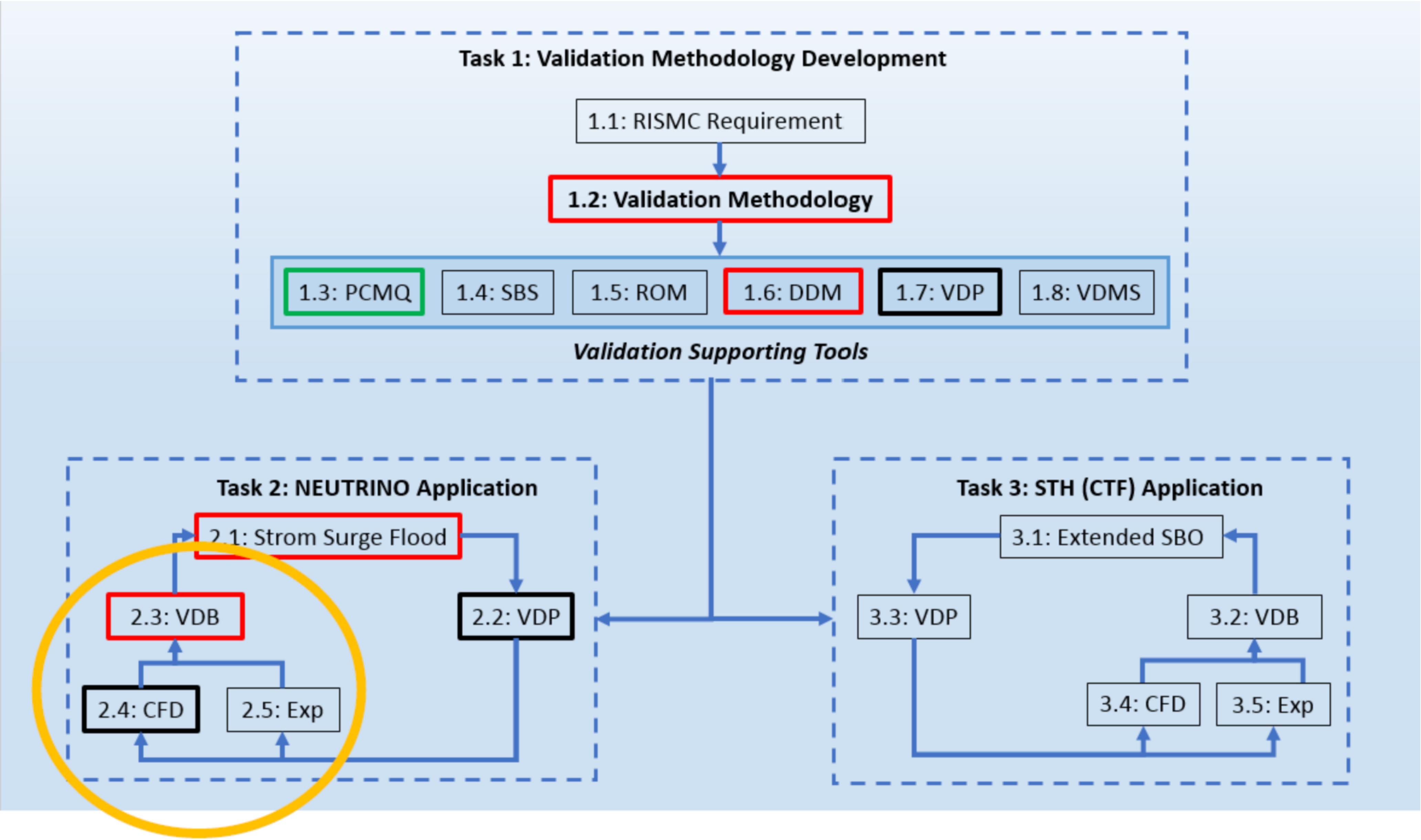
Development of Risk-Informed safety margin characterization framework for flooding of nuclear power plants

MA Andre[1], E Ryan[2,3], S Prescott[3], L Lin[4], N Montanari[5], R Sampath[5], A Gupta[4], N Dinh[4],
Philippe M Bardet[1]

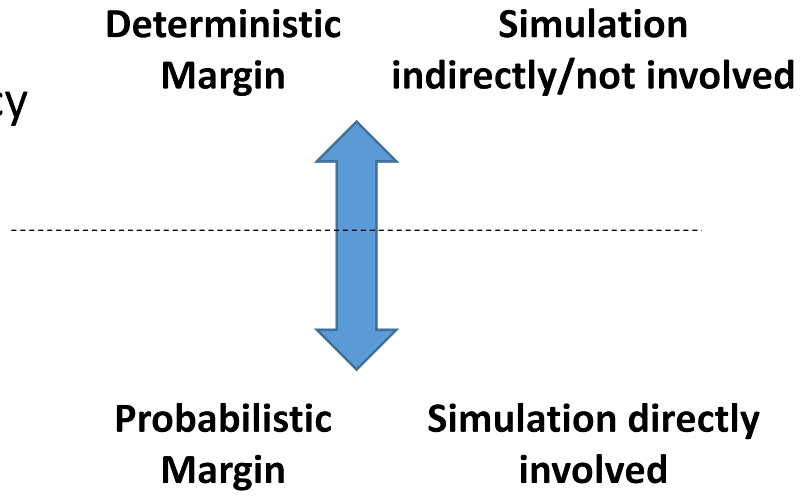
[1] George Washington University, Mechanical and Aerospace Engineering
[2] Idaho State University, Nuclear Engineering
[3] Idaho National Laboratory
[4] North Carolina State University, Nuclear Engineering
[5] Centroic Lab

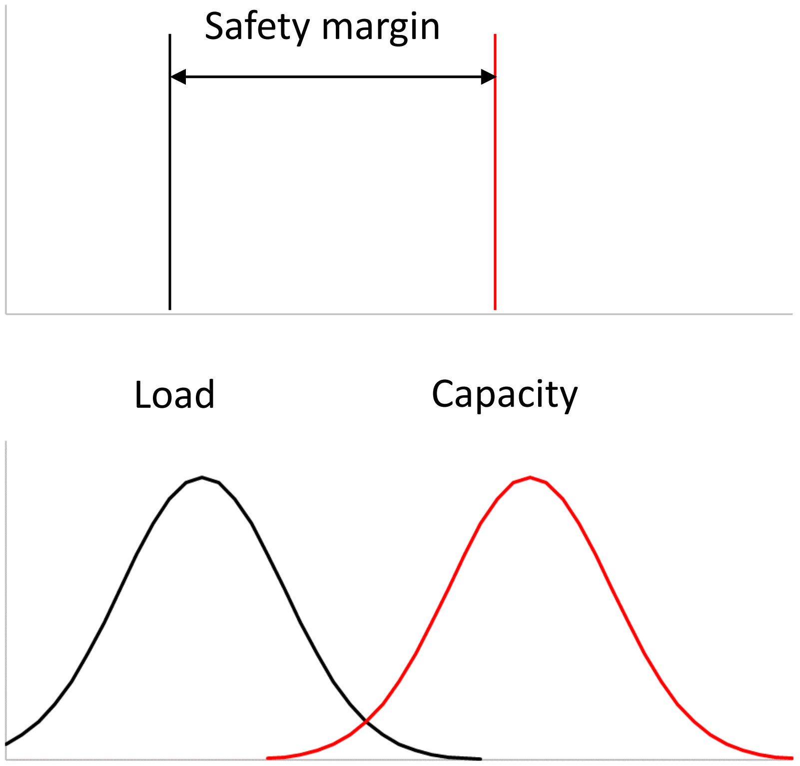
DOE – IRP project overview



Risk Informed Safety Margin Characterization - RISMC

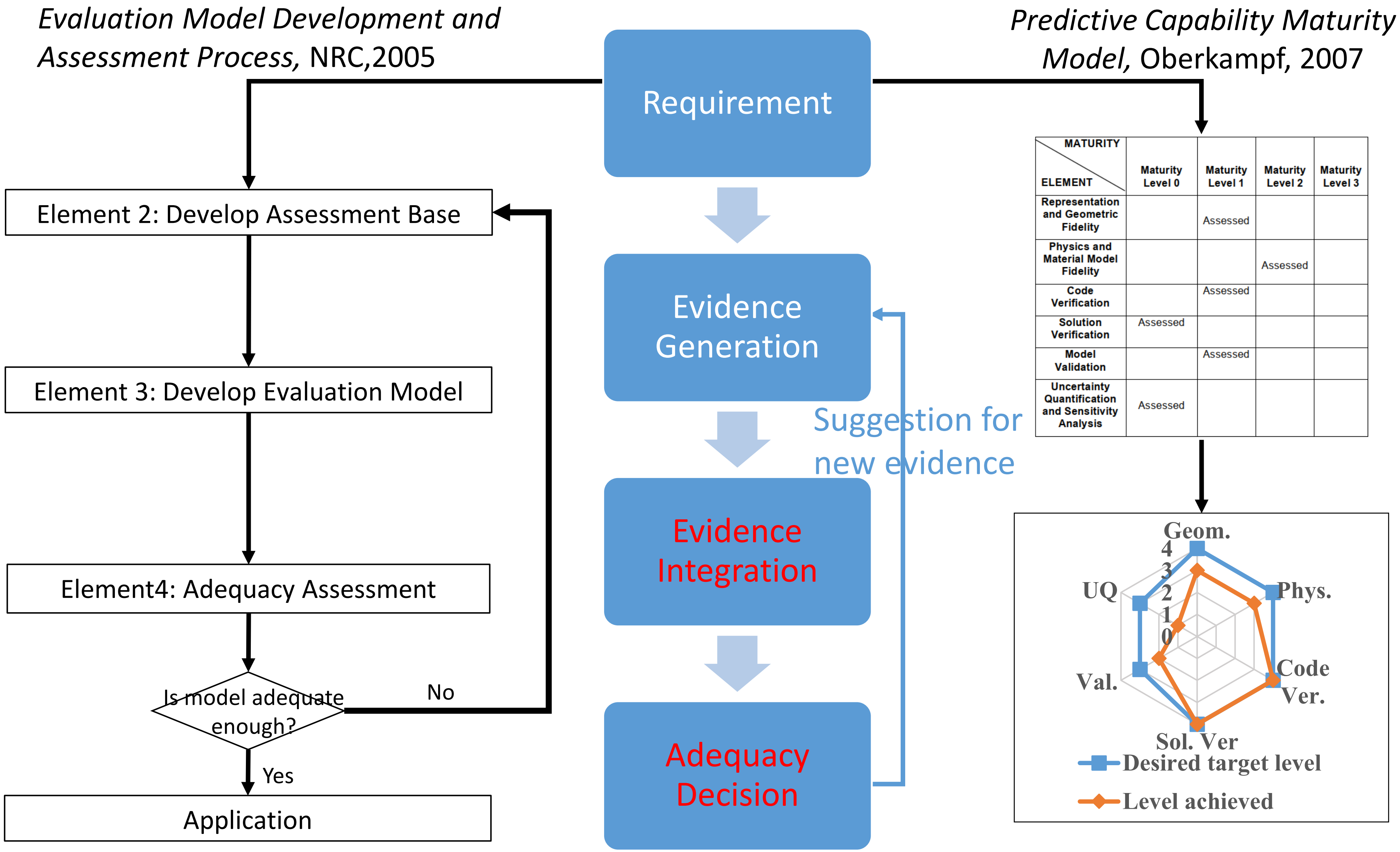
- Well-Established PRA
  - Statistical analysis
    - Estimate initiating frequency
    - Core damage frequency
- Risk-Informed Safety Margins Characterization
  - Use multi-physics, 3D + t simulations
  - Dynamically monitor event initiation and progression
    - More comprehensive/detailed descriptions
    - More effective and informative for risk management and mitigation purposes
  - Core damage frequency





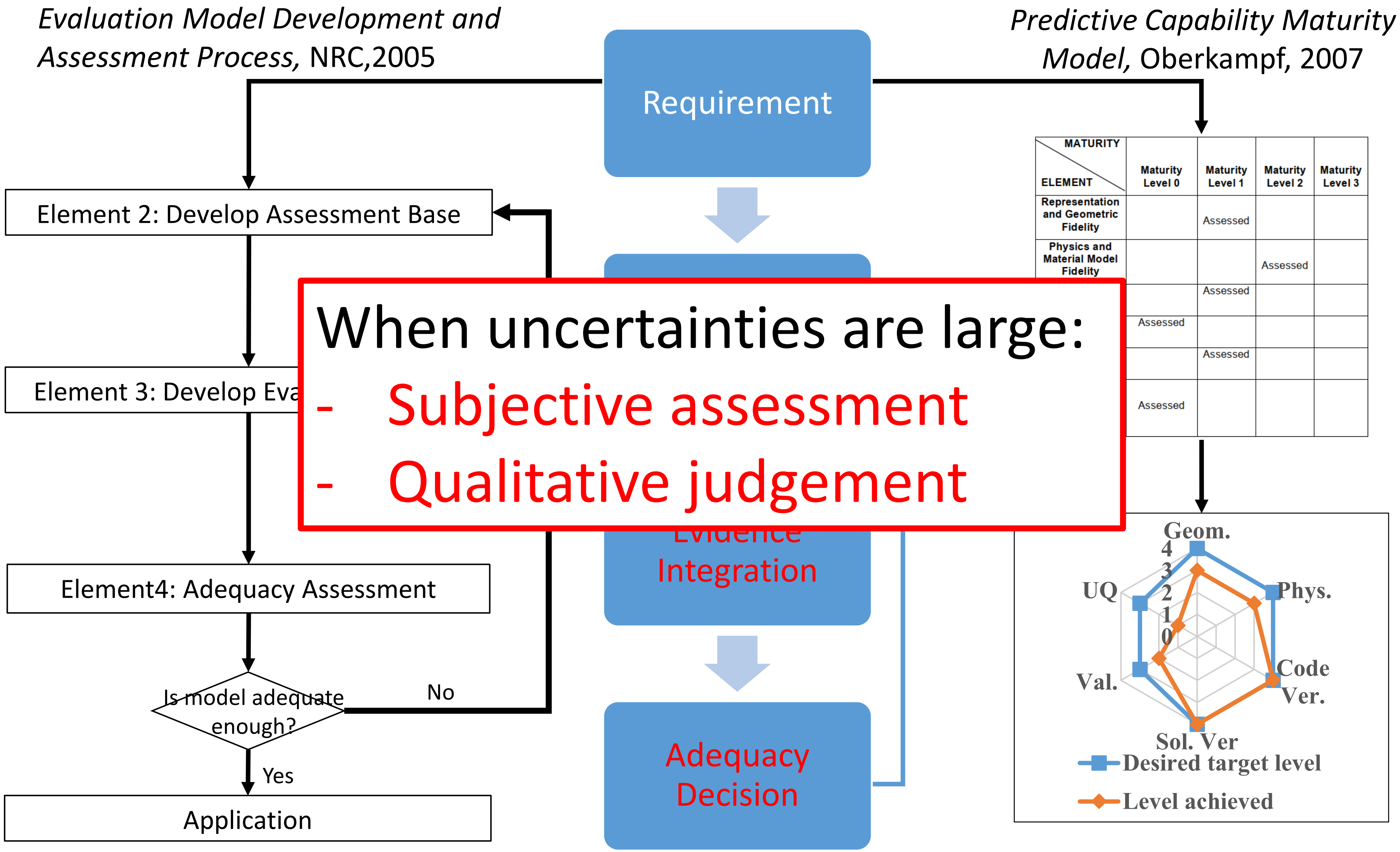
- How to assess credibility of simulation?
- How does it affect the safety decision?

