Tsunami-Induced Debris Risks
Field, Experimental and Design Lessons

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SIOP
VII Seminario Internacional de Ingeniería y Operación Portuaria | San Antonio | 2016
Puertos sostenibles: el gran desafío

Université d'Ottawa | University of Ottawa

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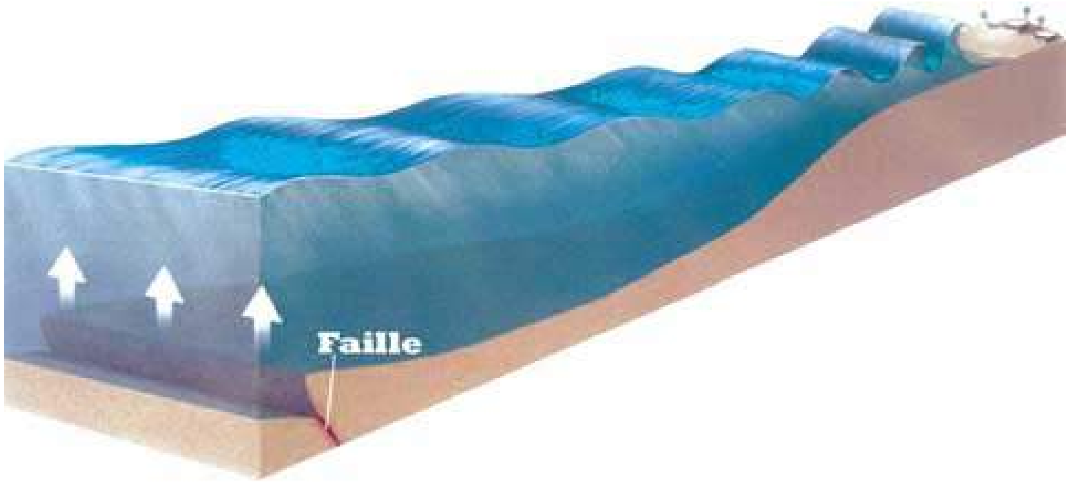
Outline

- Introduction
  - What is a Tsunami
  - Hazards of Debris Impact
- Tsunami Design Standards
- Research Needs
- Research Program at the University of Ottawa
  - Field Research
  - Experimental Research
  - Numerical Research
- Conclusions

What is a Tsunami?



- Series of long period (5 to 90 minutes) waves generated by the vertical movement of tectonic plates
- First documented by the Japanese, the term “tsunami” means “harbor wave”

Hazards involving debris motion

- Natural disasters (on-land **tsunami** flow), extreme weather and aging of infrastructure (**dams/dikes breaching**) -> extreme flow conditions

- **Characteristics** of these flows:
  - High energy, high momentum
  - Significant debris entrainment and displacement

Miyako harbor, Japan, on Mar., 11th, 2011

Tsunami Effects – Debris Hazards

Debris entrained by flows are **difficult to detect** due to:

- Partial submergence
- Agglomeration and damming of debris

Concerns:

- Multiple impact loads onto vertical structures
- Disruption of public safety or traffic infrastructure

Nistor, 2011

Roberson, 2011

Debris impacts and forces

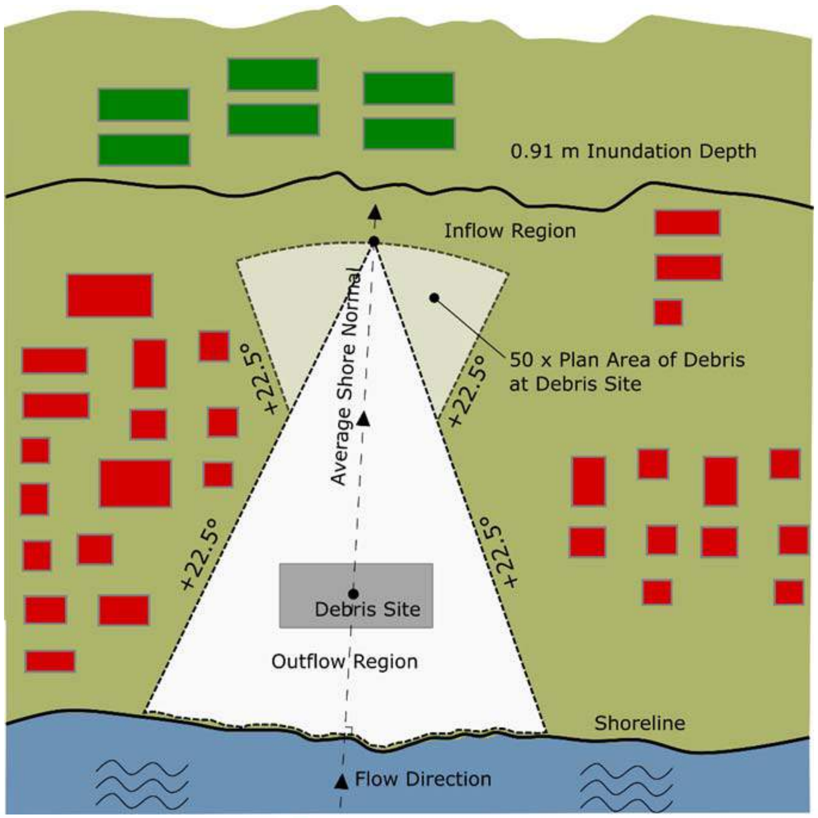
- Debris impact forces are difficult to predict and can depend on:
  - Size, shape, and mass of the debris
  - Debris Velocity
  - Duration of impact
  - Position of impact
  - Existing blockages around the debris
  - Type of structure being impacted

Tsunami Design Standards

- Spreading of debris
  - Limited guidance on debris spreading
  - Upcoming **ASCE 7-16 Standard with chapter "Tsunami Loads and Effects"**

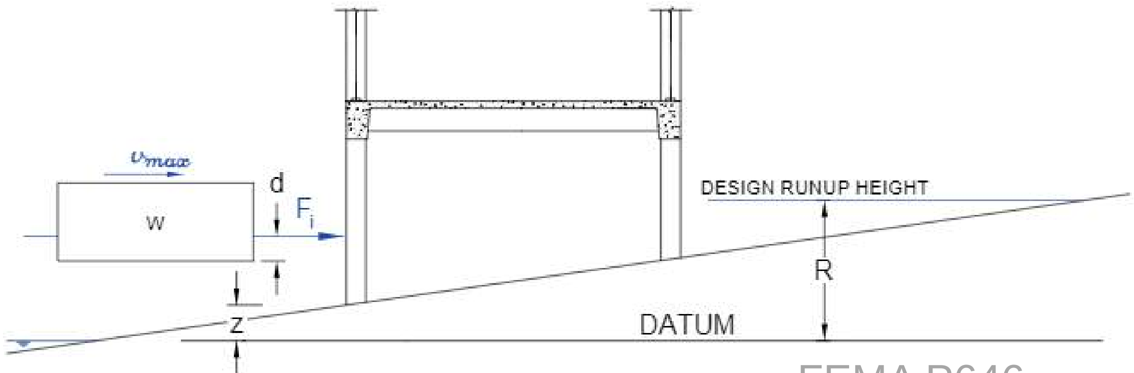
- Field investigation of debris spread
  - Based mostly on post-disaster surveys
  - Estimation of spreading angles
    - Spatial bounds from field evidence (lateral/longitudinal

