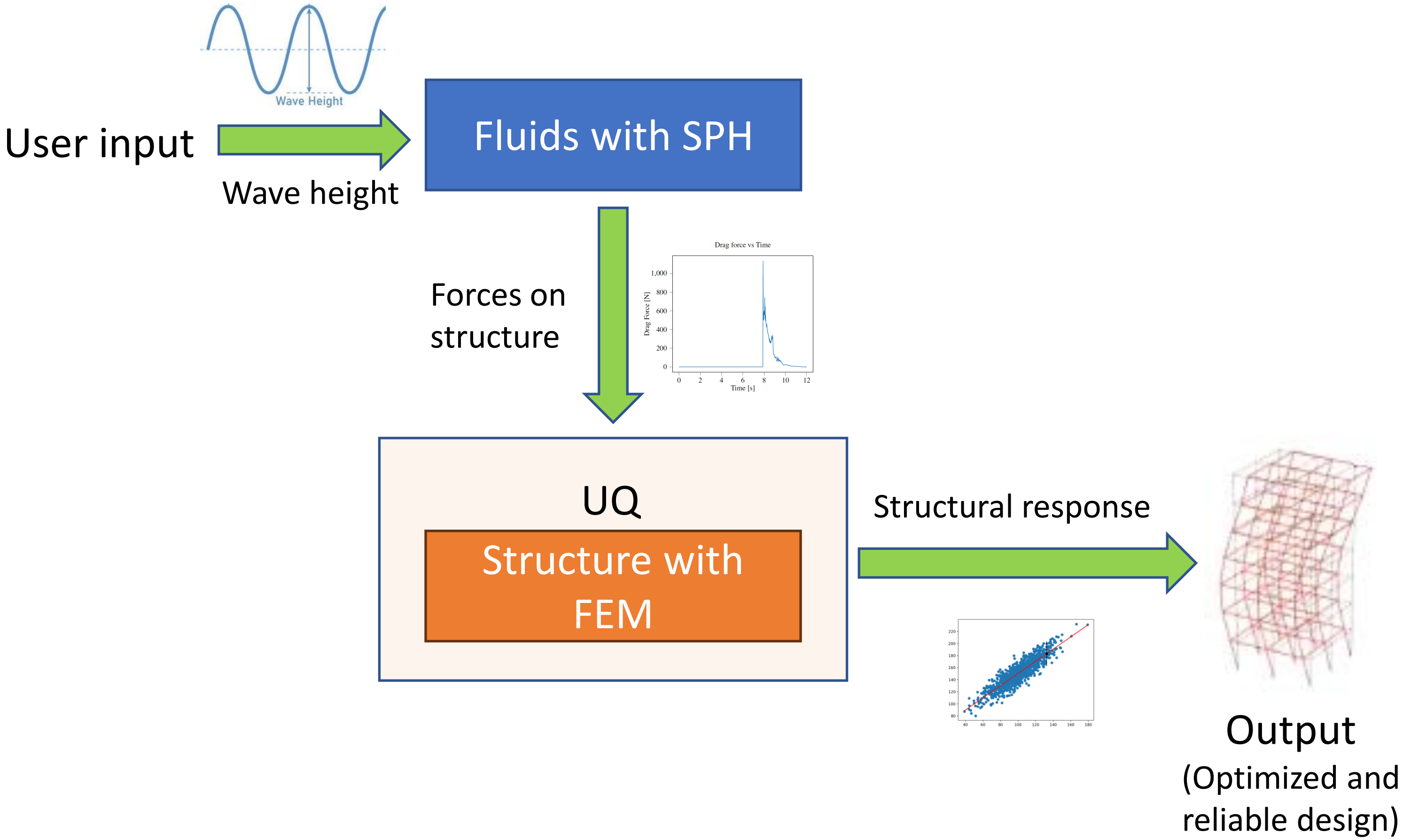
Build 25 wave gauges

To check if there is breaking point and dissipation happens in different initial wave height case



- Same: Initial wave height = 0.4m, 0.9m
- Big dump: Initial wave height = 0.5m, 0.6m
- Little dump: Initial wave height = 0.7m, 0.8m

Uncertainty Quantification



User input

Wave height

Fluids with SPH

Forces on structure

UQ

Structure with FEM

Structural response

Output

(Optimized and reliable design)

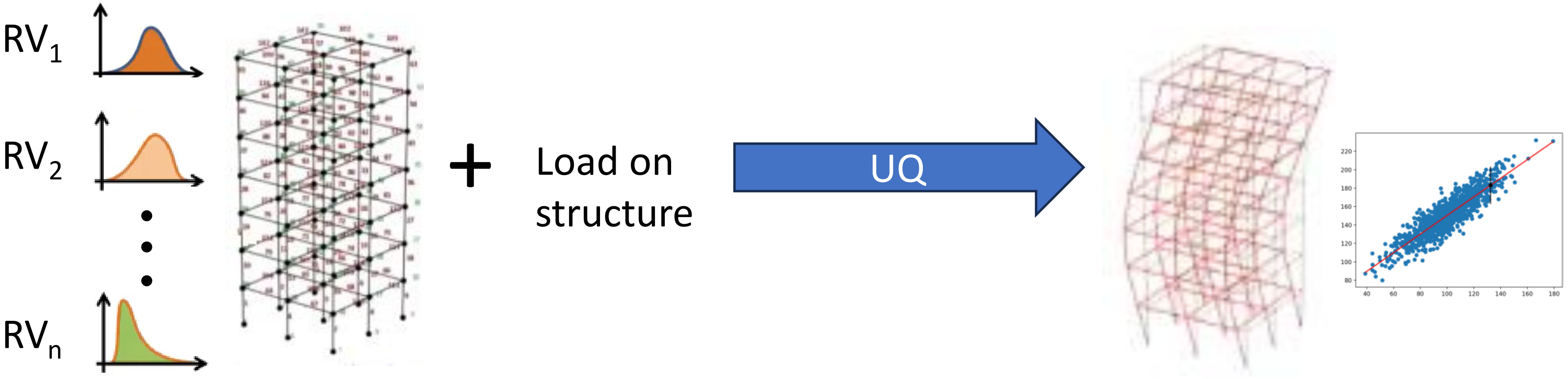
Uncertainty Quantification

- Probabilistic structural dynamic analyses are performed to identify the realistic range of building responses
- Provides more reliable estimates for practical engineering applications

- Uncertainties in structural responses typically arise from two primary sources

1. Parameters associated with coastal wave
2. **Parameters associated with building (structures)**

Forward UQ (Structures) : Quantifies the uncertainty in output parameters by propagating the uncertainties present in selected input parameters