Validation = Decision under uncertainties



MATURITY / ELEMENT	Maturity Level 0	Maturity Level 1	Maturity Level 2	Maturity Level 3
Representation and Geometric Fidelity		Assessed		
Physics and Material Model Fidelity			Assessed	
Code Verification		Assessed		
Solution Verification	Assessed			
Model Validation		Assessed		
Uncertainty Quantification and Sensitivity Analysis	Assessed			

Validation = Decision under uncertainties

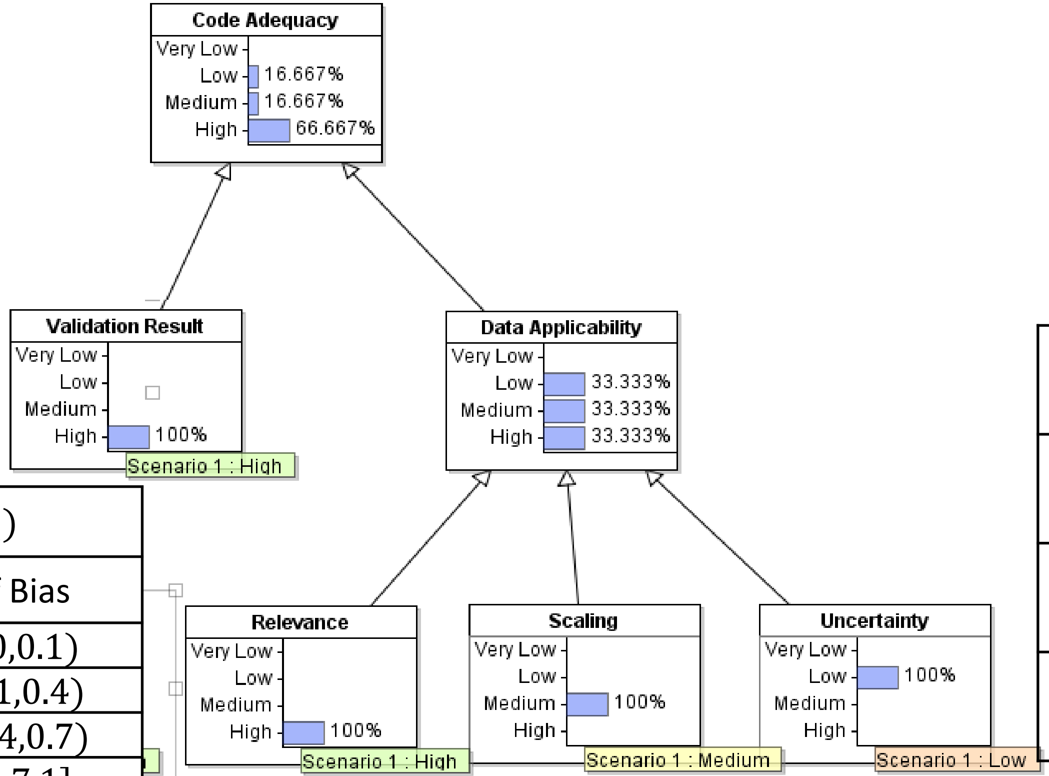


Predictive Capability Maturity Quantification by Bayesian Net - PCMQBN

- Motivation
  1. How to formalize and evaluate the subjective component of validation?
     - Subjective assessment
       - Scaling: sufficiency and relevancy of database
       - Physical processes involved
     - Qualitative judgement
       - Model adequacy
  2. How to adapt validation goals/requirements to risk-informed concept?
     - Uncertain scenario
     - Decision-dependent safety goal

- How to make convincing adequacy decision under large uncertainties?
  - Transparent
  - Robust
  - Consistent

Predictive Capability Maturity Quantification by Bayesian Net - PCMQBN



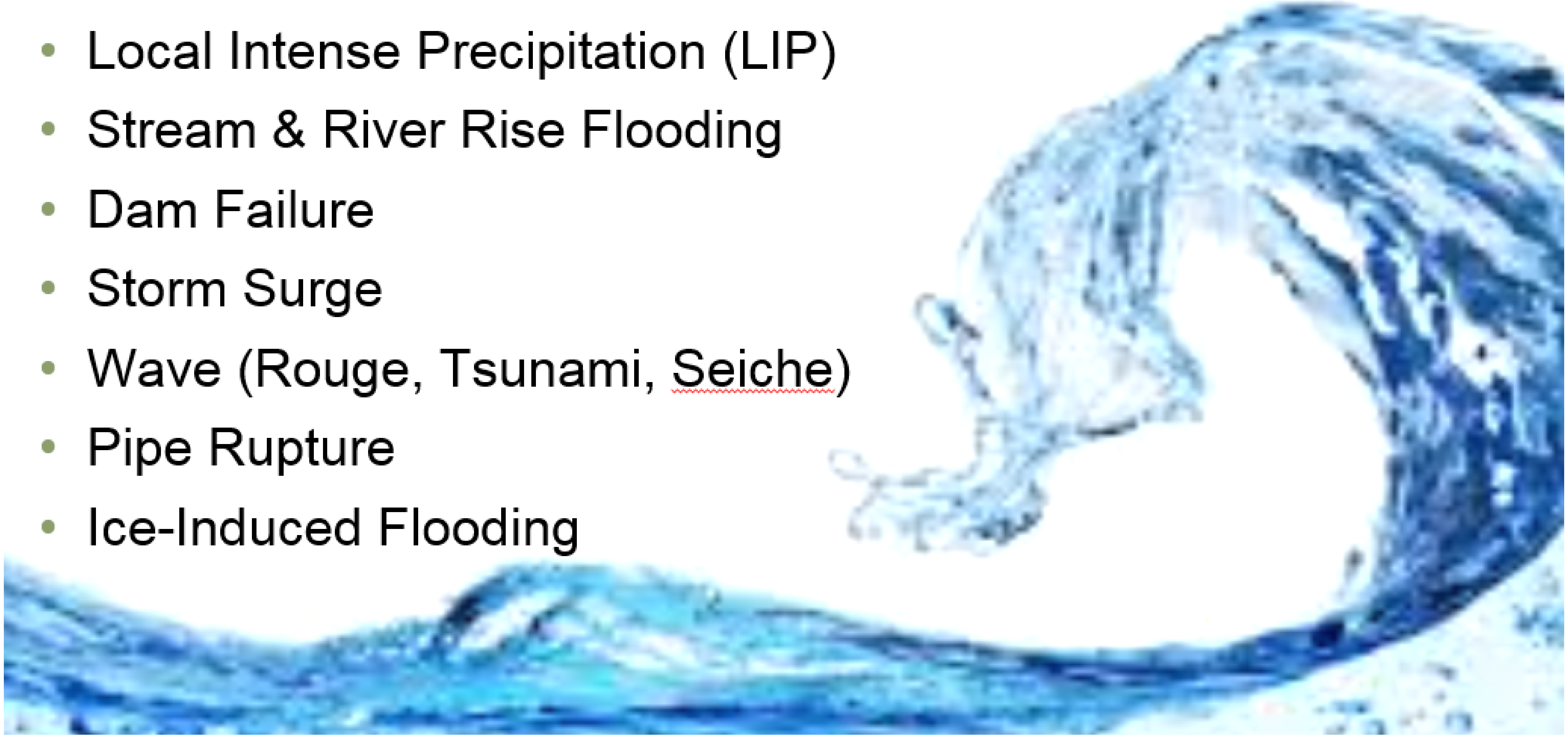
Validation results ($\boldsymbol{VR_i}$)	
Descriptor (i)	Range of Bias
VL	$VR_{VL} \in [0,0.1)$
L	$VR_L \in [0.1,0.4)$
M	$VR_M \in [0.4,0.7)$
H	$VR_H \in [0.7,1]$

Type I data (grade <U> = 1)	Potentially large bias
Type II data (grade <U> = 2)	Single point measurements without uncertainty information
Type III data (grade <U> = 3)	Single uncertainty information (experiments or simulations)
Type IV data (grade <U> = 4)	Both the model prediction and the high-fidelity data has uncertainty information

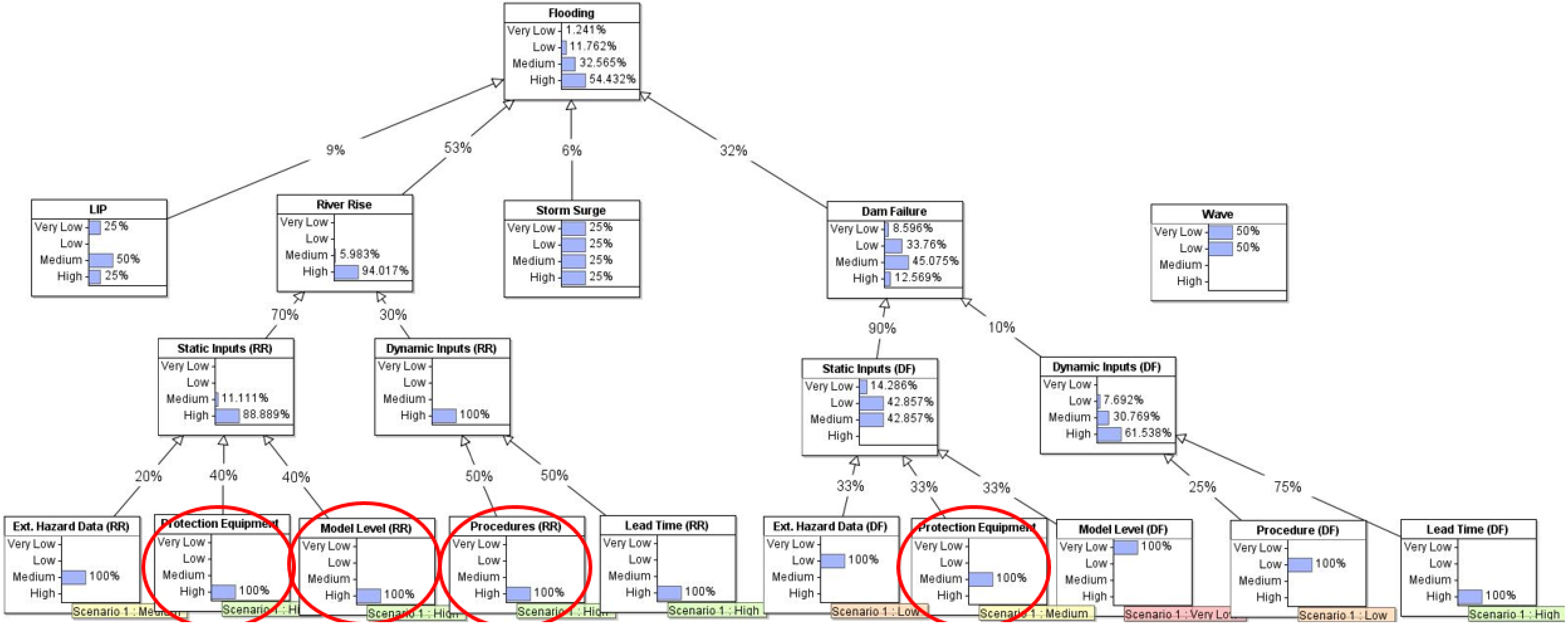
Channel Flow Reynolds number		
Sufficient	Validation database	Application
	$10^5 \sim 10^9$	4×10^6
Insufficient		1×10^4

Flooding scenarios

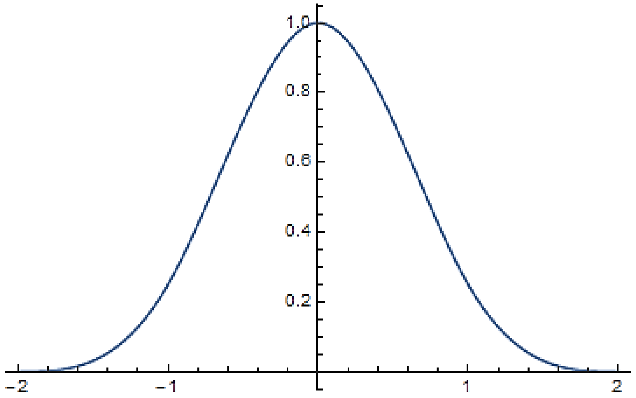
- Local Intense Precipitation (LIP)
- Stream & River Rise Flooding
- Dam Failure
- Storm Surge
- Wave (Rouge, Tsunami, Seiche)
- Pipe Rupture
- Ice-Induced Flooding