- Limitations
  - Site specific
  - No experimental validation



Tsunami Design Standardization

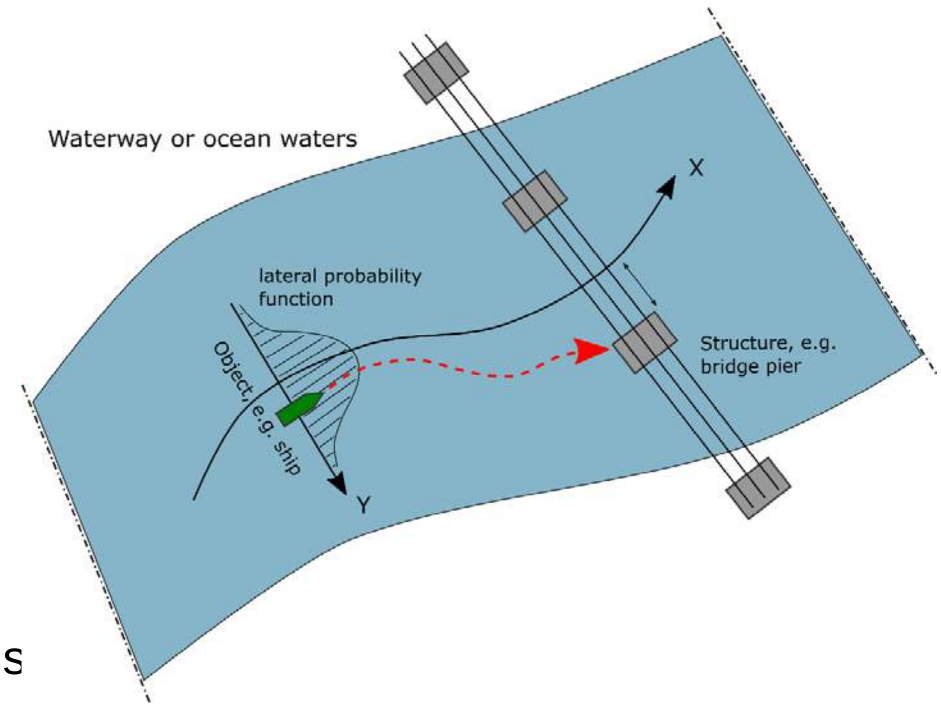
- Impact of debris on vertical structures
  - FEMA P646 $F_i = C_m u_{max}\sqrt{km}$
  - FEMA P55 $F_i = WVC_D C_B C_{str}$
  - ASCE 7-16 Chapter 6. $F_i = C_0 u_{max}\sqrt{km}$
- Limitations
  - No prescriptions for multiple impacts



FEMA P646

Tsunami Design Standards

- Eurocode EN 1991, Chapter 1-7 (2006): “Accidental Actions on Structures”
  - Considerations for impact of:
    - Vehicles and trains
    - Helicopters
    - Ships
  - Framework for risk analysis



- Limitations
  - No prescriptions for multiple impacts
  - Does not consider extreme conditions
  - No consideration for cascading effects

Research Objectives

- Investigation of tsunami damage to structures including buildings, bridges, seawalls and harbor facilities
  - Measurement of inundation levels and structural component details of surviving and near-failure building
- Physical and numerical modeling of debris motion and impact forces on structures
  - Research on single and multiple debris impacts
  - Research on debris spread and movement
- Incorporation of observations and lessons into structural design standards being prepared for the ASCE

Research Program – Post-Tsunami Forensic Engineering

Banda Aceh, Indonesia

Post-Tsunami Surveys – Debris Impact

Chile

(Palermo et al., 2013b)

Japan

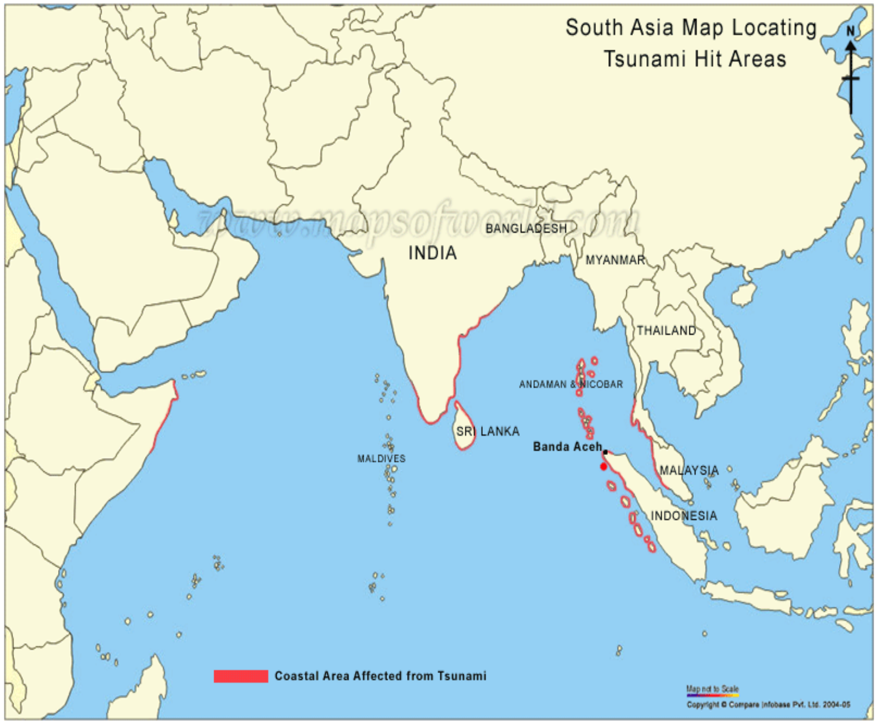
Nistor, I. (2012)

Indonesia

(Saatcioglu, M., Ghobarah, A., and Nistor, I., 2006b)

December 2004 Indian Ocean Tsunami

- **Magnitude:** 9.0 (USGS), 9.3 (Northwestern University)
- **Location:** 150 km W of Sumatra
  225 km SE of Banda Aceh, Indonesia
- **Fault length:** 1200 km
- **Depth**: 30 km
- **Width:** 150 km



- **Uplift:** Several meters (reports of 6 to 16 m)

Tsunami Forces on Structures
Ottawa U. Tsunami Survey Team – Thailand and Indonesia - January 2005