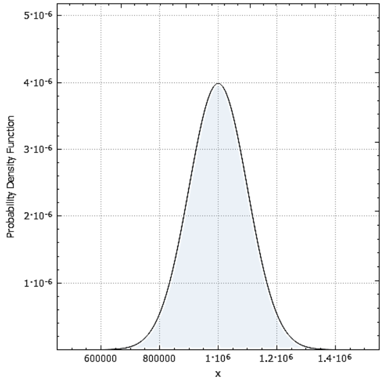
Structural input uncertainty

Structural response probability

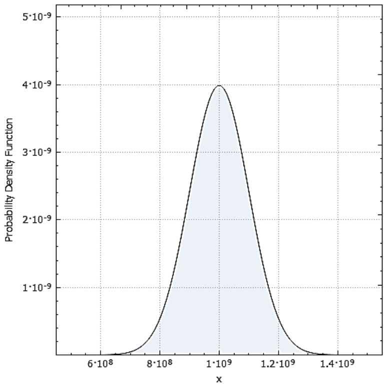
Forward UQ: Inputs

Random Variables

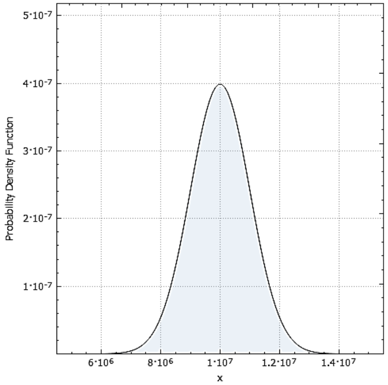
Yield strength (F)
Distribution – Normal
Mean = 1e6
Standard deviation = 1e5



Stiffens (K)
Distribution – Normal
Mean = 1e9
Standard deviation = 1e8

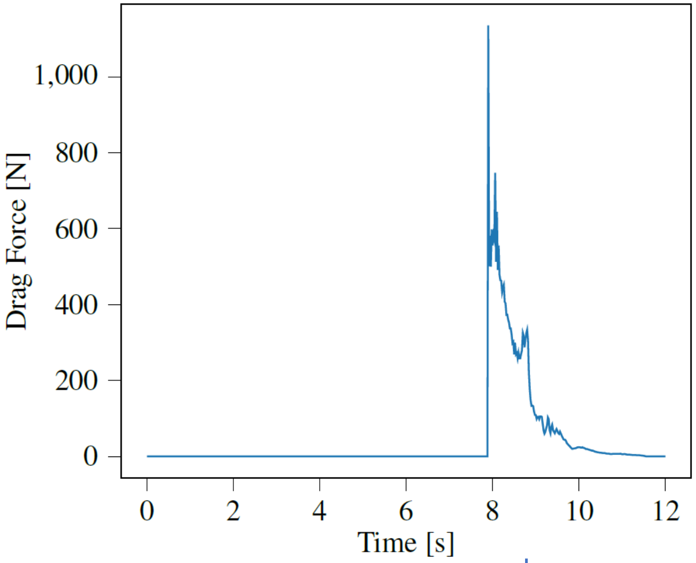


Floor weight (W)
Distribution – Normal
Mean = 1e7
Standard deviation = 1e6



Load – time history

Drag force vs Time



Considered a single story building

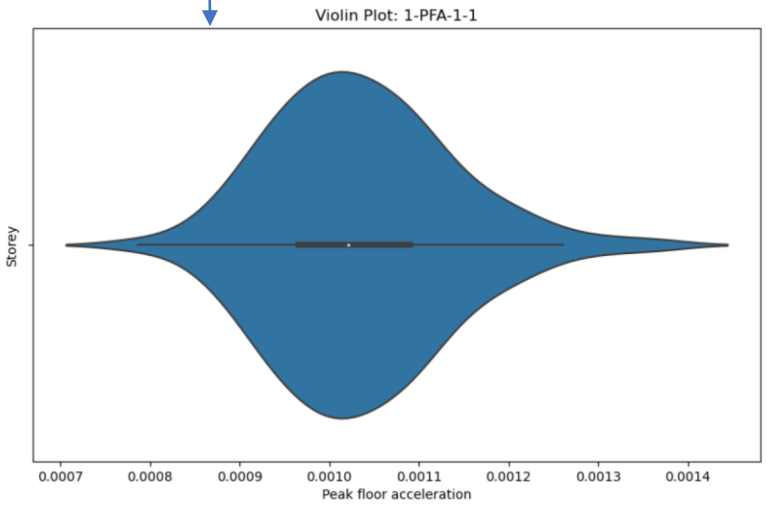
Latin Hypercube Sampling (LHS) with sample size = 100