RISMC Simulations Confidence Increase



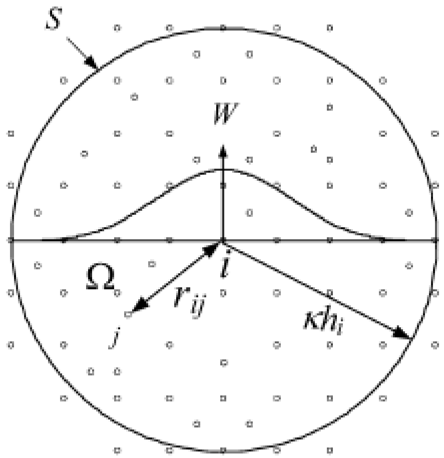
Smoothed Particle Hydrodynamics



- Initially developed by Monaghan in 1977, Smoothed Particle Hydrodynamics method is a computational method for simulating the mechanics of continuum media

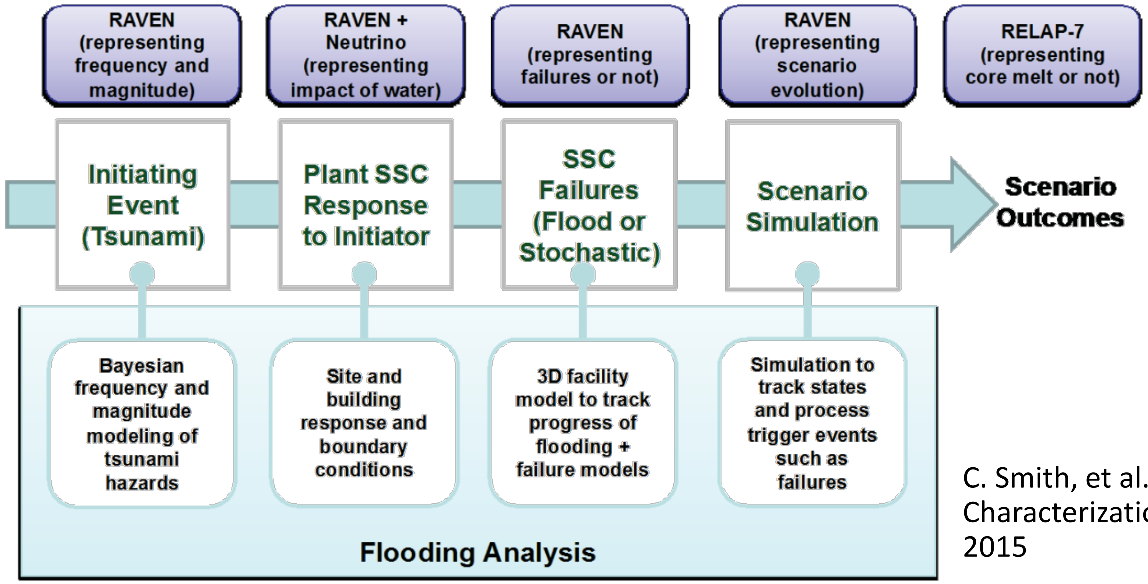
$$f(\vec{r}) = \int f(\vec{r}')W(\vec{r}-\vec{r}',h)d\vec{r}' = \sum_b f(\vec{r}_b)W(\vec{r}-\vec{r}_b,h)\,\Delta V_b = \sum_b \frac{m_b}{\rho_b} f(\vec{r}_b)W(\vec{r}-\vec{r}_b,h)$$

Smoothing | Discretized | Particle Approximation



- As a mesh-free method, SPH is found to be capable of dealing with complex boundary and interface. It's also found to be naturally conserved and easily parallelizable.

- SPH has been applied in the RISMC analysis as the simulation tool for external floods



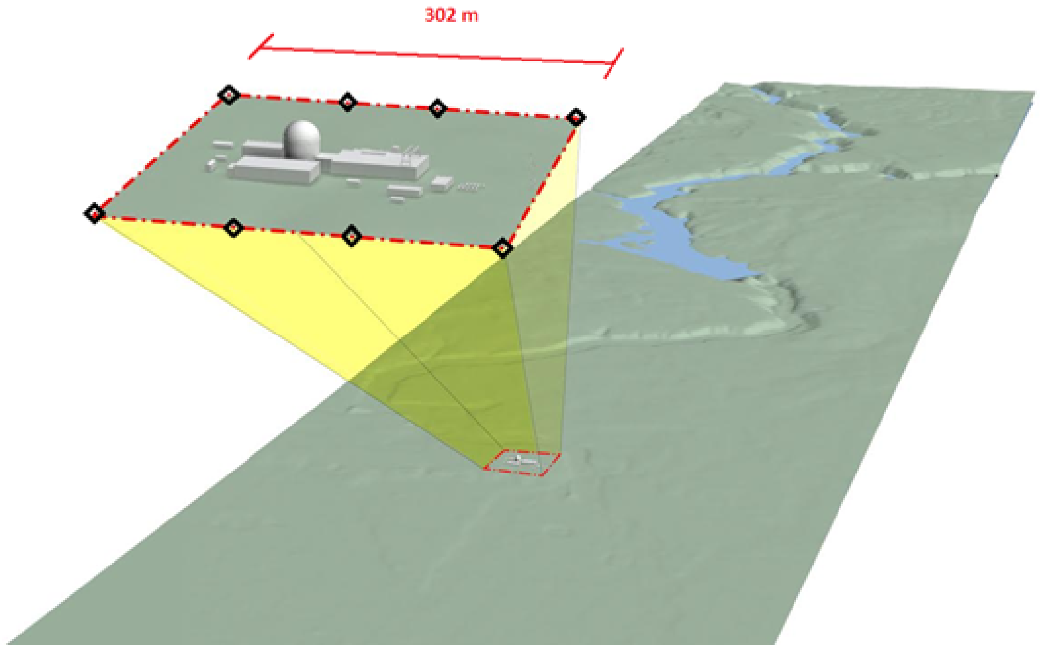
C. Smith, et al., "Risk-Informed Safety Margin Characterization (RISMC) Path Technical Program Plan", 2015

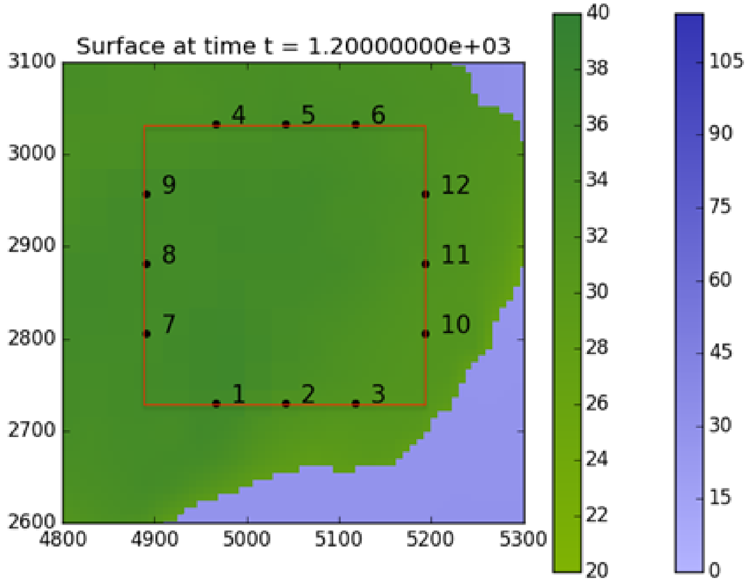
NEUTRINO – SPH code

- Neutrino's Boundary Implicit Incompressible SPH Solver
  - Rest Density based formulation of Incompressibility
  - Iterative Pressure Solver
  - Hydrostatic/Hydrodynamic Coupled Simulation
  - Rigid/Fluid Coupling
- Requirements for flooding
  - Deal with Complex Geometry
  - Robust
  - Fast Realization of Simulations
  - Tracking Interfaces
    - Free Surface (For Measuring Fluid Height)
    - Fluid-Structure. (Computing Forces/Pressure etc)
  - Verification & Validation
  - Ability to couple with PRA Simulations

NEUTRINO – case study: Dam Break

- Couple SPH to shallow water model (GeoClaw)
- Shallow Water model for dam break until region of interest
  - Solve the Navier-Stokes equations with SPH – Flow Structure
  - Couple Domains - In/out flow boundaries
    - Horizontal velocity components + Height.





NEUTRINO – case study: Dam Break

Requirements for Validation Data for Safety Margin Analysis

1. Need data that complement existing validation studies
   - Literature review
2. Need data with high statistical significance
   - Highly repeatable measurements with well characterized boundary condition and initial values
3. Need high quality data with quantified uncertainty

VUQ Quality	Grade			
	4	**3**	**2**	**1**
Relevance [R]	Very High (direct)	High	Medium	Low
Scaling [S]	Prototypic (full-scale)	Adequately scaled	Medium	Inadequately scaled (large distortions)
Uncertainty [U]	Well-Characterized	Characterized	Medium	Poorly-Characterized

Flexible experiment to address specific needs as they are identified

Large scale experiment (can also be adapted for smaller scale tests)
Scaling parameters can also be used (e.g. Froude number)

Measurements performed by trained experimentalists

Quantities of interest

Event Confidence - Scenario Dependent
(high impact scenarios)

	Pressure/Impulse	Duration	Max Height / Splash	Velocity	Turbulence
Door Failure	High	-	-	-	-
Barrier Over-Top	-	High	Med	Med	-
Barrier Failure	High	*Low	-	-	*Med
Penetration	-	High	-	High	-
Exhaust Vent	-	-	High	-	-
Ducting	High	-	-	-	-
Debris Impact	-	-	Low	High	Med

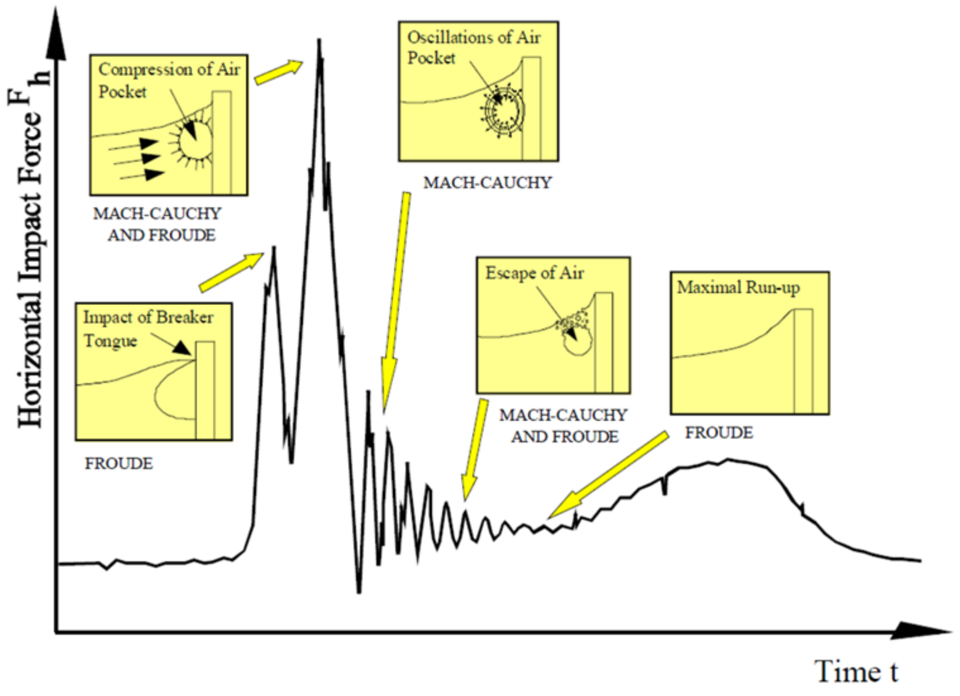
"*" Type Dependent

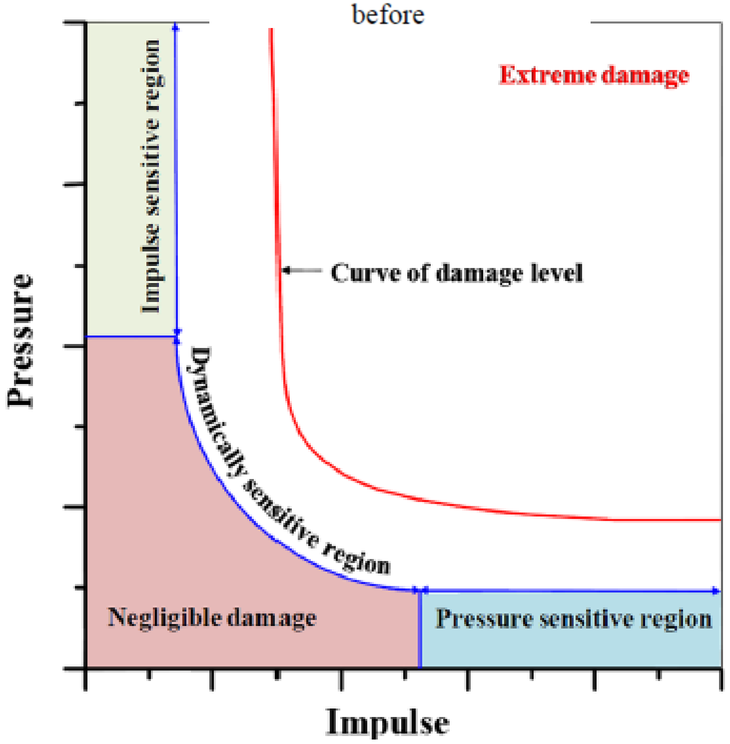
(Example - needs to be developed and approved by a standards committee/NRC)