Nan Thong, Thailand, 2004

Banda Aceh, Indonesia, 2004

Saatcioglu and Nistor - 2005

Phi Phi Island, Thailand – debris accumulation

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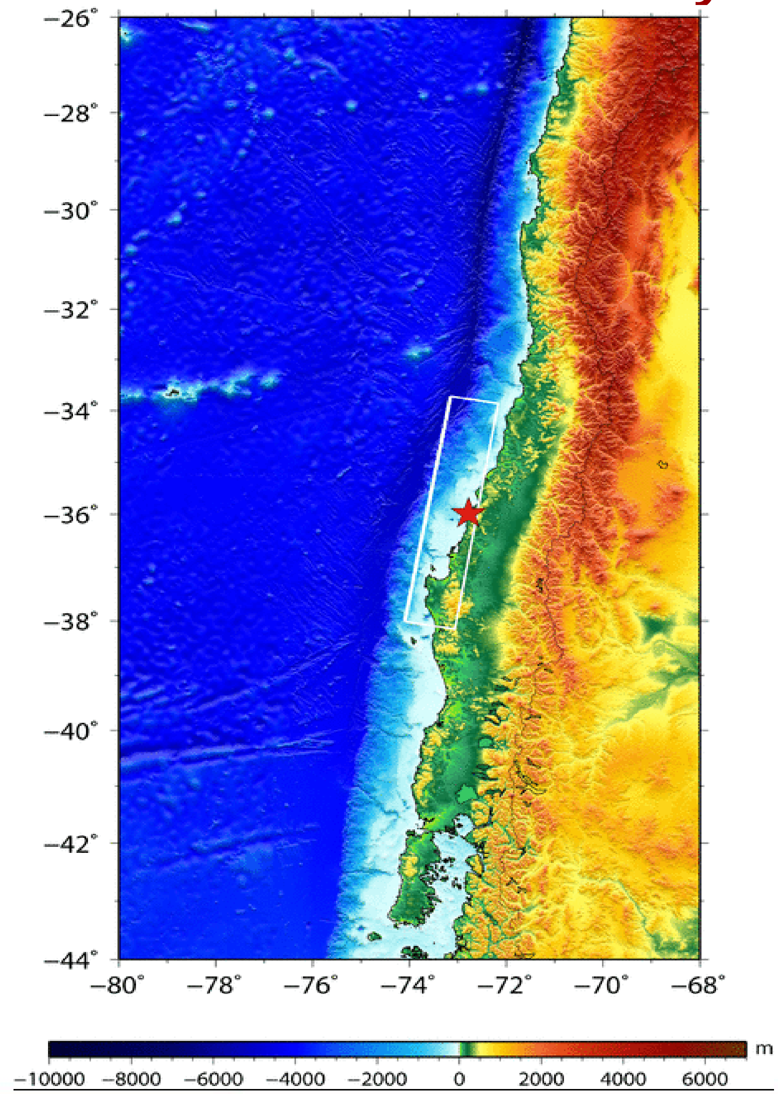
Banda Aceh, Indonesia – Debris impact

Banda Aceh, Indonesia – Debris impact

2010 Chile Tsunami – Ottawa U. Field Survey

- **Magnitude:** 8.8 Richter
- **Aftershocks:** 421 (as of March 18 2010)
- **Location:** Offshore Maule
- **Fault line:** 1000 x 200 km
- **Significant coastal inundation height:** several meters



Survey Route

Tsunami Forces on Structures
Ottawa U. and CSCE Field Survey Team – Chile
February 2010


Nistor, Palermo, Saatcioglu - 2010

Talcahuano – Port City – Suburb of Concepcion – Debris impacts

Talcahuano – Port City – Suburb of Concepcion

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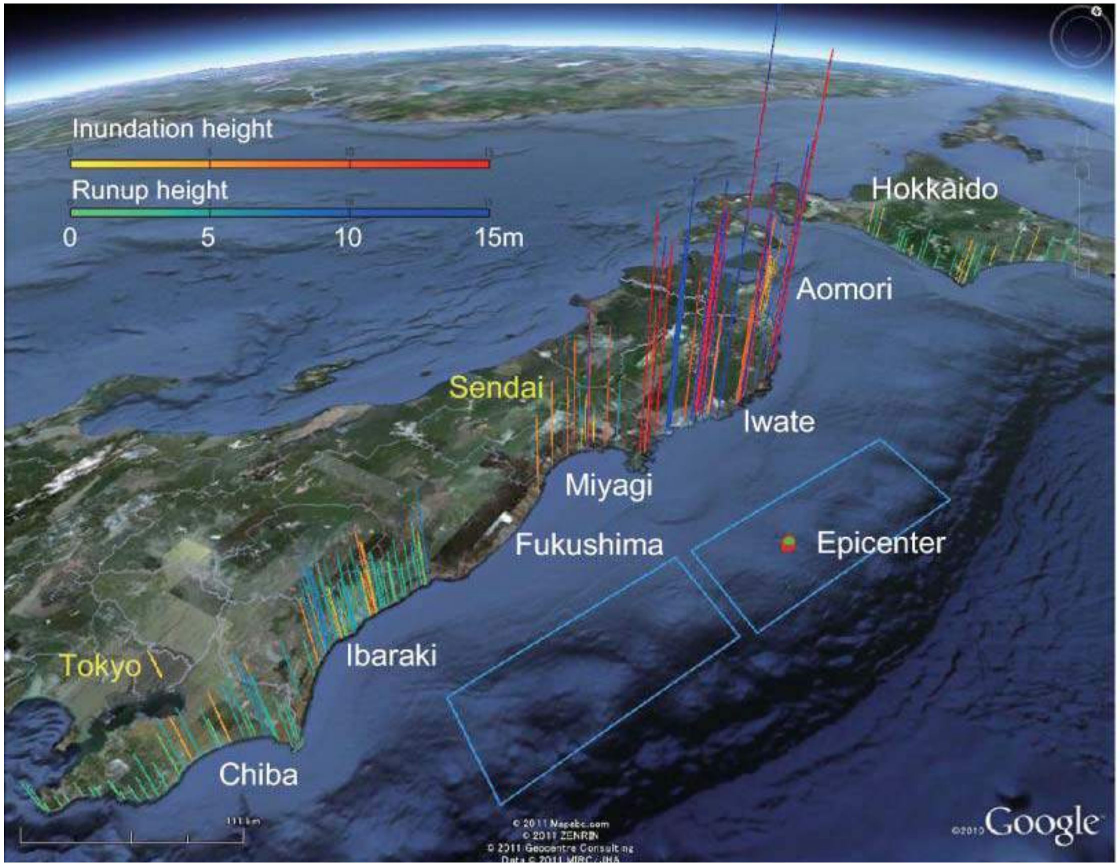
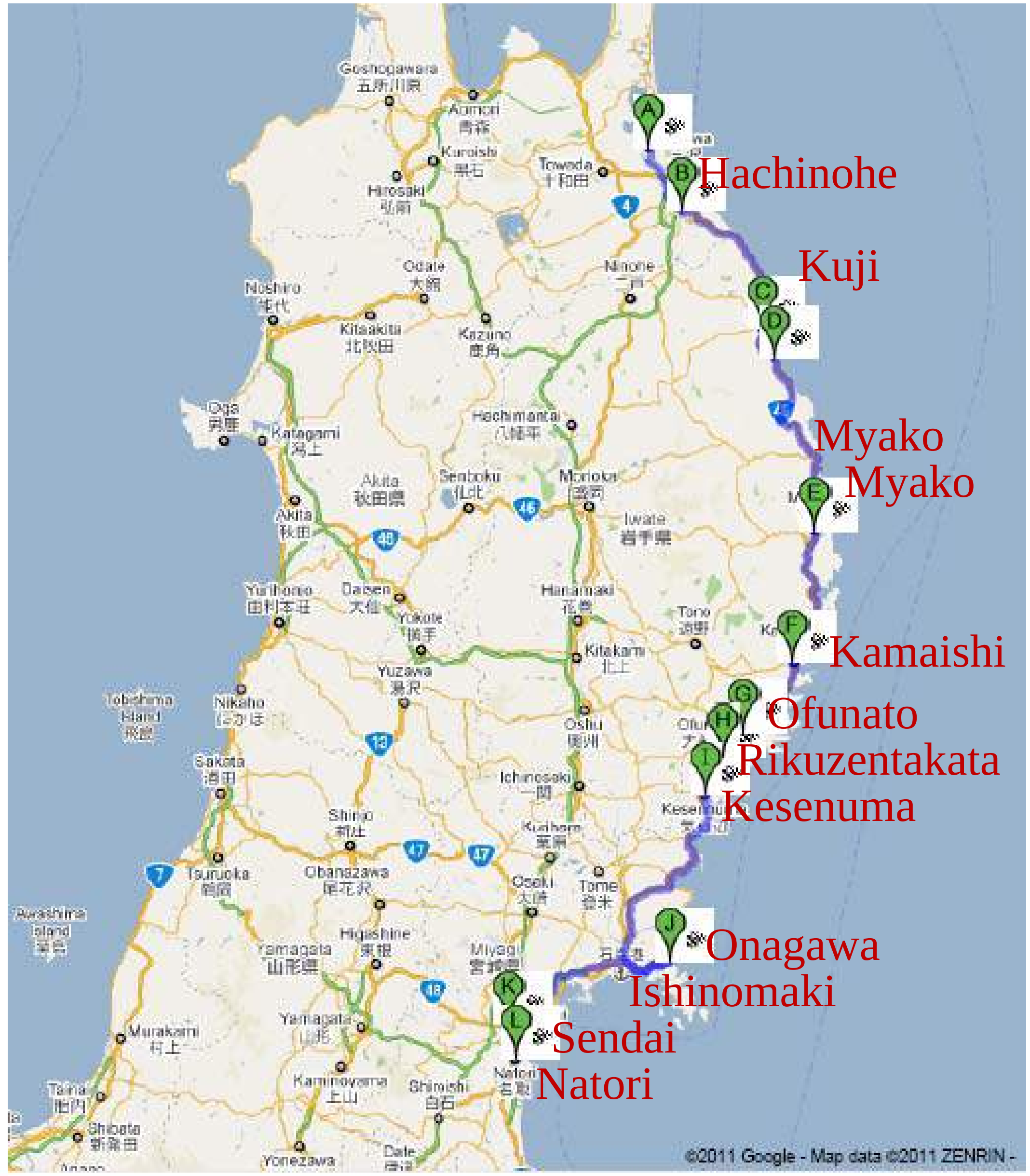
March 2011 Japan Tsunami – ASCE-JSCE Post-tsunami Survey