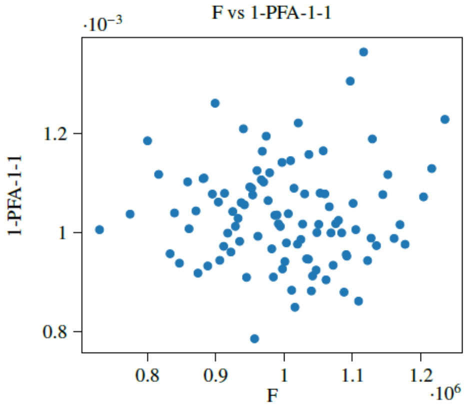
Forward UQ
Using
WE-UQ tool

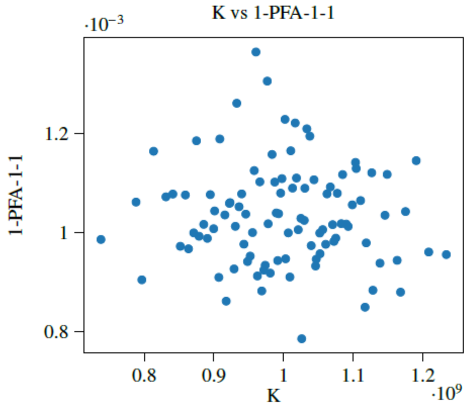
Forward UQ: Outputs

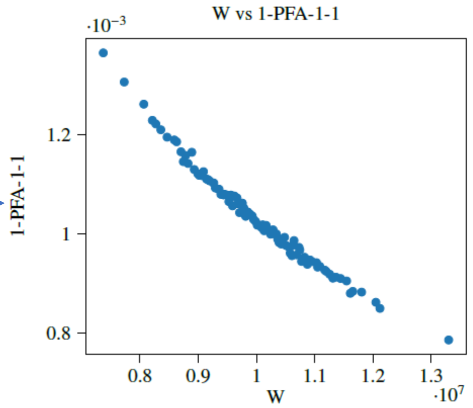
Forward UQ
Using
WE-UQ tool

Structural response:
Peak floor acceleration







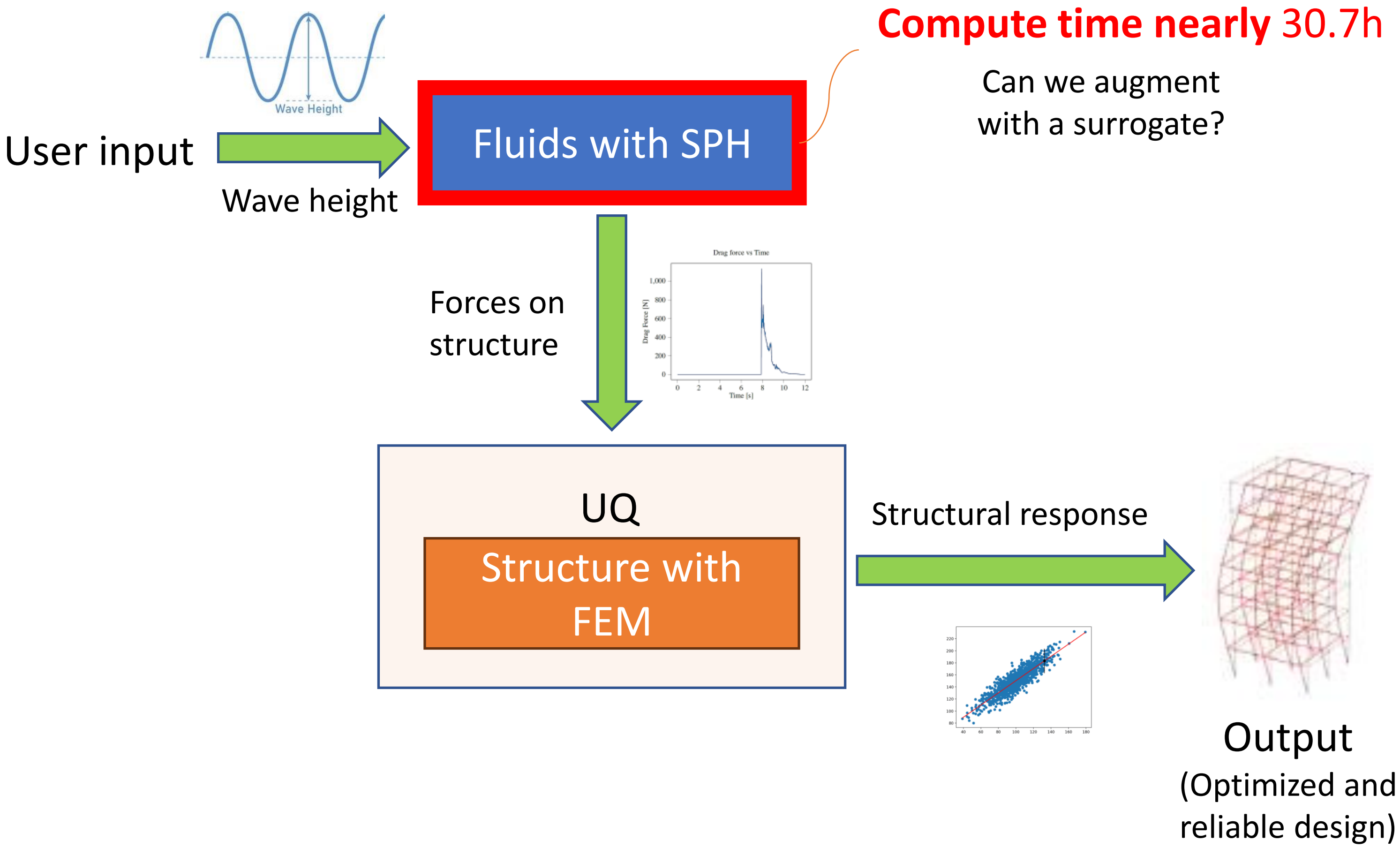


- Near-symmetrical shape, indicating a balanced distribution
- Notable concentration around middle of acceleration range
- Mean = 0.0010 m/s^2
  Standard deviation = 0.0001 m/s^2

Yield strength versus peak floor acceleration and stiffens versus peak floor acceleration plots displayed a random distribution with **no discernible correlation**

Floor weight exhibited **a strong negative correlation** with peak floor acceleration

Need for Surrogate Modelling



Compute time nearly 30.7h

Can we augment
with a surrogate?

User input

Wave height

Fluids with SPH

Forces on
structure

UQ

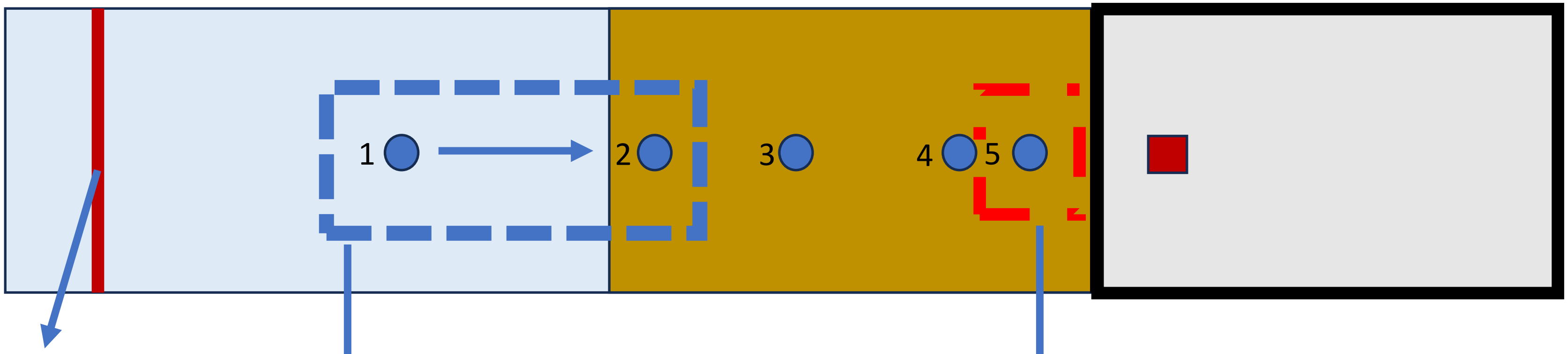
Structure with
FEM

Structural response

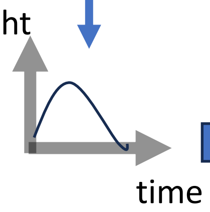
Output
(Optimized and
reliable design)

Need for Surrogate Modelling

Reduce domain size



Moving wall (piston)



Use ML to predict

Last wave gauge's wave height

- 🟦 Fluid
- 🟫 Slope
- ⬜ Flat platform
- ● Wave gauge (WG)
- 🟥 Rigid fixed structure