Quantities of interest

- First phase focuses on wave impacts
- Pressure ~ Force ~ Structural damage
- Also Impulse

$$P(\mathbf{x}) = \int_{\text{before}}^{\text{after}} p(\mathbf{x}, t)\mathrm{d}t$$





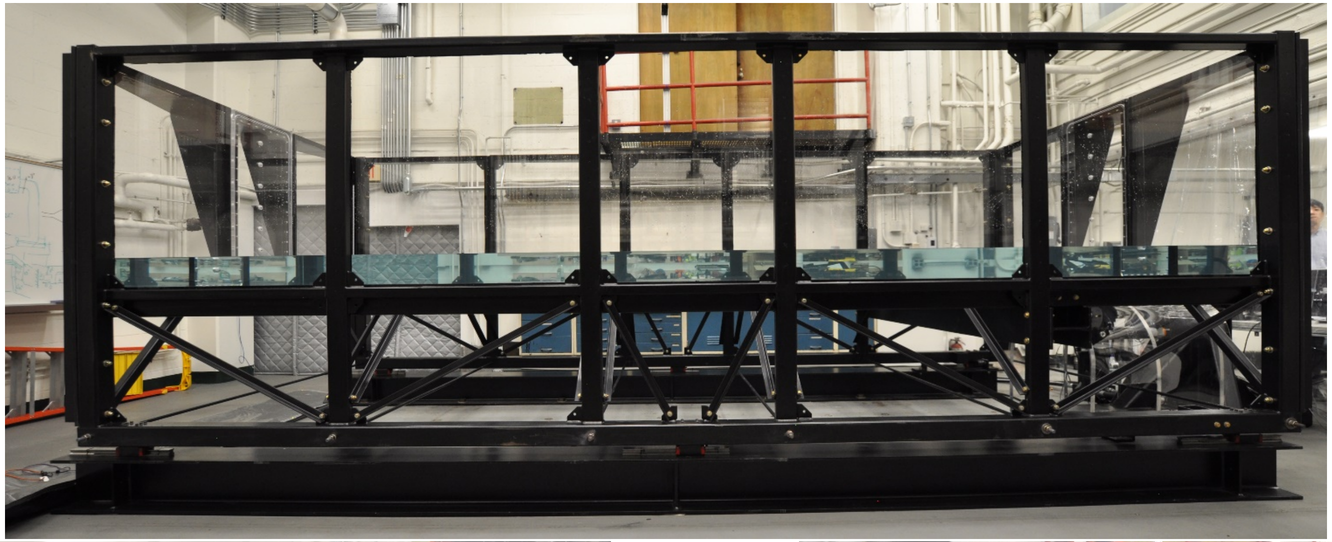
In-house design

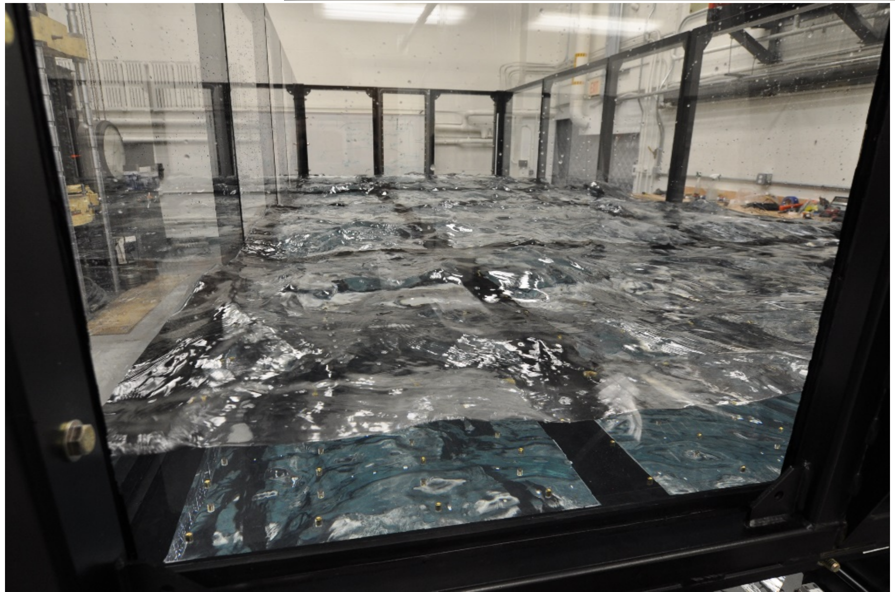
By doing the design in-house, and already having access to some of the infrastructure, a large scale facility has been built at modest cost

- Location
  - GWU Tompkins Hall: In a former civil engineering lab, equipped with a strong floor and hydraulic controllers
- Tank
  - 20’ x 8’ x 4’ (6m x 2.4m x 1.2m) L x W x H
  - 10 tons (10 m^3) of water
  - Structural steel frame with acrylic walls
- Forcing
  - Up to 10” (25 cm) amplitude
  - Up to 20”/s (0.5 m/s) velocity
  - Up to 0.5g (5 m/s^2)
  - 22 kips Hydraulic actuator, linear bearings on precision rails

Construction of the facility

Facility now completed

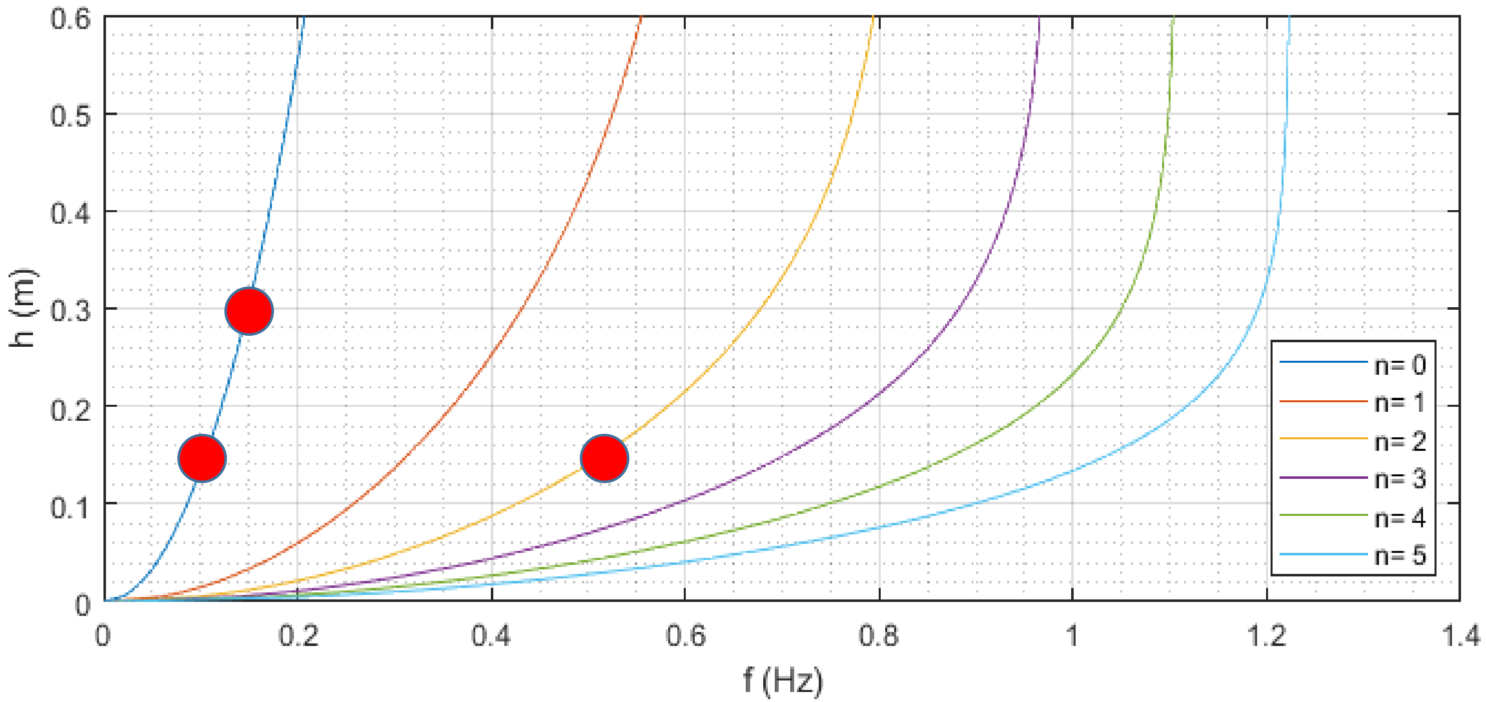




Shakedown Tests

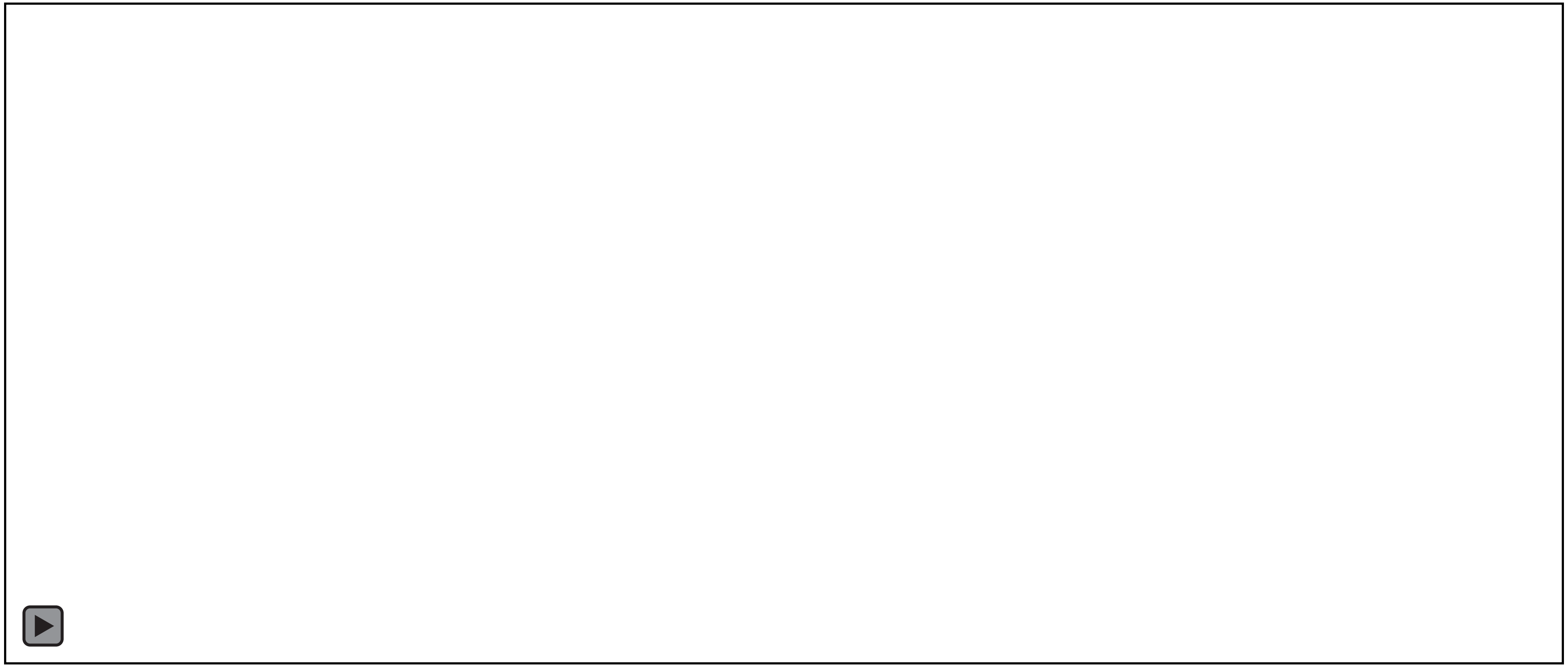
2D Wave natural frequency

$$f = \sqrt{\frac{(2n+1)g}{4\pi L}\tanh\left(\frac{(2n+1)\pi h}{L}\right)}$$



Shakedown TEsts

6” depth, 4” 0.49 Hz forcing (3rd mode)