- **Magnitude:** 9.0 Richter
- **Location:** 38.322° N, 142.369° E
- **Depth:** 32 km
- **Horizontal Displacement:** 500 km x 200 km
- **Vertical ocean bottom displacement:** 10 to 20 m
- **Runup height: up to 40 m!**



Survey Route

- Group 1 started at the North end of the Tohoku Coastline at Hachinohe and visited most coastal communities from there to Natori in the South (9 days in 12 cities)



Tsunami Forces on Structures
ASCE Field Survey Team – Japan
April 12-24, 2011

Onagawa

Kriebel, 2011

Otsuchi

Nistor, 2011

Sendai Port – debris

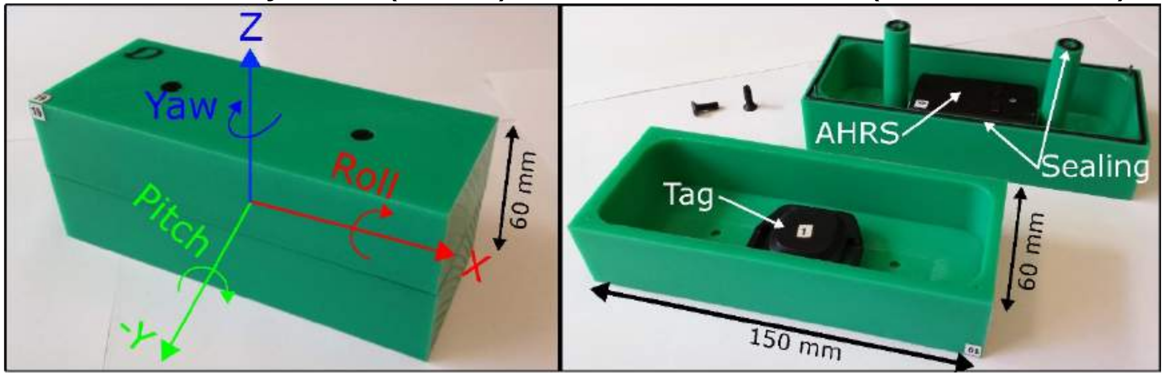
Sendai Port – Ship Impacts


Experimental Research Program
Ottawa U – Waseda U. –Hannover U.
Stolle

Non-Intrusive Debris Tracking – "Smart" Debris

- **Motivation for innovation**
  - Characteristics of extreme flow conditions
    - Low visibility through sediment-laden fluid
    - Turbulence-induced whitish surge/bore front
    - Occlusions through grouped debris

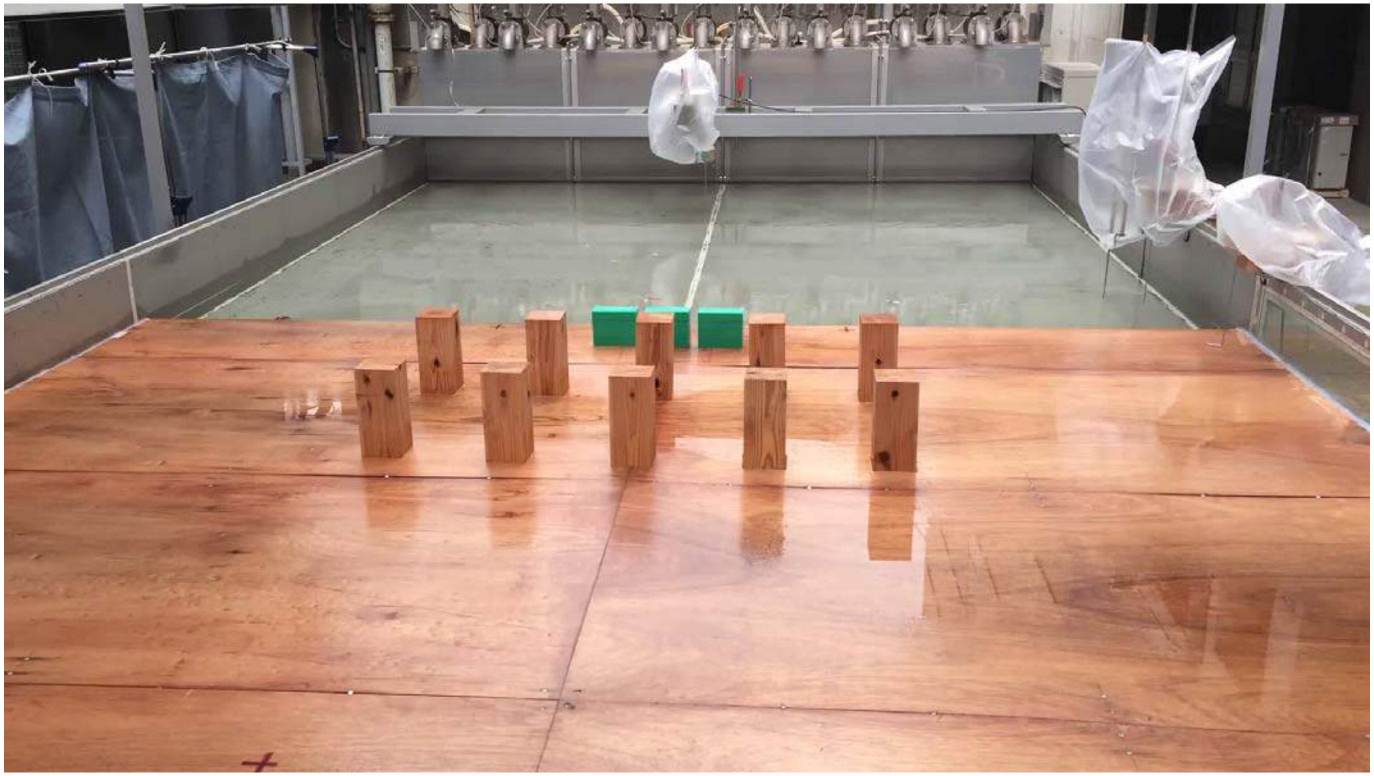
- ***"smart" debris*** – Non-intrusive 6 degrees-of-freedom debris tracking
  - Sensor-fusion of miniaturized instruments
    - Motion sensors (AHRS) (3 rotations)
    - Real-time Location System (RTLS) (3 translations)