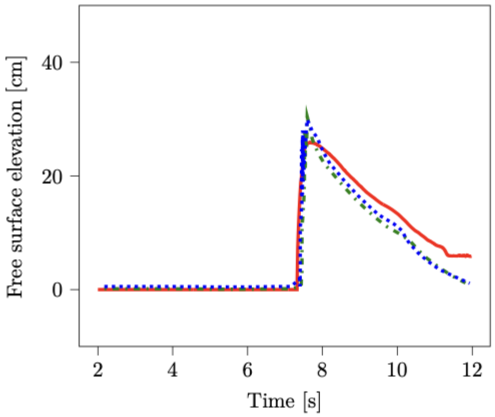


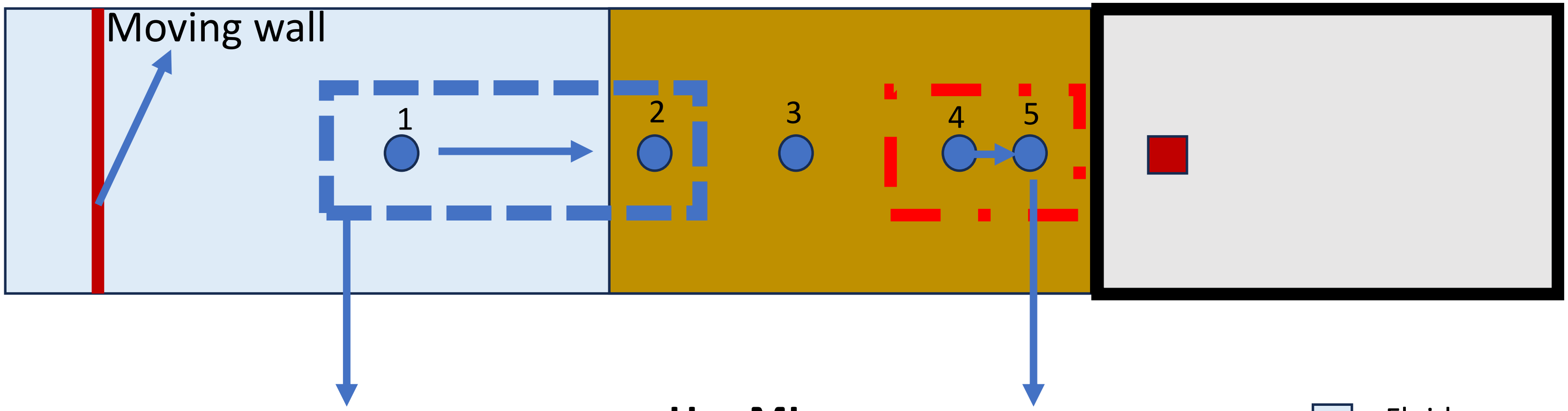
Figure. Last column of wave gauge's wave height vs. time

Need for Surrogate Modelling

Reduce domain size

&

Simulate more cases



wave height at WG1&WG2
(Initial wave height is 0.4m)

Use ML →

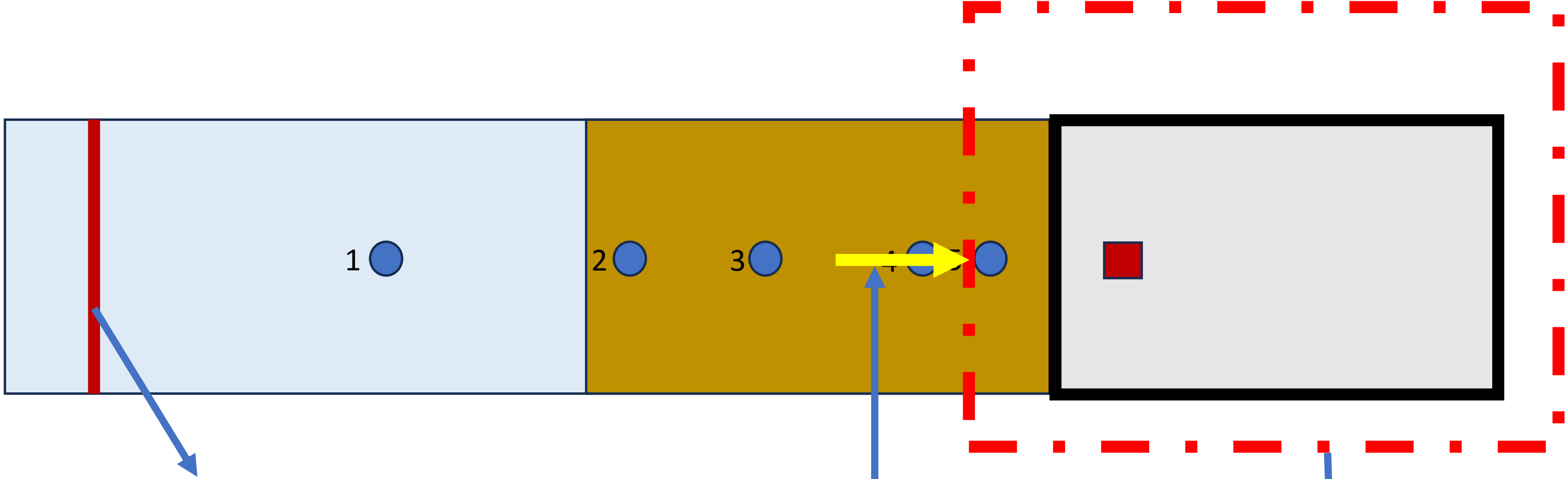
wave height at WG5
(Initial wave height is 0.6m)

- 🟦 Fluid
- 🟨 Slope
- ⬜ Flat platform
- ● Wave gauge (WG)
- 🟥 Rigid fixed structure

Need for Surrogate Modelling

Reduce domain size

Simulate more cases



Moving wall (piston)