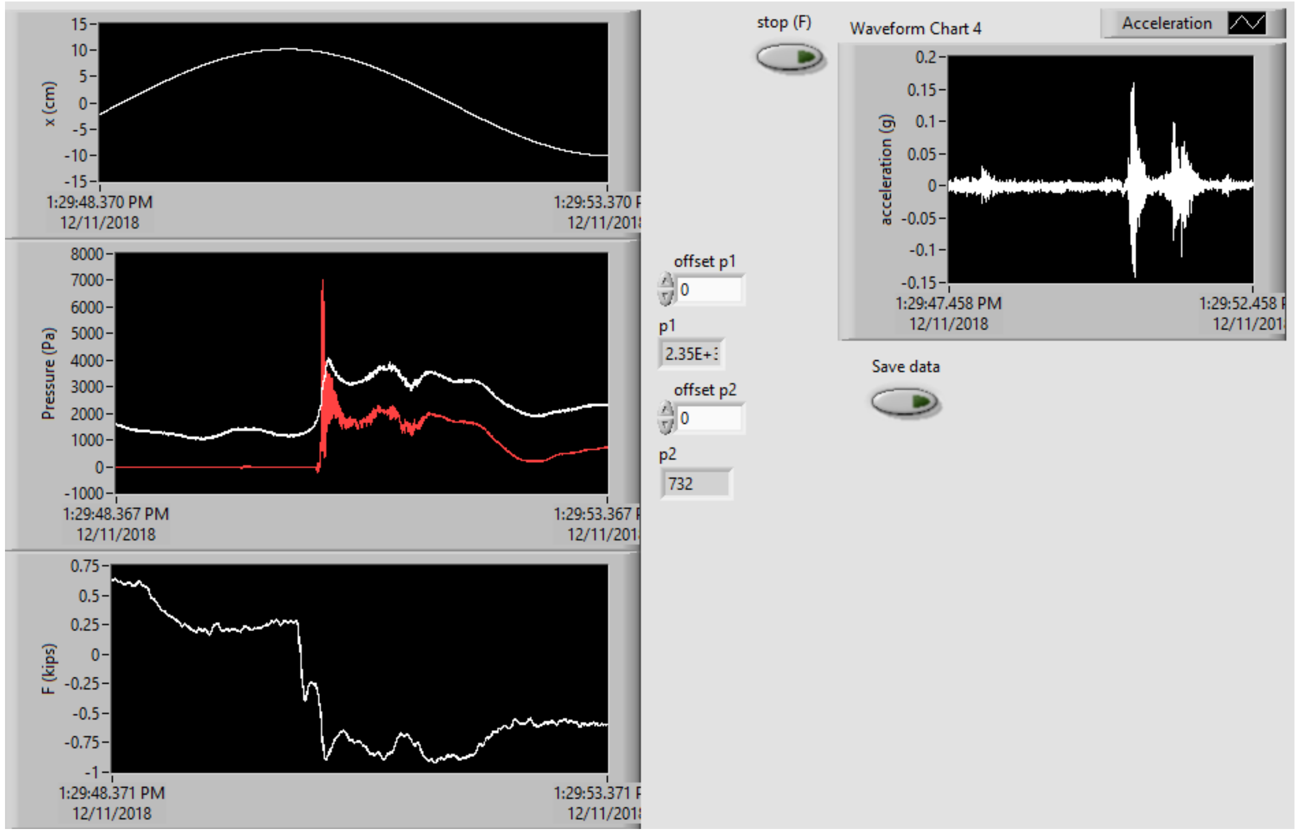
Shakedown TEsts

12” depth, 4” 0.155 Hz forcing (1st mode)

Instrumentation

Pressure probes (end wall center, z=4 and 10”)
Accelerometer
Forcing data
NI DAQ (2 kHz acquisition)

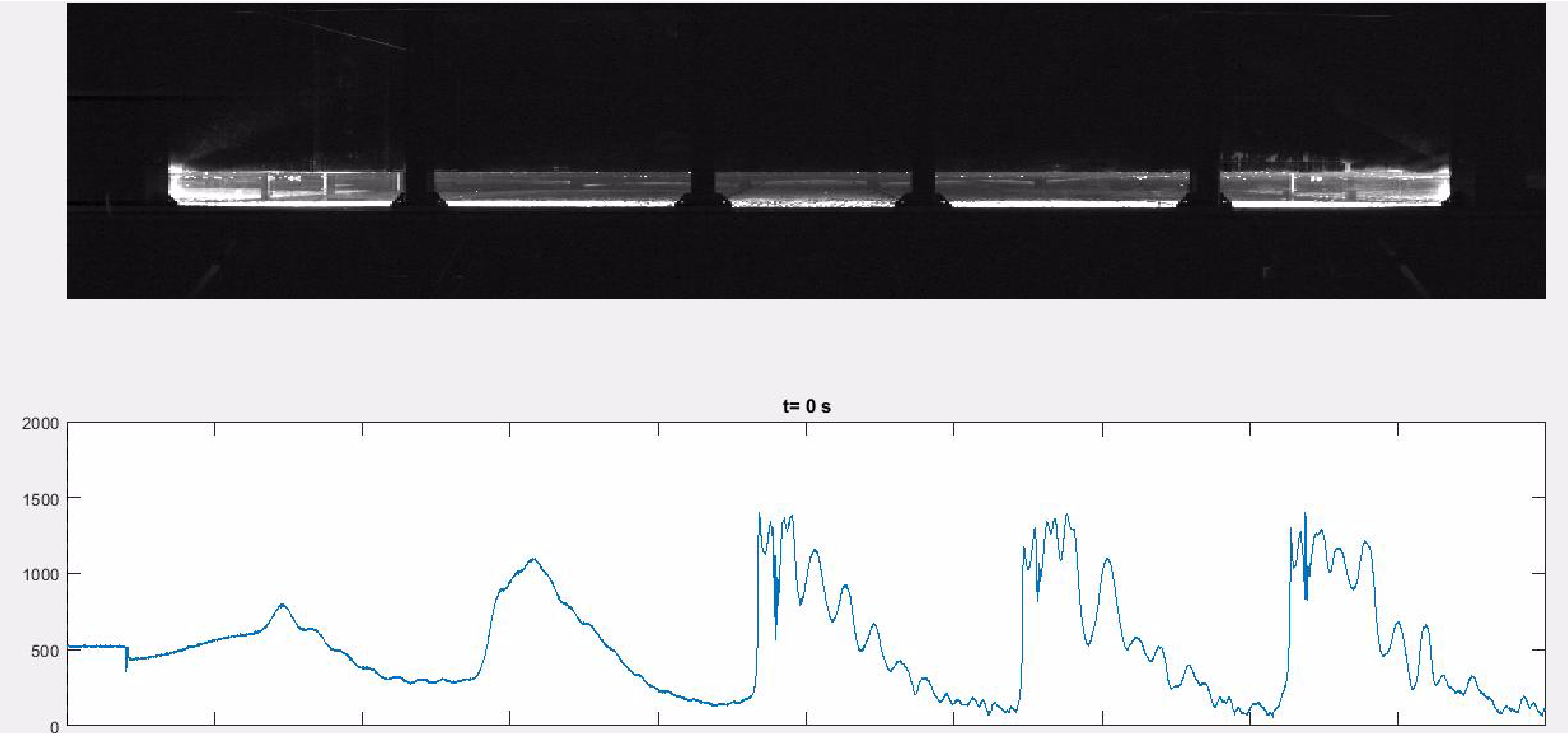
ε=35 Pa
f_c=1 kHz



First test case:

6” depth, 4” 0.11 Hz forcing (1st mode)

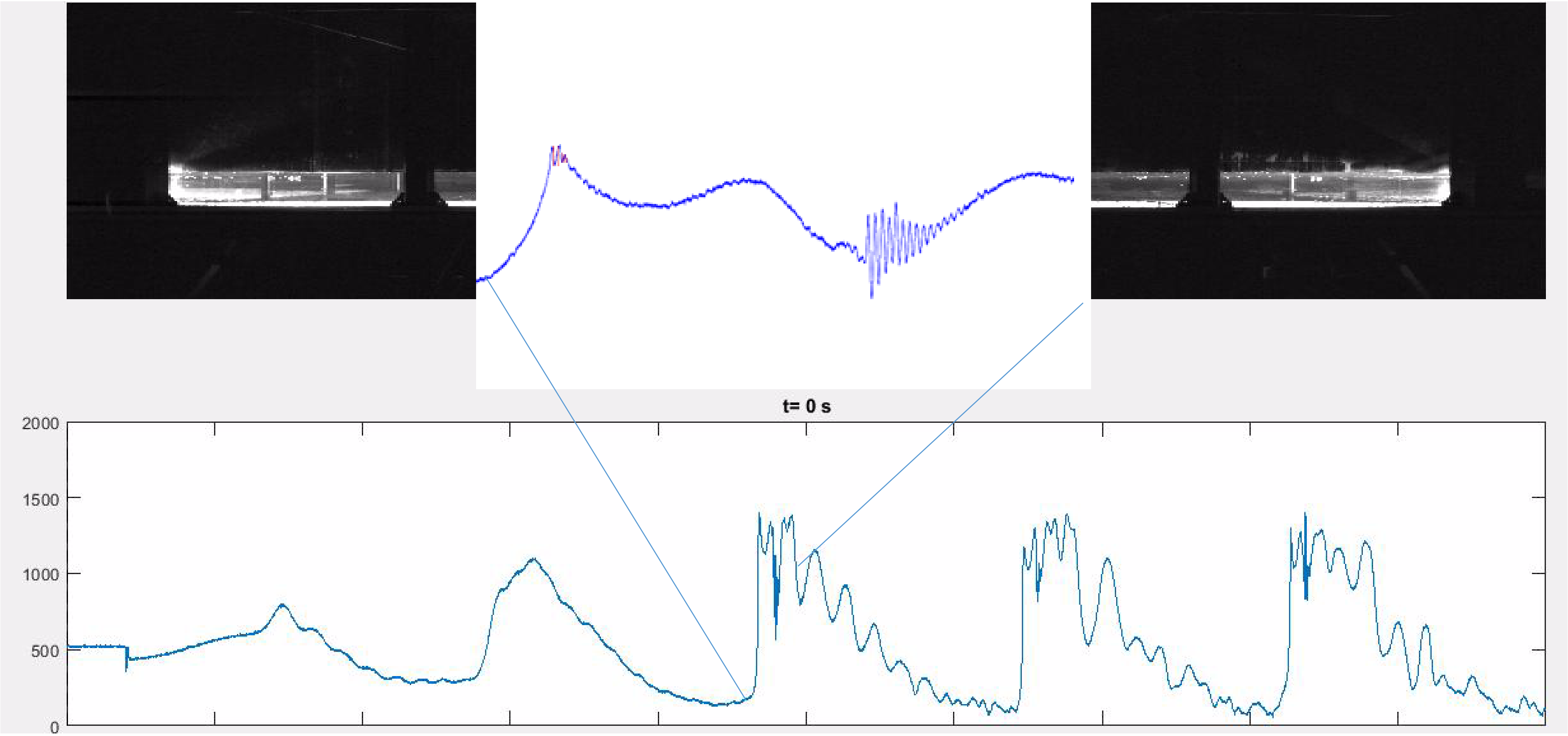
Pressure measurement at end wall



First test case:

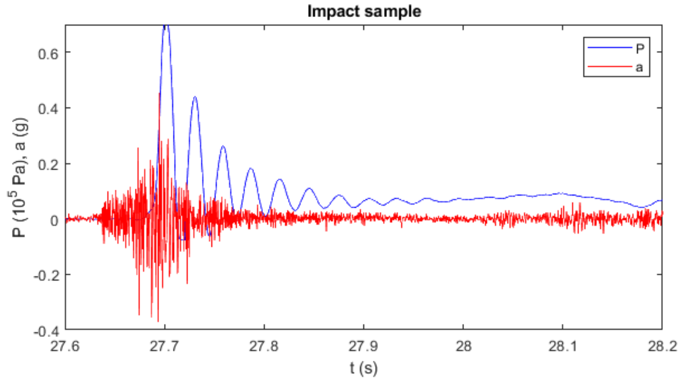
6” depth, 4” 0.11 Hz forcing (1st mode)

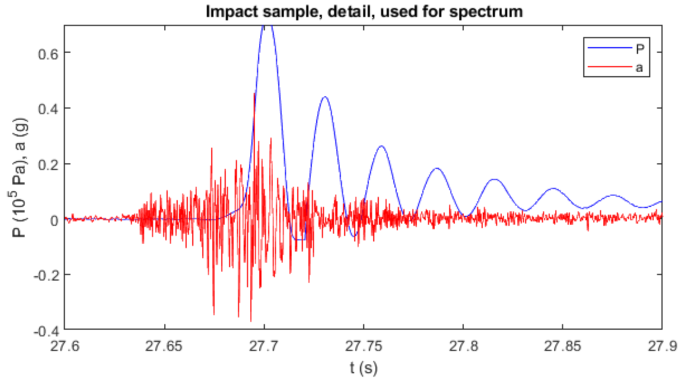
Pressure measurement at end wall

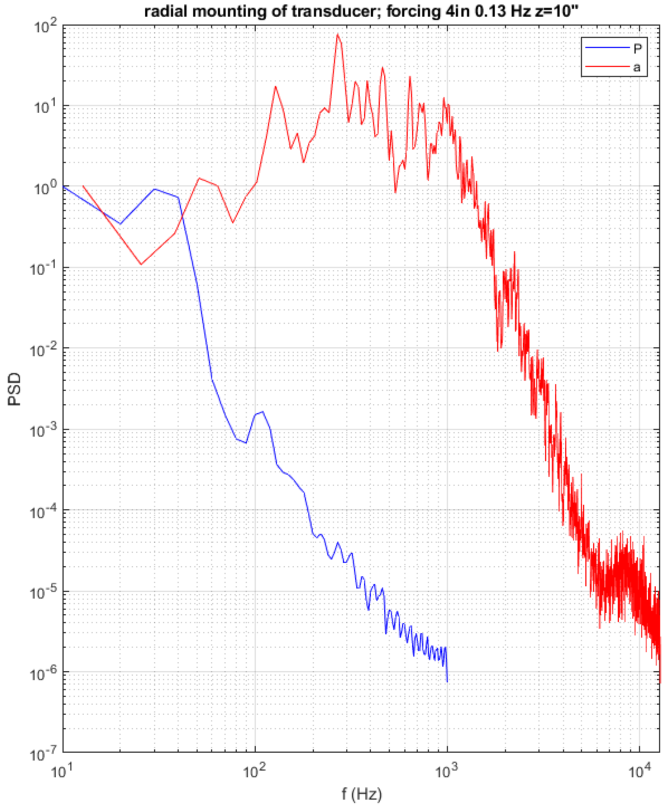


Check panels vibrations

Pressure signal shows high frequency during impact.
Could be bubble oscillations, but need to rule out acrylic vibrations