Nistor *et al. 2016, J. Waterway, Port, Coastal, Ocean Eng.*

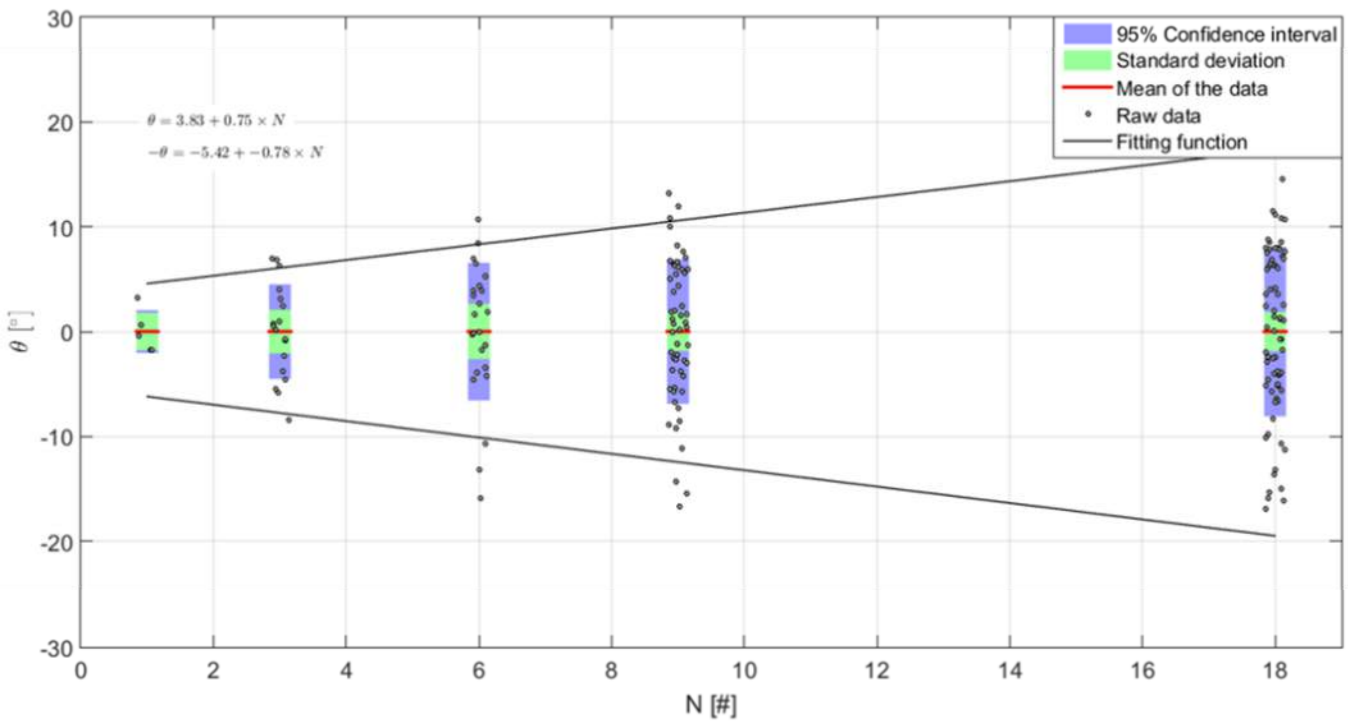
Non-Intrusive Debris Tracking

- Model of a harbour setting accomplished at Waseda University, 2014
  - Horizontal apron and horizontal sea bead
  - Tsunami-like inflow condition
  - 1:40 scaled-down shipping containers (*“smart” debris*)

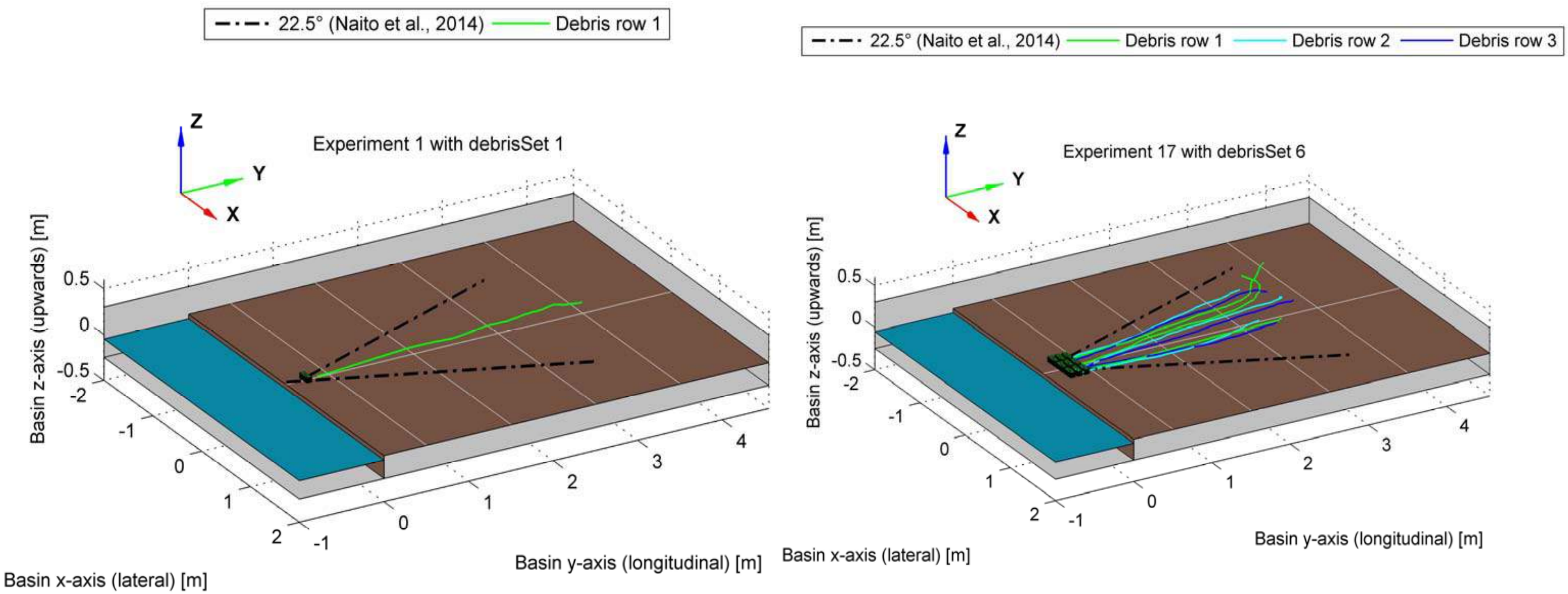


Non-Intrusive Debris Tracking

- How can designers reliably determine debris impact prone zones?
  - ASCE 7-16 suggests zones with ±22.5° bounds
- Debris dynamics on horizontal surfaces (Nistor et al., 2016, in press)
  - Inland displacement
  - Debris spreading / dispersion