ML-derived boundary condition

New domain size for SPH

🟦 Fluid

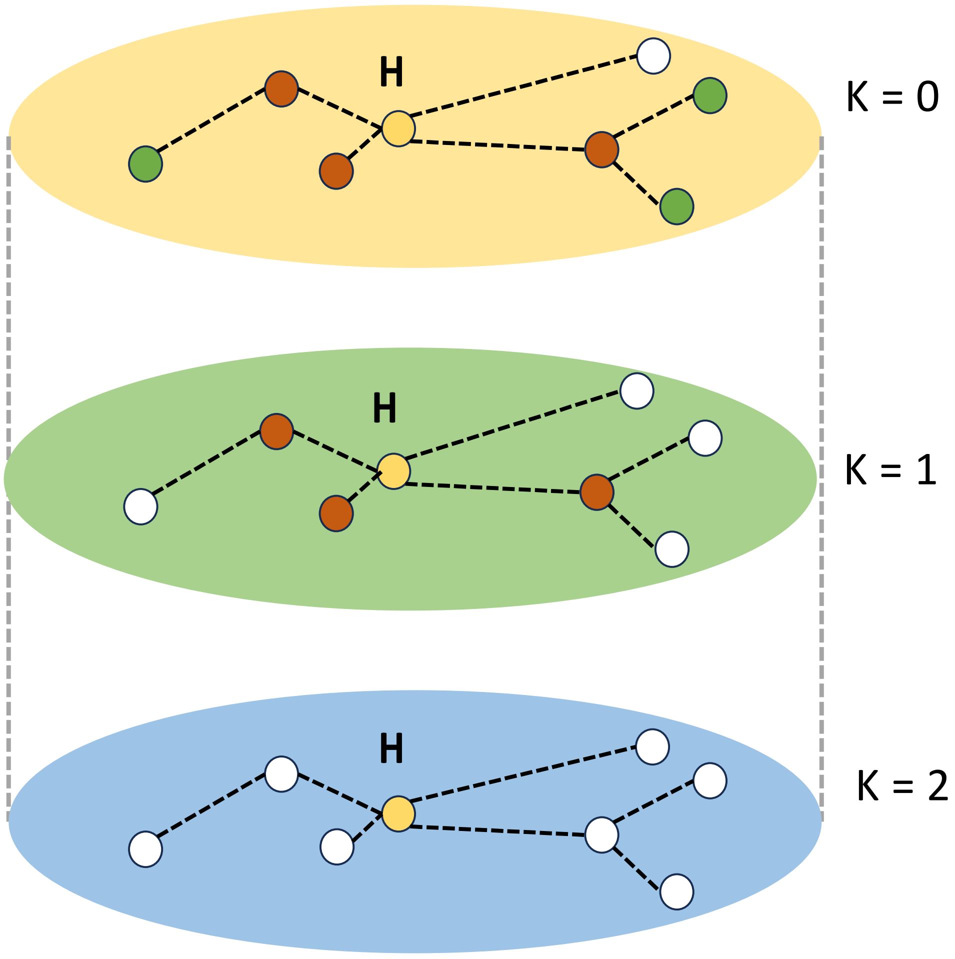
🟫 Slope

⬜ Flat platform

● Wave gauge (WG)

🟥 Rigid fixed structure

Graph Sample and Aggregate (GraphSAGE)



Neighbour node sampling

Generate target node embedding

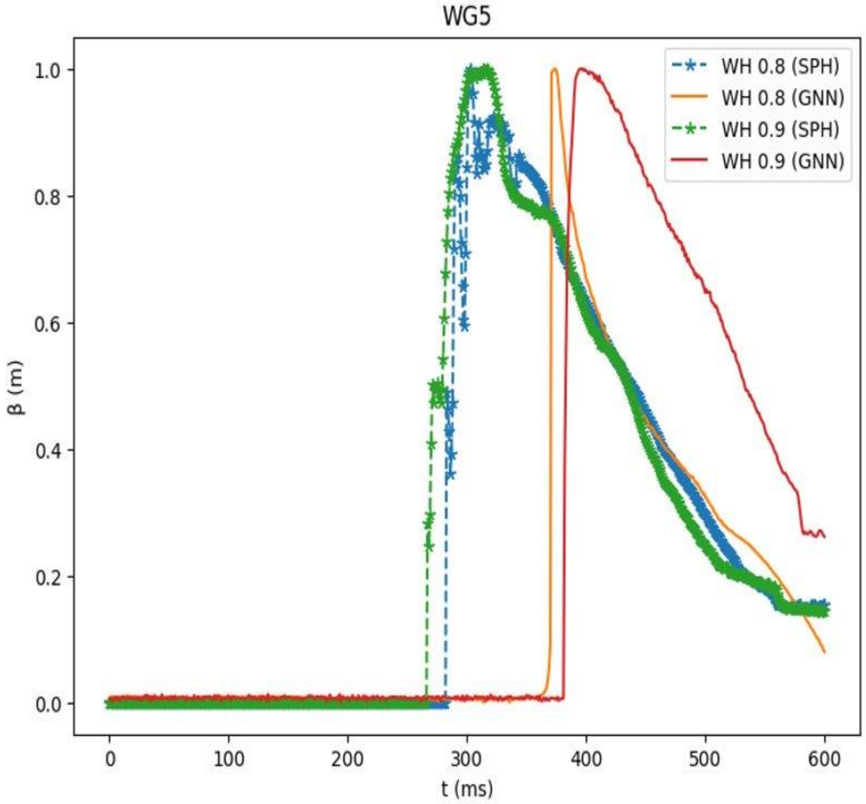
Prediction

GraphSAGE in Wave Propagation Prediction

Advantage for using GraphSAGE:

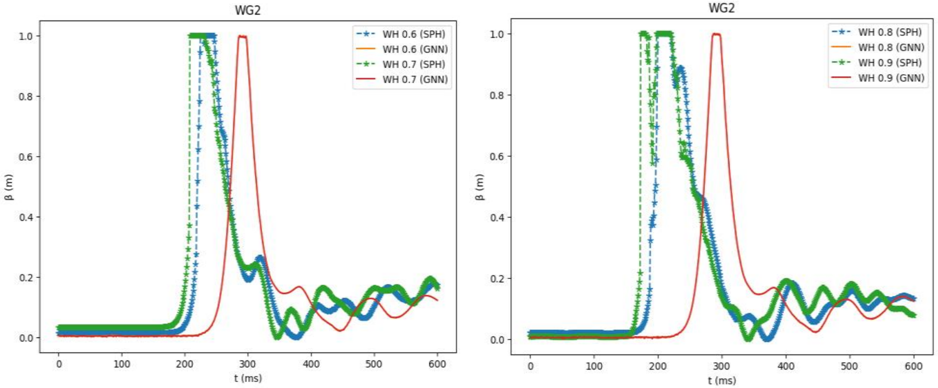
- Considering the relationships between nodes
- Incorporating node features
- Learning node embeddings
- Predictive capability

	Train_x	Train_y
Training set (Initial wave height 0.4m)	Wave Gauge 4	Wave Gauge 5
Validation set (Initial wave height 0.5m)	Wave Gauge 4	Wave Gauge 5
Testing set (Initial wave height 0.8m and 0.9m)	Wave Gauge 4	Wave Gauge 5



GraphSAGE in Wave Propagation Prediction

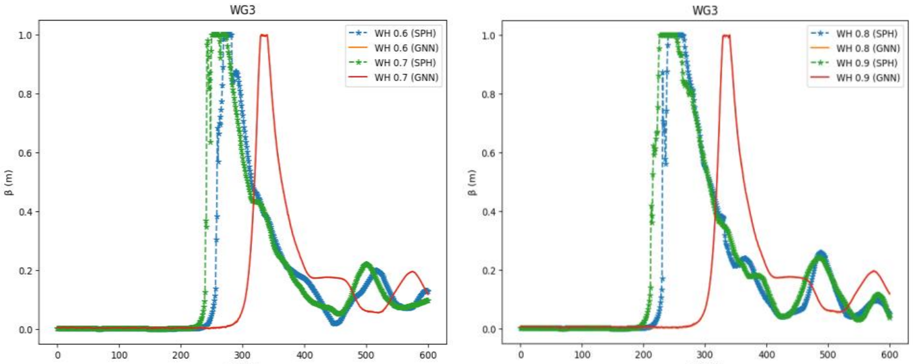
Prediction at Wave Gauge 2



Initial wave height (0.6m, 0.7m)

Initial wave height (0.8m, 0.9m)