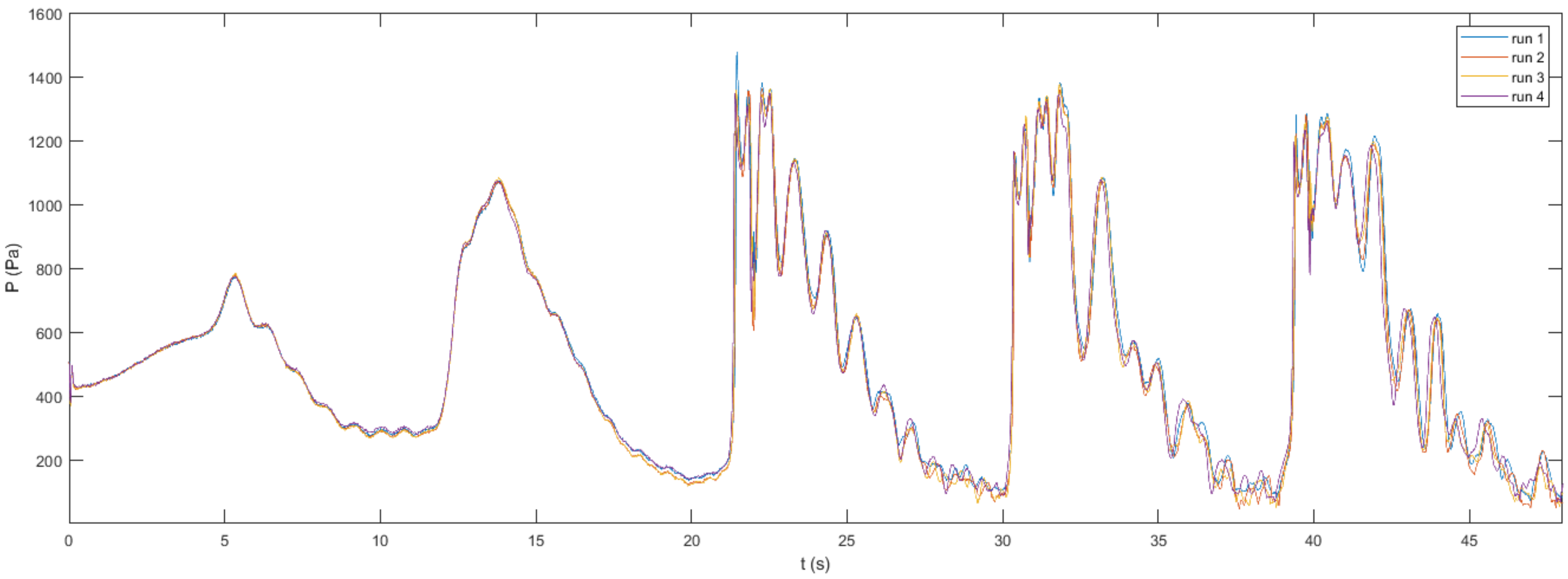
Pressure oscillation not linked to panel vibration
Likely due to bubbles (not modeled in Neutrino)

First test case:

6” depth, 4” 0.11 Hz forcing (1st mode)

Assessment of repeatability

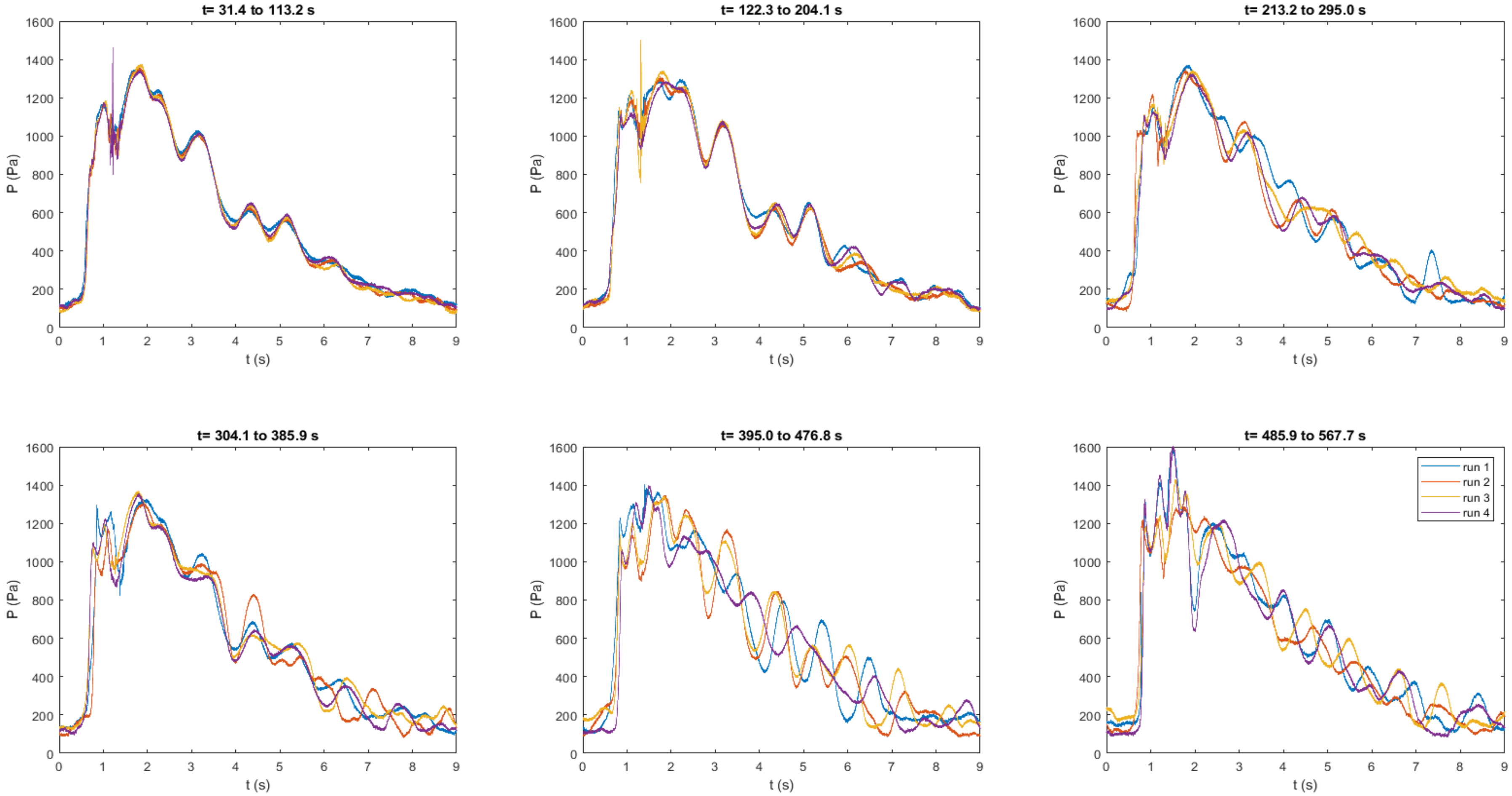
Run	h (mm)	f (Hz)	A (mm)	Comments
1	152.4	0.11	101.6	Reference run
2	152.4	0.11	101.6	Identical to Run 1
3	152.4	0.11	102.108	Change of the forcing amplitude by 1%
4	153.4	0.11	101.6	Change of the water depth by 1 mm



First test case:

6” depth, 4” 0.11 Hz forcing (1st mode)

Assessment of repeatability

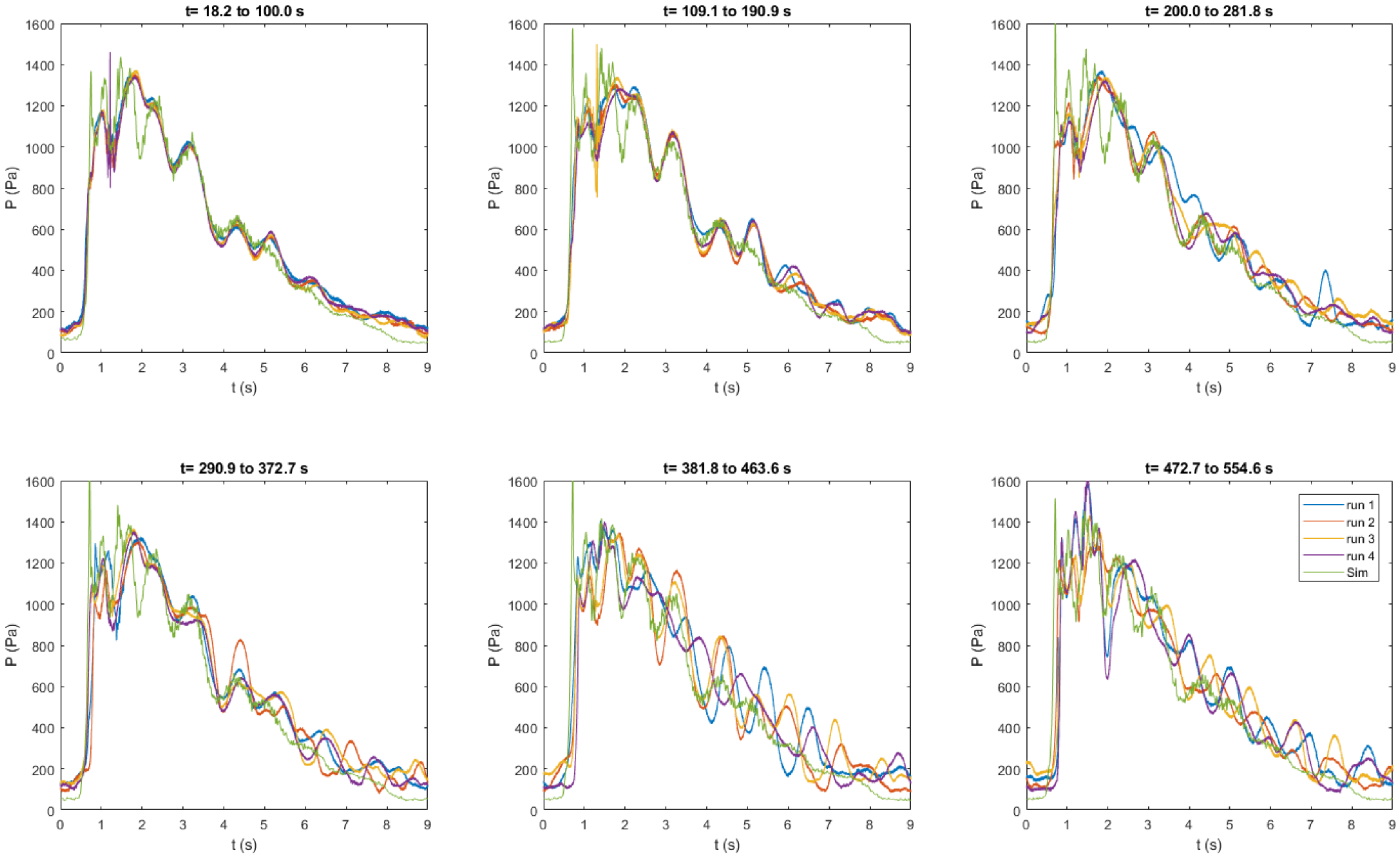


Sloshing Tanks

- Simulation has been performed by Emerald Ryan in Idaho State University
- Simulation Tank width is less than the real facility (0.2m compared to 2.4m)
- Particle size is 0.0125m and the results are acceptable.
- Simulation takes around 10 hours for 30 cycles, and the output frequency is 50Hz

Sloshing Tank

- SPH predicted pressure force are compared against the measurements
- Hard to visualize the quality of SPH predictions, especially when the pressure fluctuations are large
- It’s suggested that sophisticated validation metrics should be used for better characterizing the credibility of SPH methods in predicting the sloshing tank phenomenon



Sloshing Tank

- Root mean square error

$$(L_2)_m = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left((\overline{P_i})_m - (\overline{D_i})_m\right)^2}$$

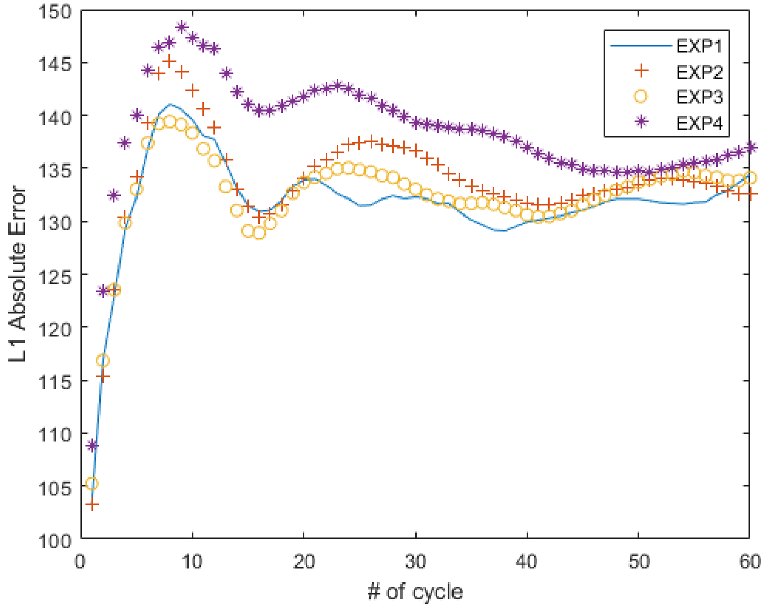
- Absolute Error

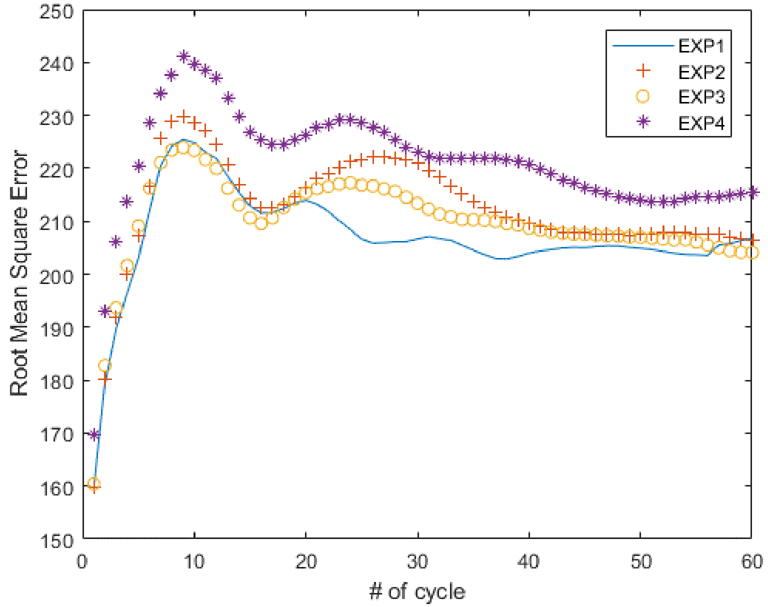
$$(L_1)_m = \frac{1}{N}\sum_{i=1}^{N}\left|(\overline{P_i})_m - (\overline{D_i})_m\right|$$