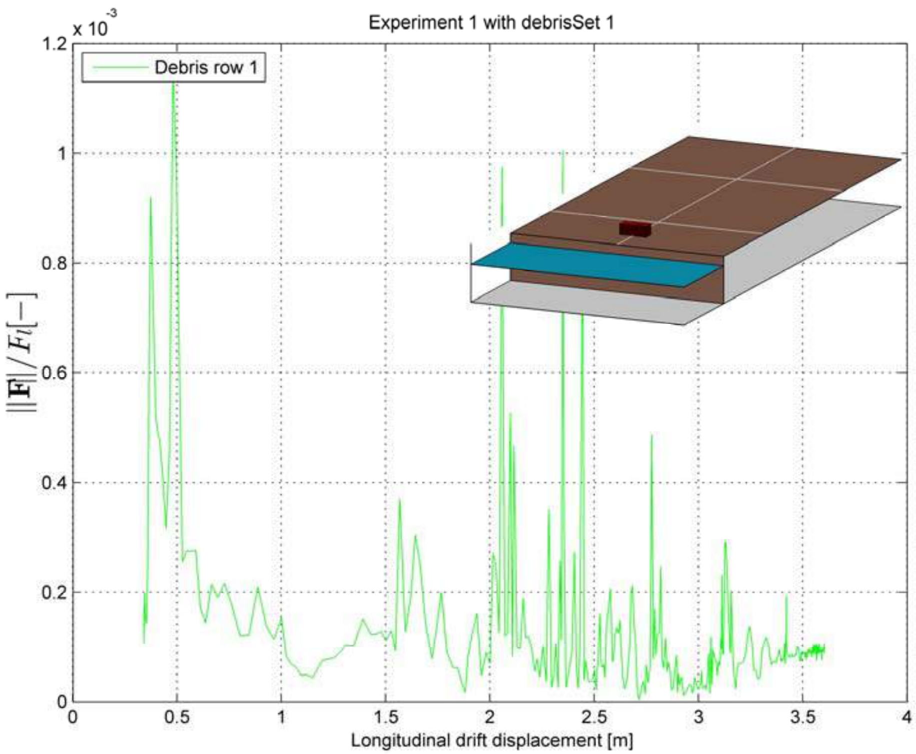
Non-Intrusive Debris Tracking – Motion

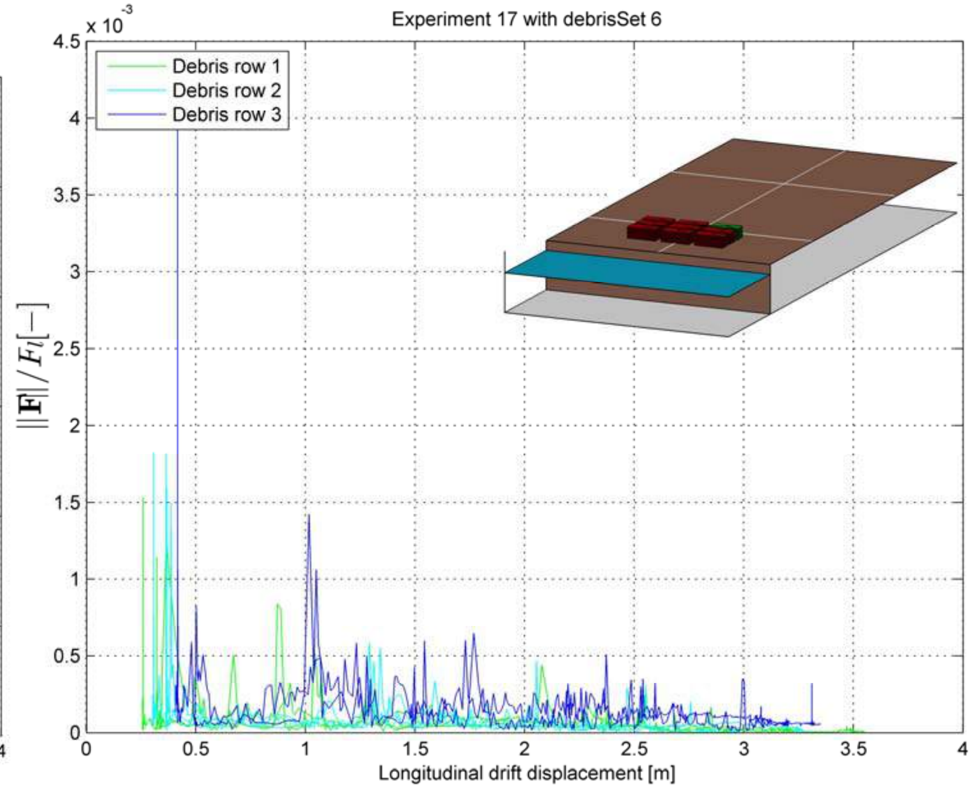


- Compared to assumptions by Naito et al. (2014)
  - $\mp 22.5^{o}$ spreading angle

Goseberg *et al. 2016, J. Hydraul. Eng.*

Non-Intrusive Debris Tracking – Forces

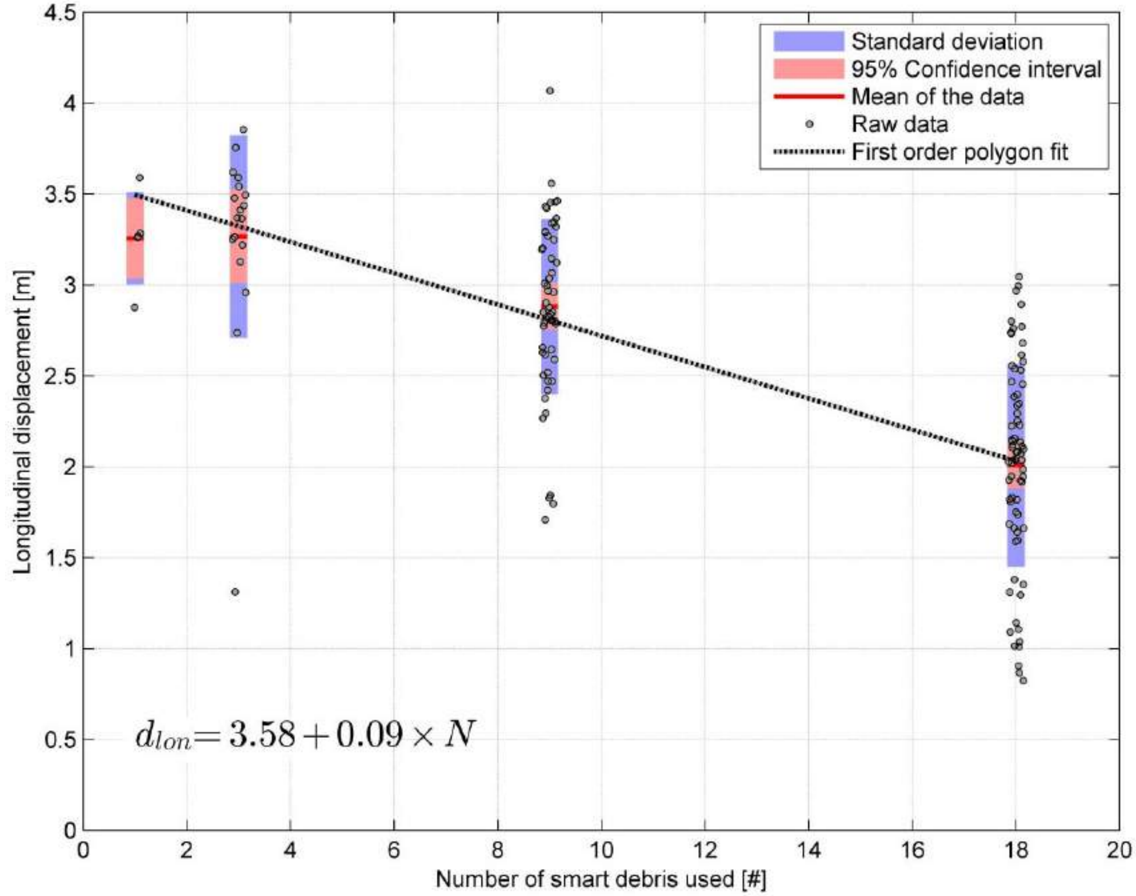




- Forces normalized using Cross (1967).
  - Wave height and velocity.