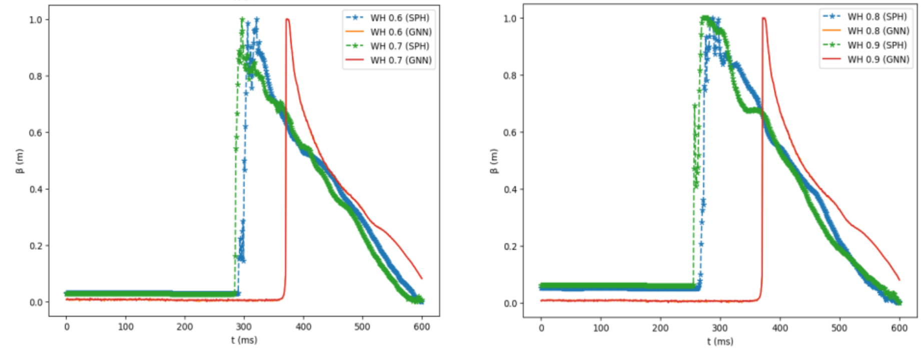
Prediction at Wave Gauge 3



Initial wave height (0.6m, 0.7m)

Initial wave height (0.8m, 0.9m)

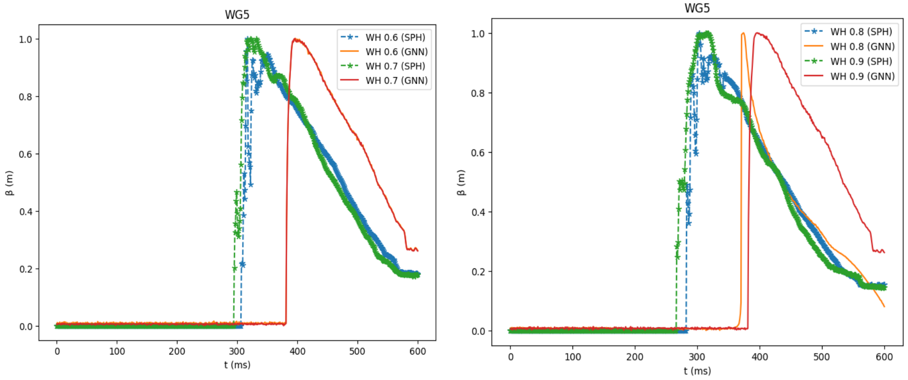
Prediction at Wave Gauge 4



Initial wave height (0.6m, 0.7m)

Initial wave height (0.8m, 0.9m)

Prediction at Wave Gauge 5



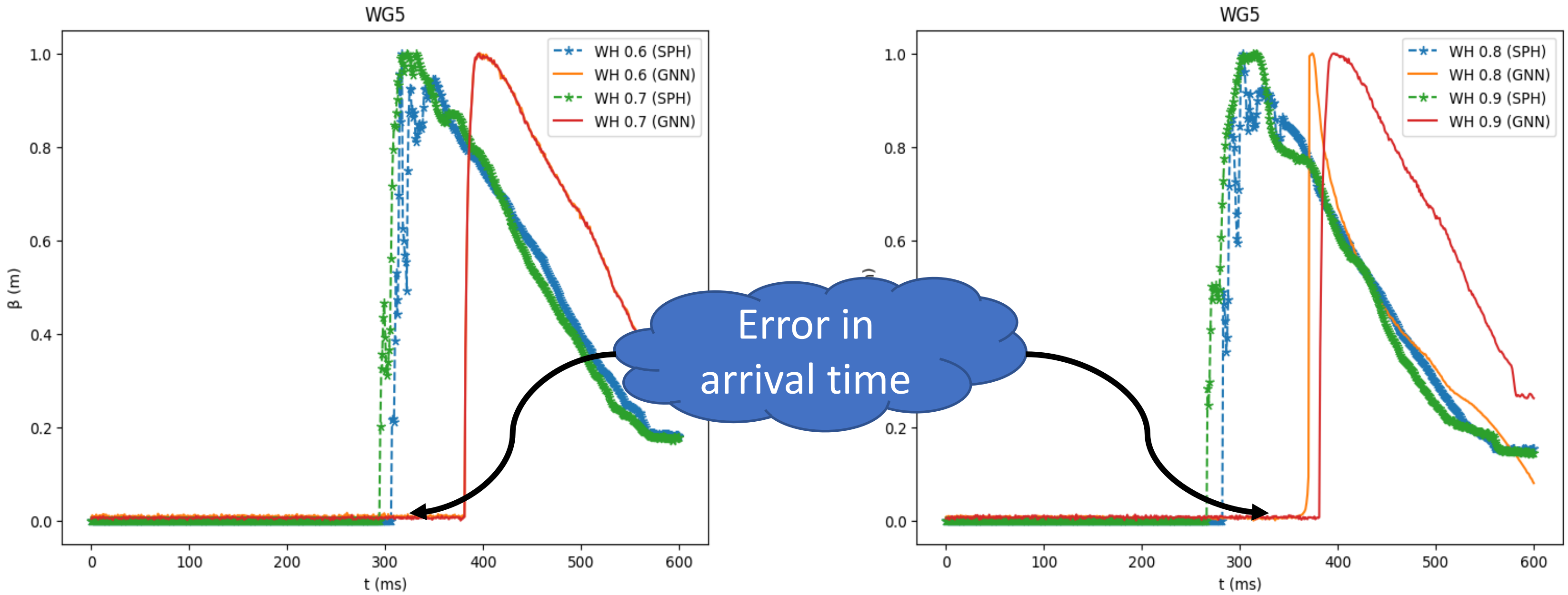
Initial wave height (0.6m, 0.7m)

Initial wave height (0.8m, 0.9m)

GraphSAGE at Wave gauge 5

Initial wave height
(0.6m, 0.7m)