- Confidence Interval

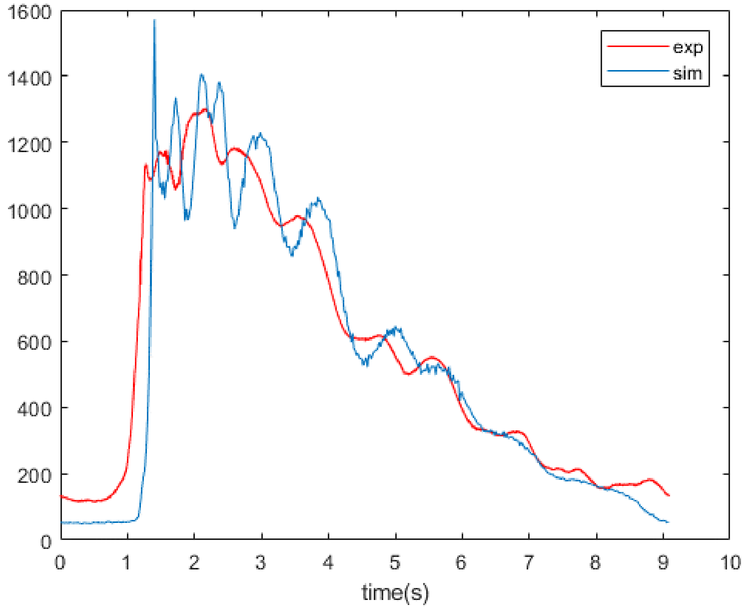
$$P_{i,m} = \mathbb{N}((\overline{P_i})_m, \mu_m)$$

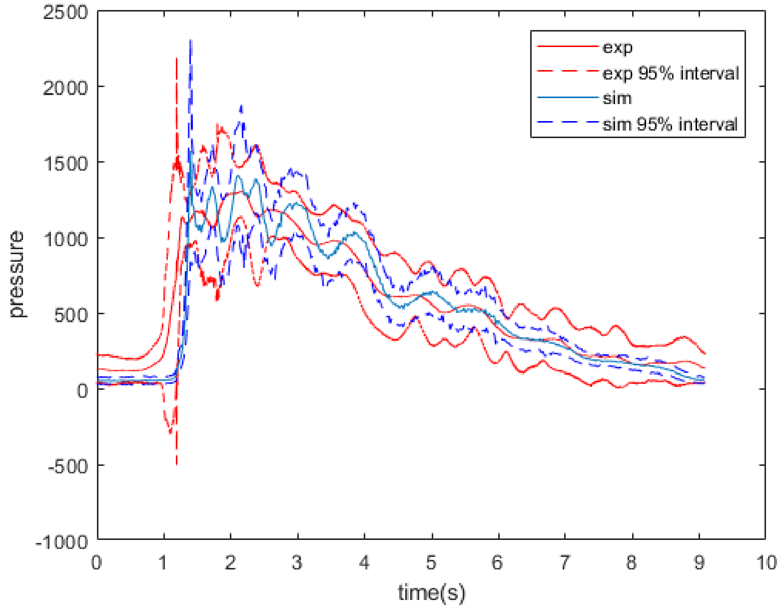
- Simulation errors are bounded after 20 cycles
- Absolute distance metrics serve the purpose quite well
- The EXP data band covers the SIM data band, observed phenomena (turbulence, void) are not captured by NEUTRINO simulation





Averaged by 60 cycles





Sloshing Tank

- Probability distributions for both simulation $PDF(P_i)$ and measurement distributions $PDF(D_i)$

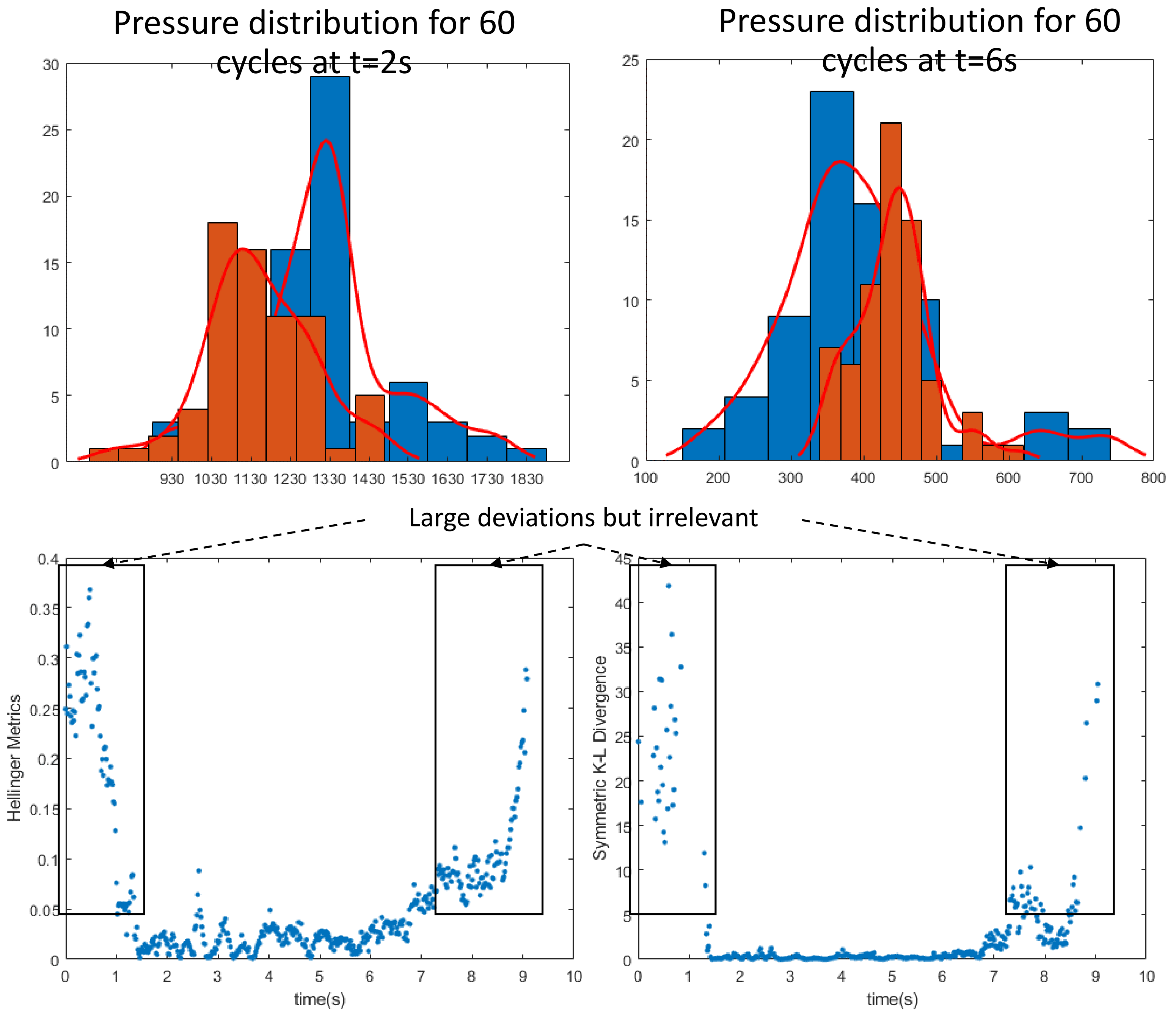
- Fit the distribution to Kernel Density Estimation (multi-variant distributions)

$$PDF(P_i) = \frac{1}{N h_1 h_2 \ldots h_d} \sum_{i=1}^{N} \prod_{j=1}^{d} k\left(\frac{x_j - y_{ij}}{h_j}\right)$$

- K-L Divergence and Hellinger metrics for measuring the "similarity" of two distributions

$$D_{KL}(P, D) = \sum_i P(i) \log\left(\frac{P(i)}{D(i)}\right) + D(i) \log\left(\frac{D(i)}{P(i)}\right)$$

- Ranges with less similarity are found

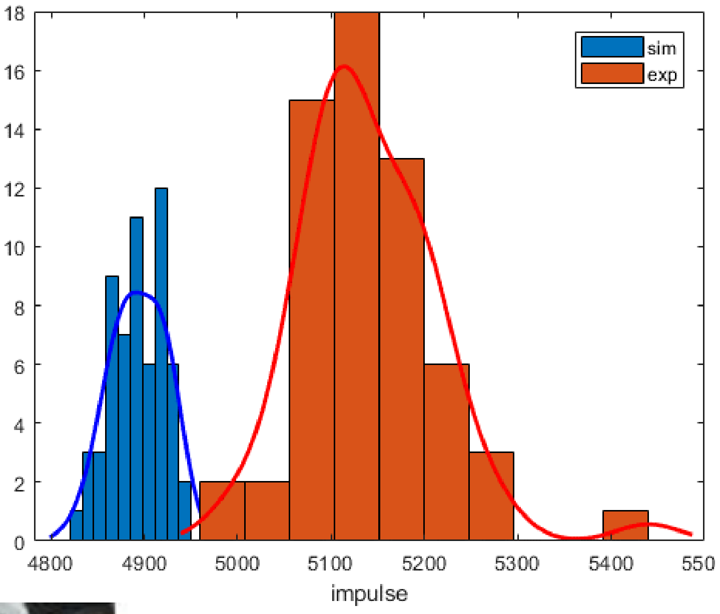


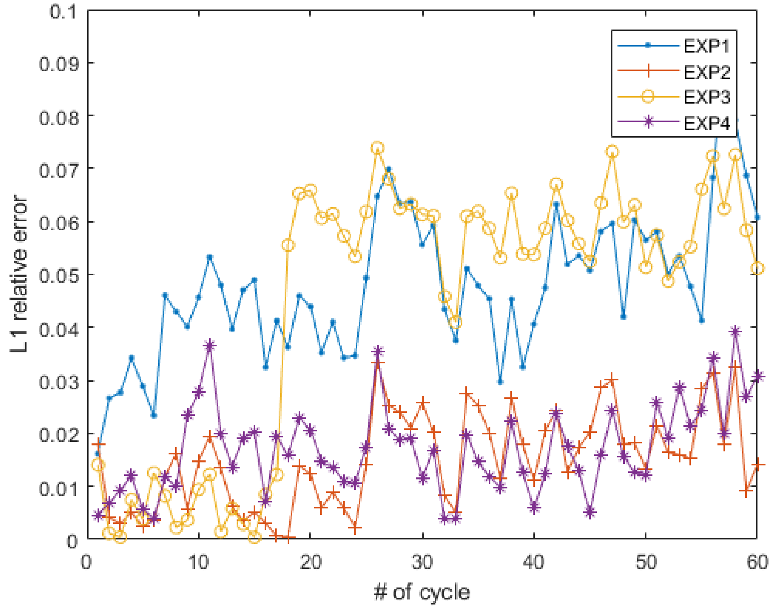
Sloshing Tank

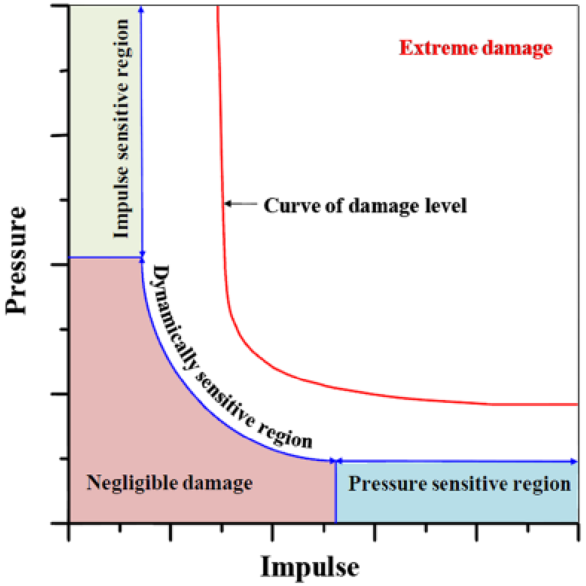
- NEUTRINO has better predictions for impulse than pressure
- P-I curve suggests the limiting surface of SSC structures
- Incorporate model adequacy results into the P-I curve

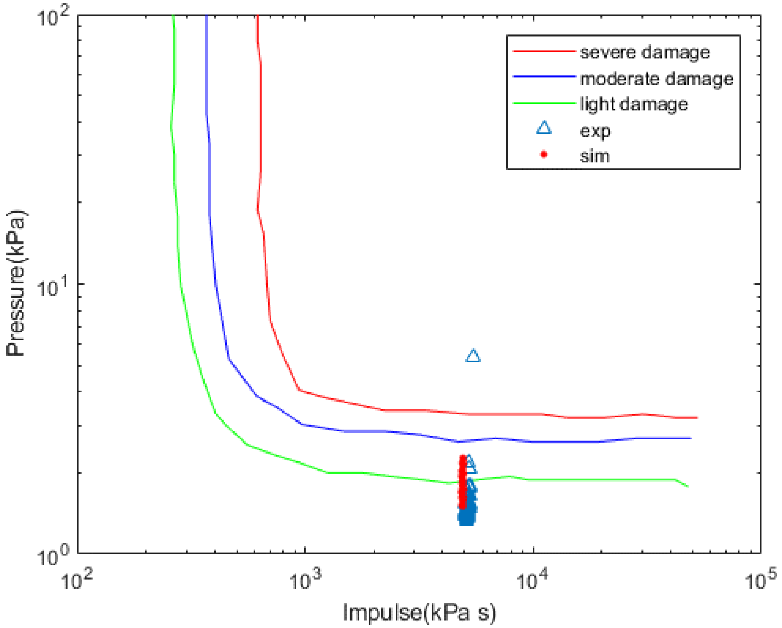
Damage Level	NEUTRINO	EXP
No	44/60	57/60
Light	16/60	2/60
Moderate	0/60	0/60
Severe	0/60	1/60