Non-Intrusive Debris Tracking – Debris Displacement

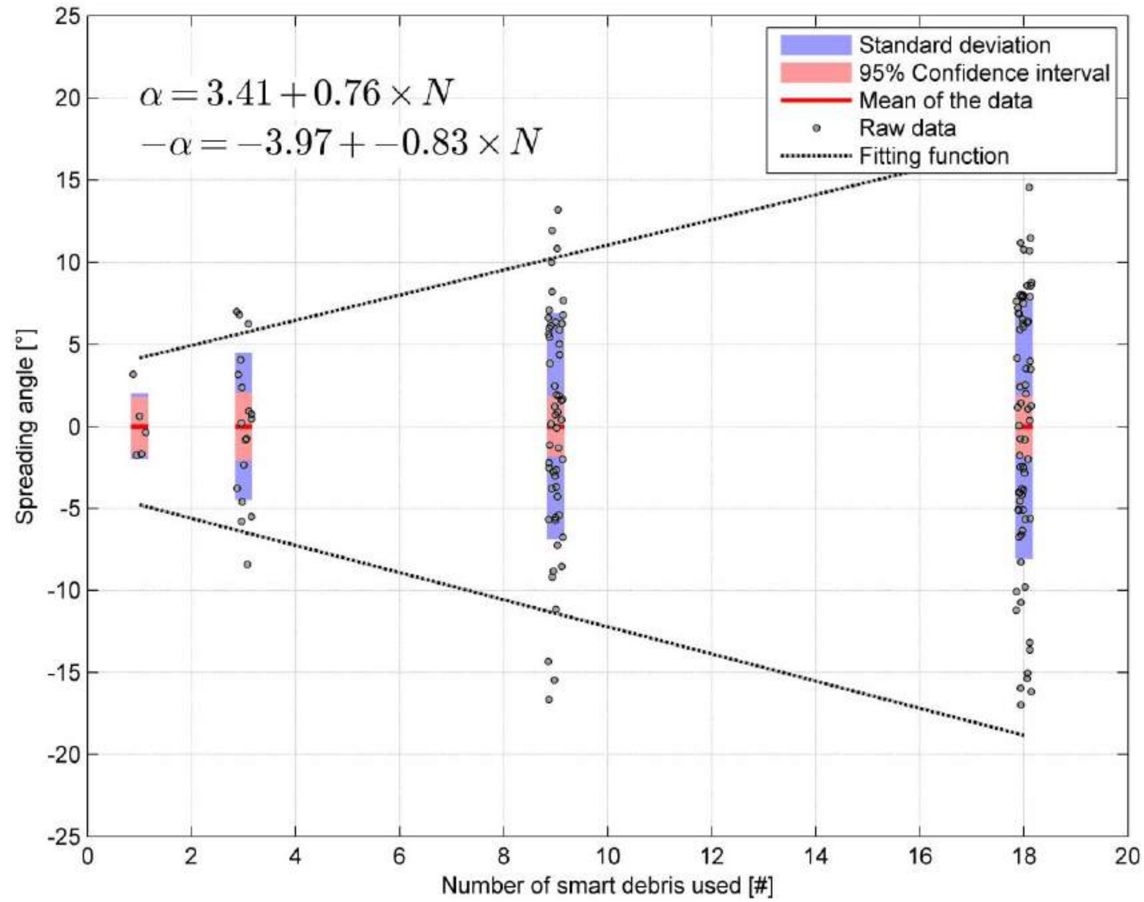
- Displacement in flow direction from initial position
- Decrease in displacement with increase in debris



Nistor *et al. 2016, J. Waterway, Port, Coastal, Ocean Eng.*

Non-Intrusive Debris Tracking – Debris Spread

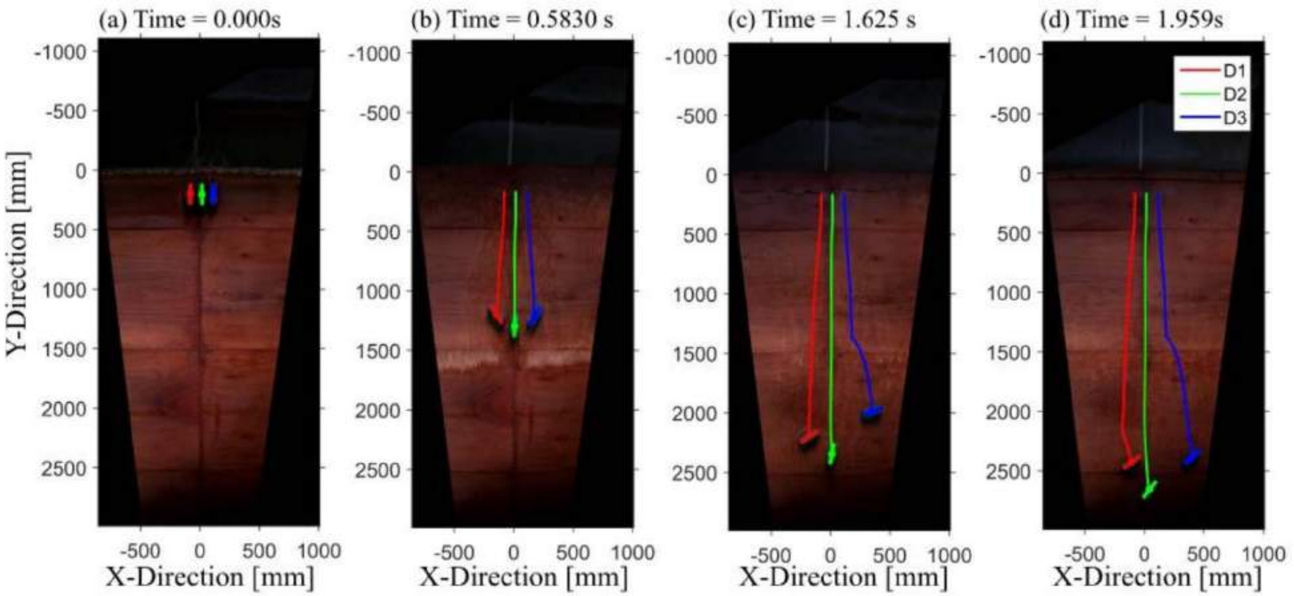
- Angle from centroid of initial position of container
- Increase in spreading angle with increase in debris