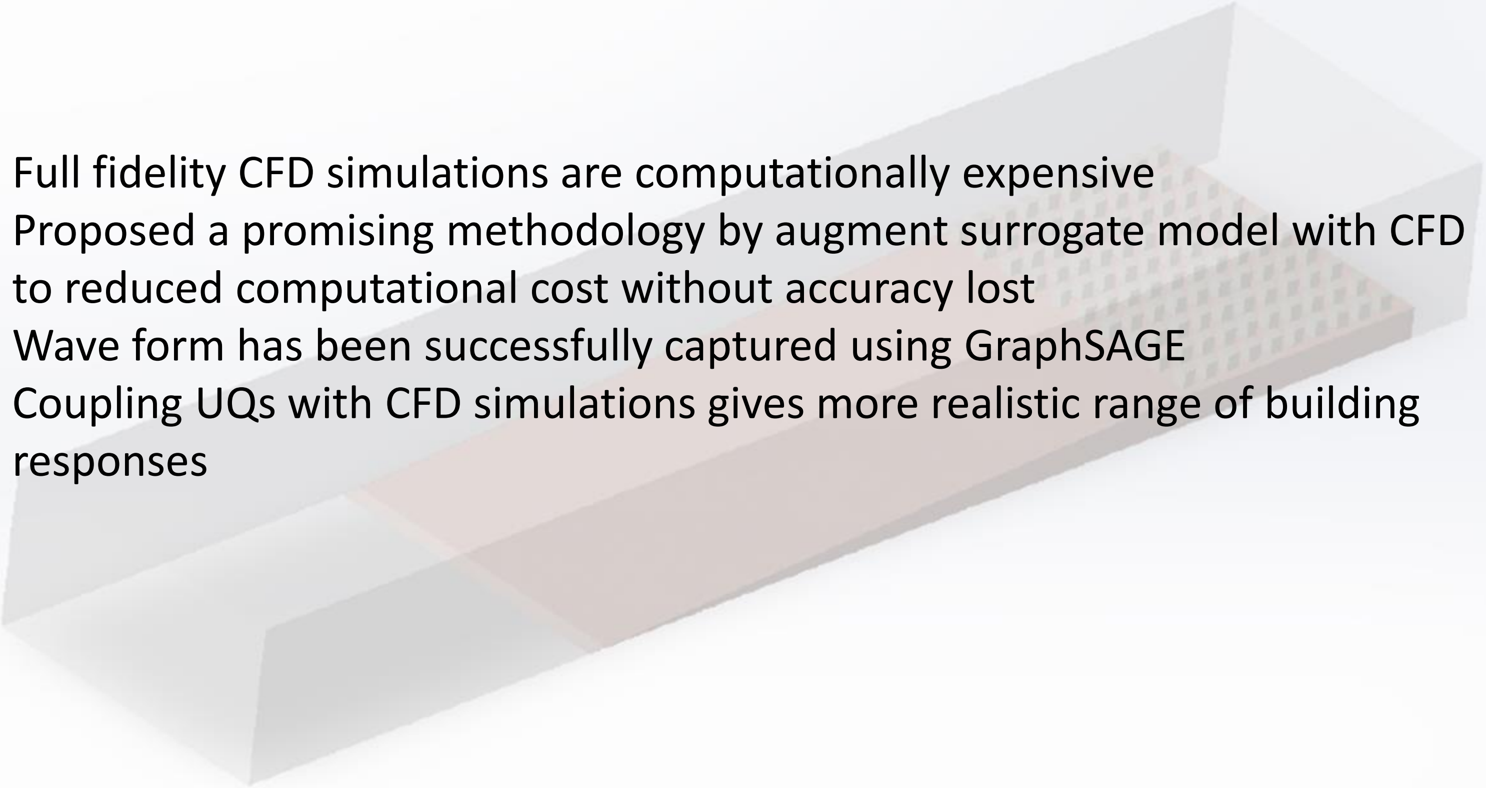
Initial wave height
(0.8m, 0.9m)



Error in arrival time

- The arrival time values are not important– Structural response is not depending on arrival time
- **Wave form** is only important information! - as we use this as boundary conditions to CFD

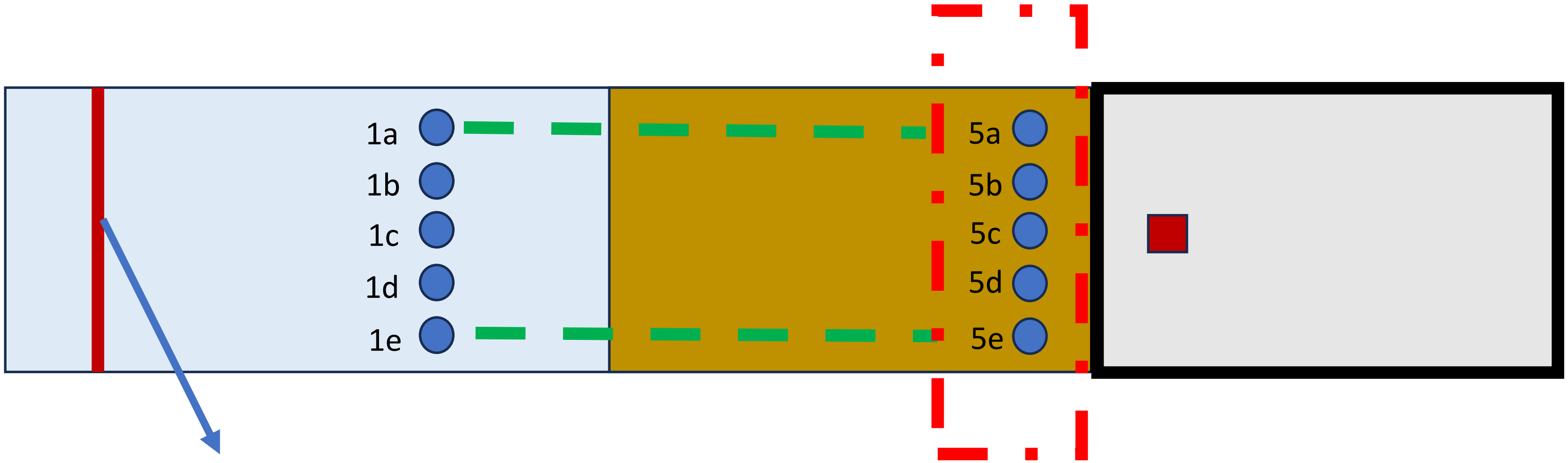
Conclusions



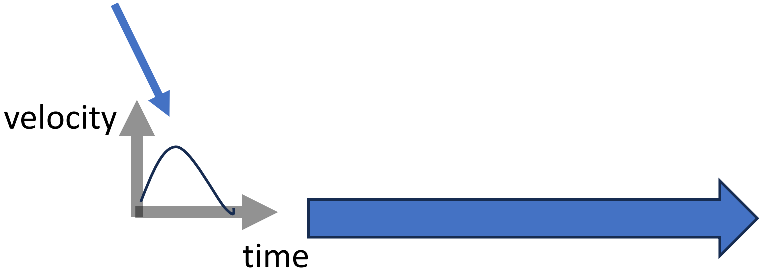
- Full fidelity CFD simulations are computationally expensive
- Proposed a promising methodology by augment surrogate model with CFD to reduced computational cost without accuracy lost
- Wave form has been successfully captured using GraphSAGE
- Coupling UQs with CFD simulations gives more realistic range of building responses

Future Work

Reduce domain size



Moving wall (piston)