Impulse predictions







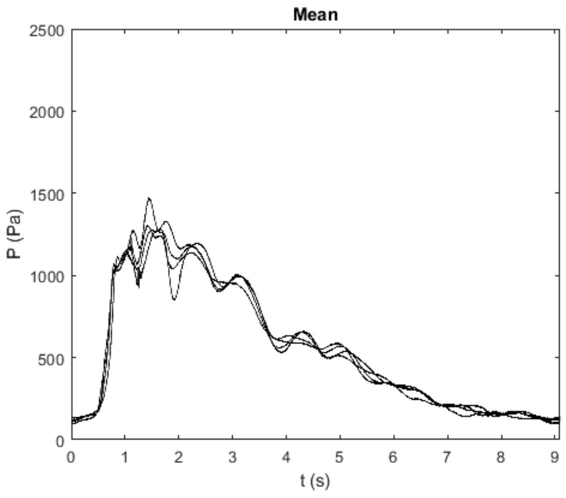


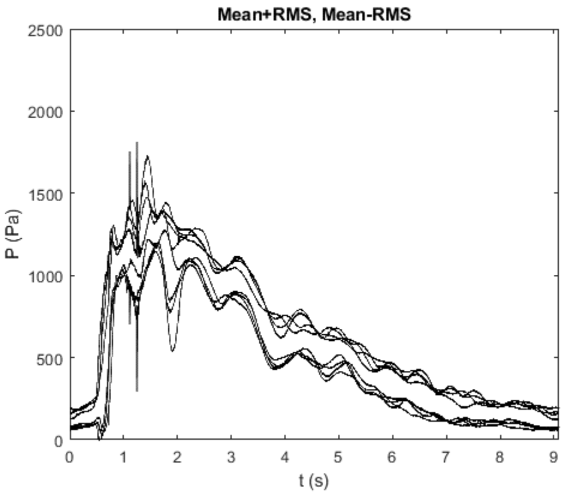
M. Abedini, etc., “Pressure-Impulse (P-I) Diagrams for Reinforced Concrete (RC) Structures: A Review”, 2018

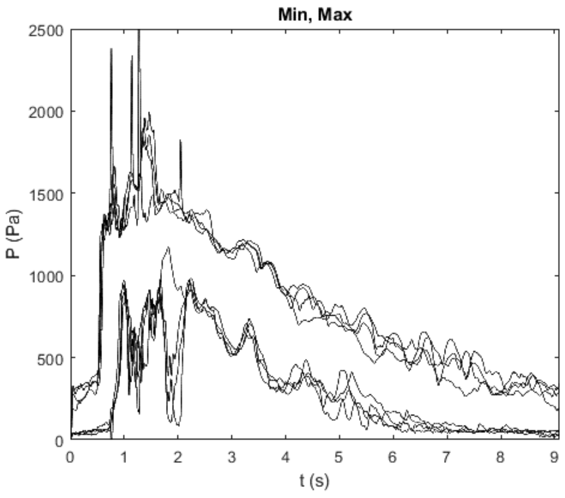
First test case:

Two ways of comparing experiment and simulations:

1. Exact temporal evolution of pressure
   a) Useful for single event (tsunami)
   b) Cannot be applied past ~10 cycles (random and chaotic flow)
2. Statistical approach (phase averaged pressure)
   a) Provide better estimation of the accuracy of simulation
   b) Can be used for Bayesian analysis
   c) Computationally more expensive

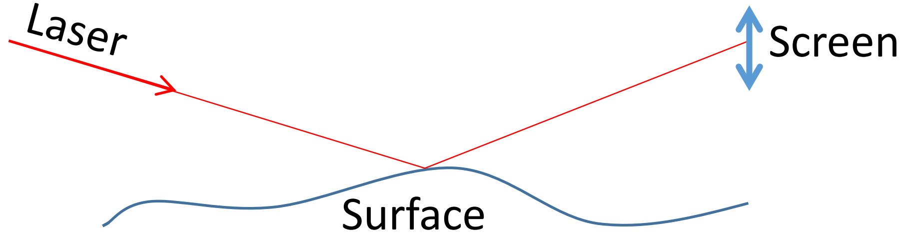


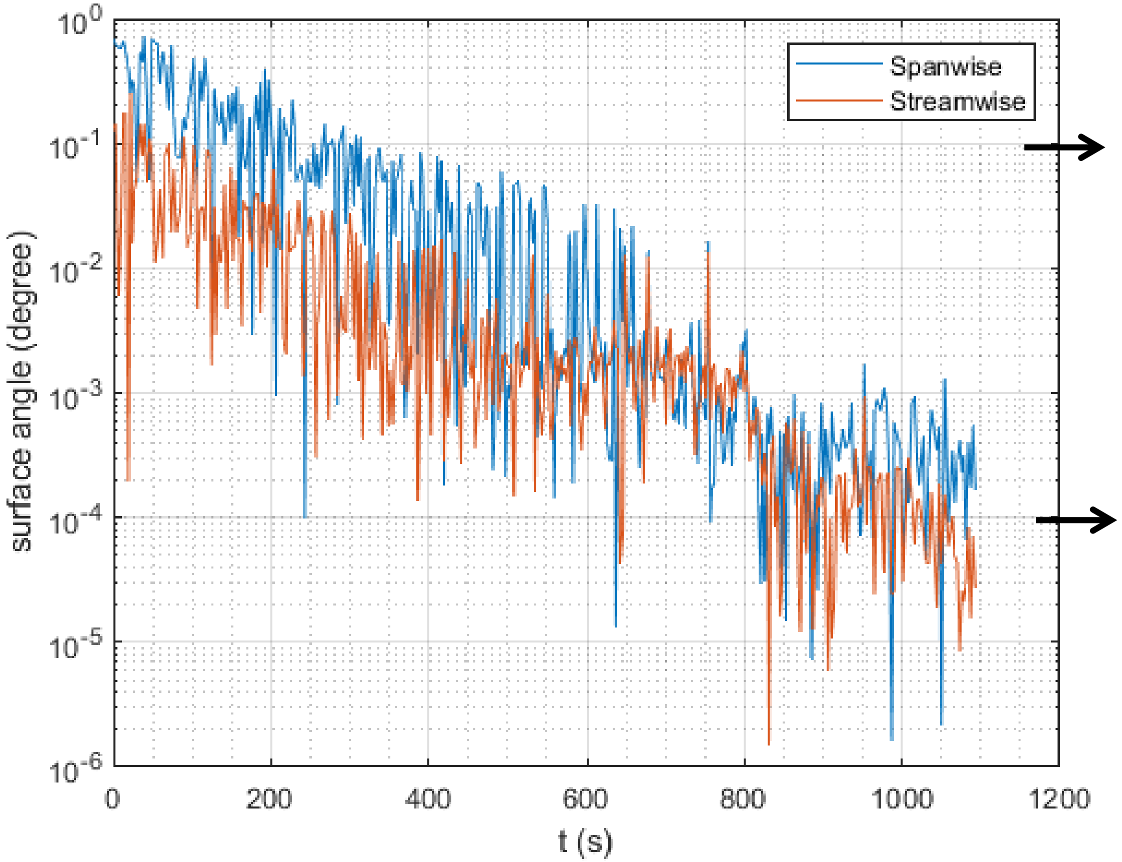




INSTRUMENTATION development

- Laser-based slope measurement for initial flow conditions





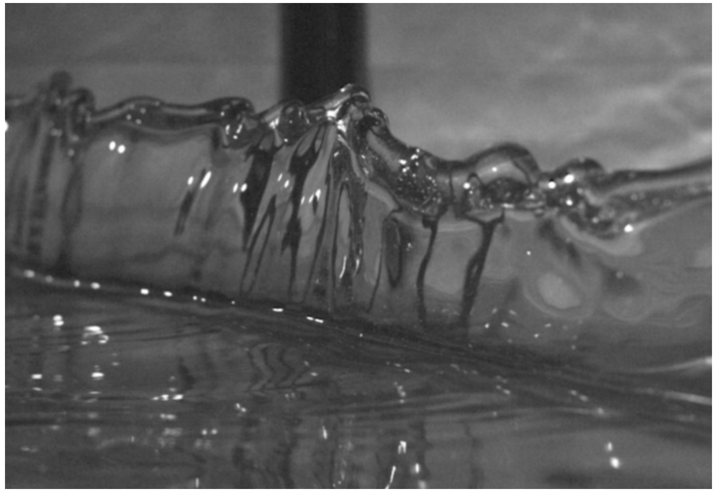
1 mm over tank length

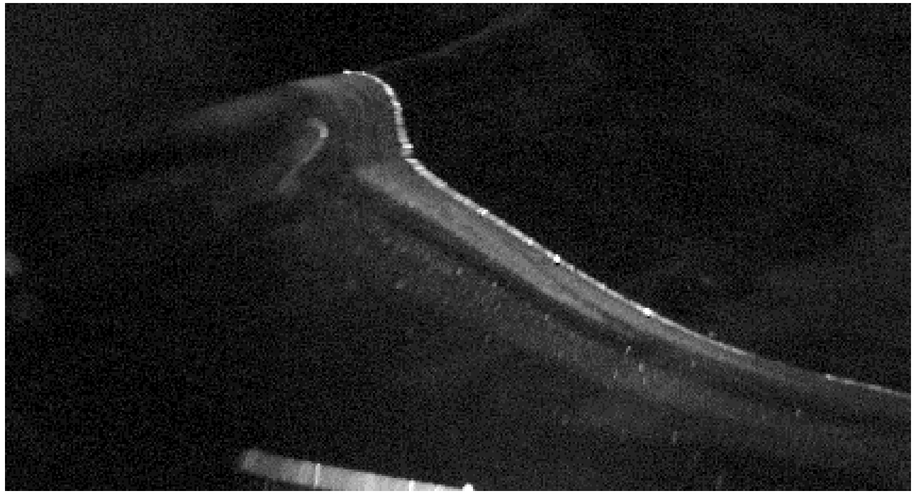
10 µm over tank length

INSTRUMENTATION development

- High Speed stereo-imaging

Wave impact, bubble formation, detailed profilometry





Scaling analysis

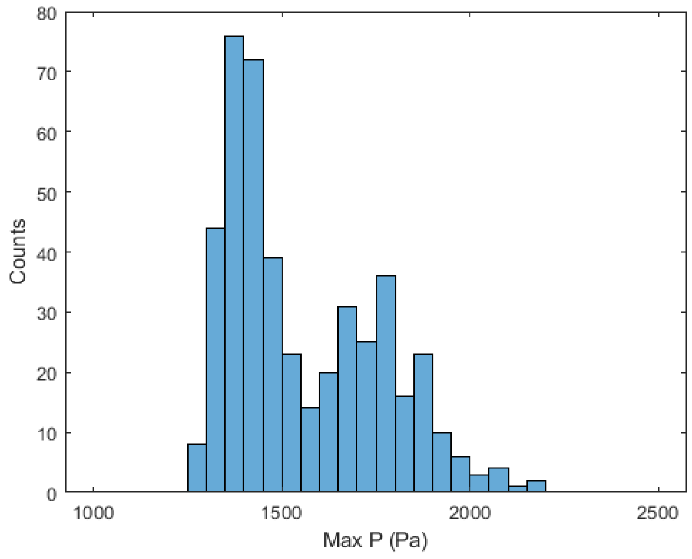
- Scaling with water depth

$$P^* = \frac{P}{\frac{1}{2}\rho V^2}$$

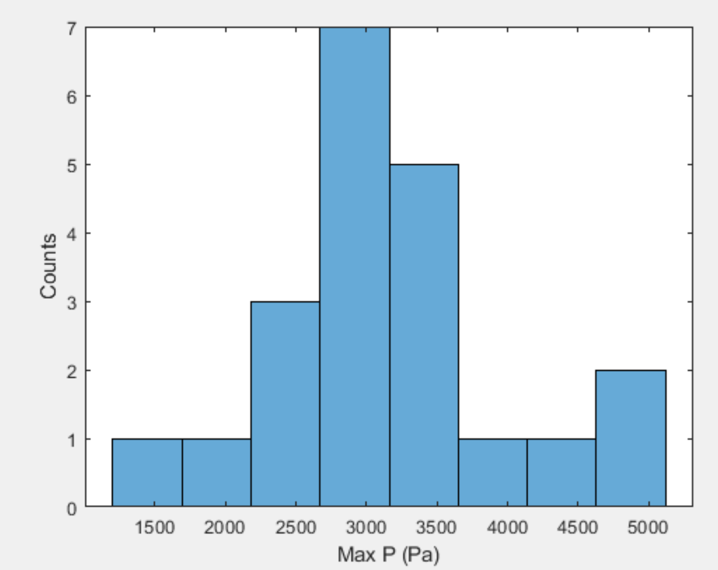
$$V = c = \sqrt{gh}$$

$$P^* = \frac{P}{\frac{1}{2}\rho g h}$$

Impact pressure (h=6”)



Impact pressure (h=12”)



Future tests

- Many types of structures can be mounted to the tank:
  - Dike, barriers, building models