Last column of wave gauges

Use ML to find correlation

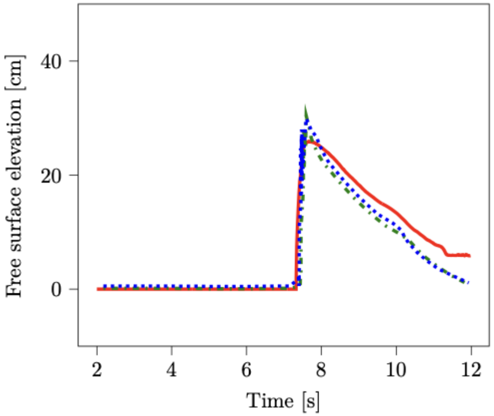
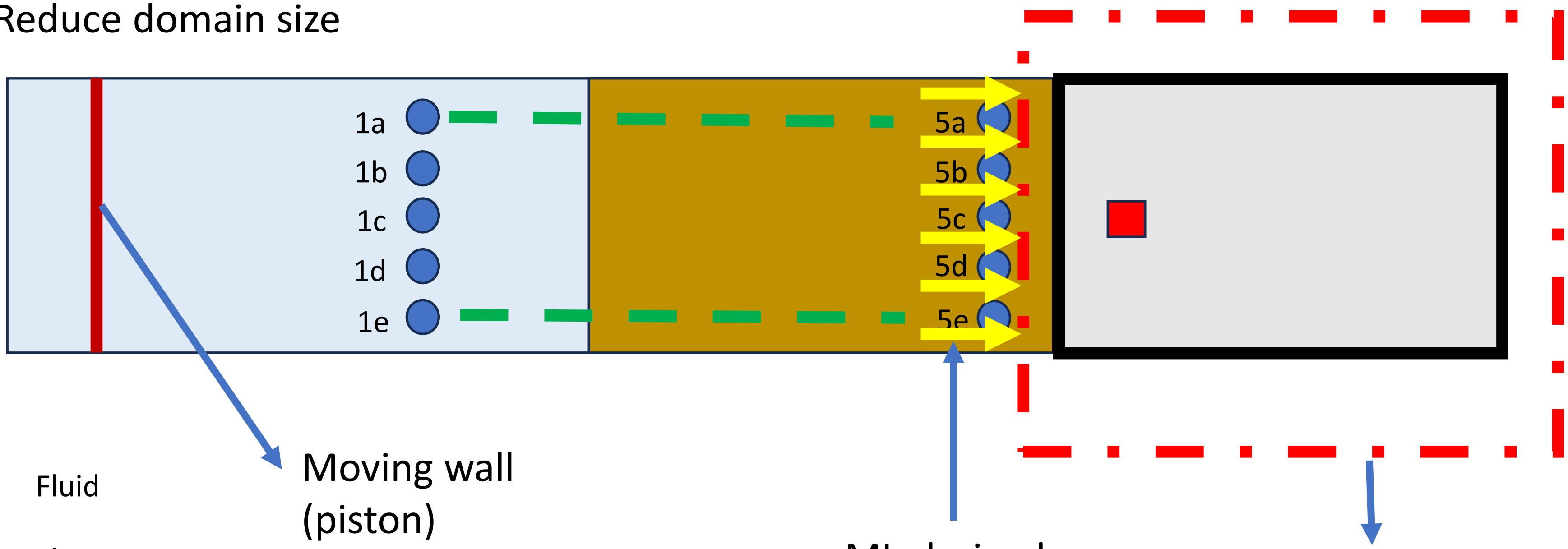


Figure. Last column of wave gauge's wave height vs. time

- ▢ Fluid
- 🟫 Slope
- ▢ Flat platform
- ● Wave gauge
- 🟥 Rigid fixed structure

Future Work

Reduce domain size



Moving wall (piston)

ML-derived boundary condition

New domain size for SPH

- ☐ Fluid
- 🟫 Slope
- ☐ Flat platform
- ● Wave gauge
- 🟥 Rigid fixed structure

Appendix 1

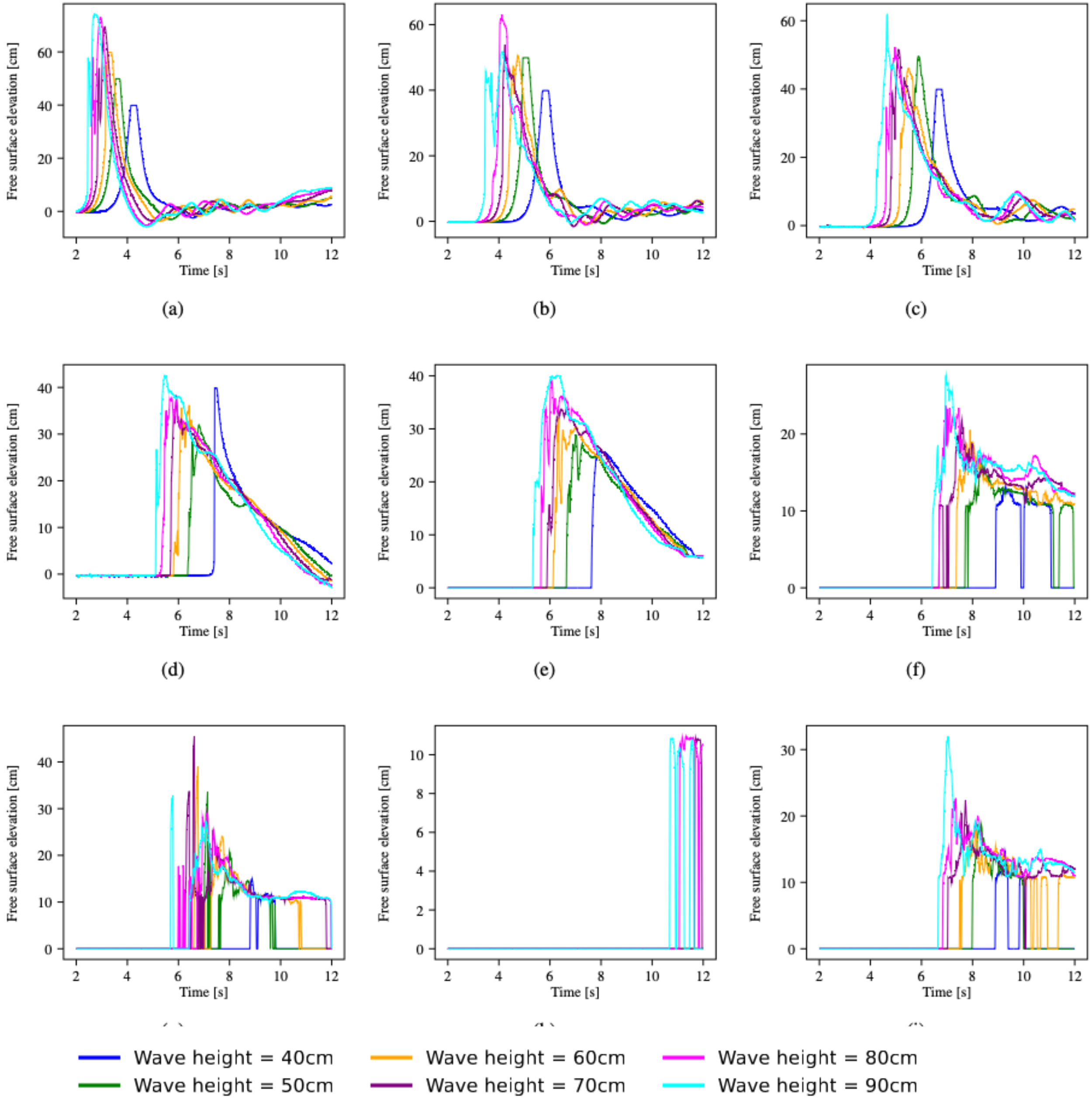


Fig. Free surface elevation for different wave heights for wave gauges

(a) WG1
(b) WG2
(c) WG3
(d) WG4
(e)WG5
(f) WG7
(g) WG8
(h) WG9
(i) WG10