Nistor *et al. 2016, J. Waterway, Port, Coastal, Ocean Eng.*

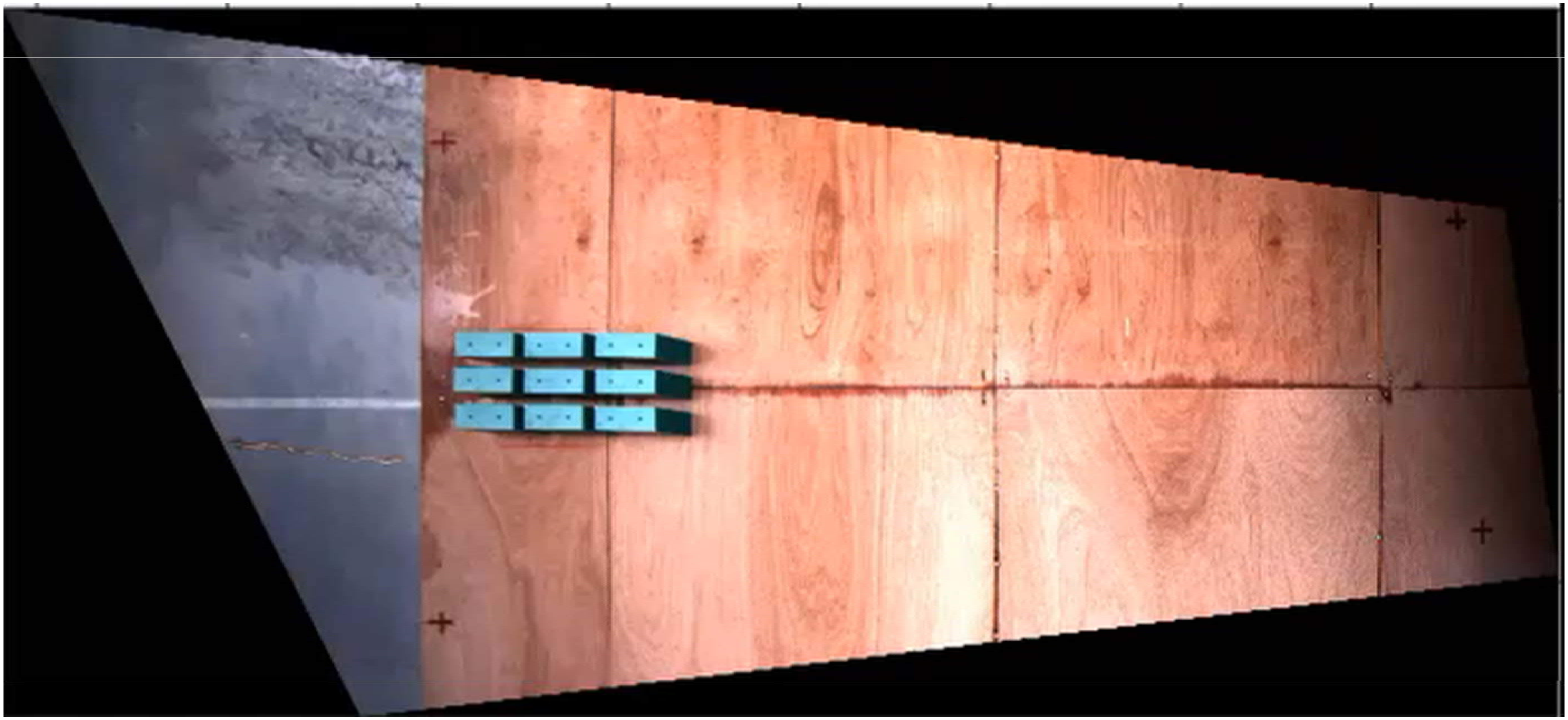
Optical Non-Intrusive Debris Tracking

- Based on image capture from motion
- Algorithm detects and tracks debris
  - Color space conversion and color thresholding
  - Kalman-filter and Hungarian algorithm



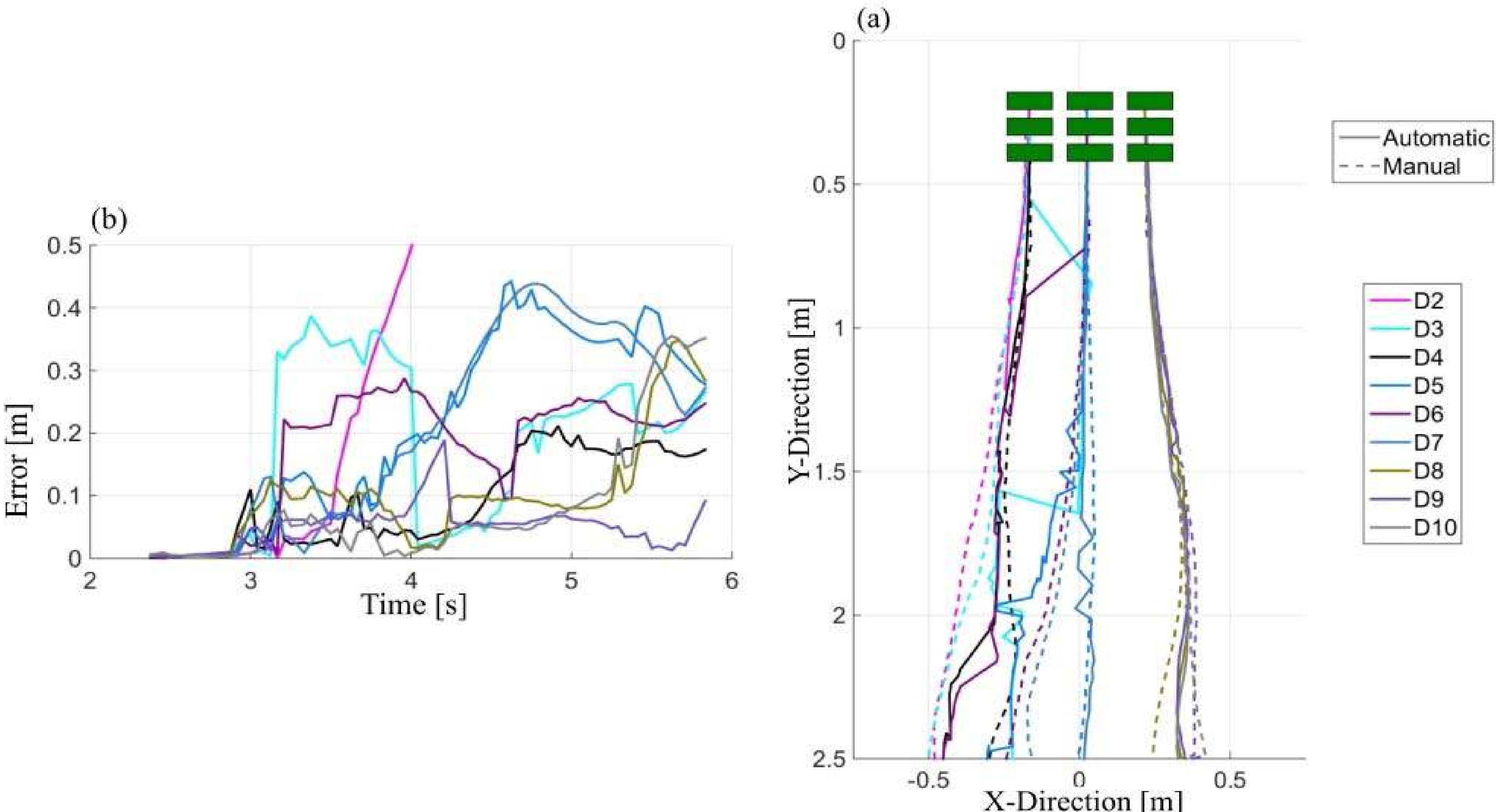
Stolle *et al. 2016, Resilient Infrastructure*

Optical Non-Intrusive Debris Tracking



Goseberg, 2016

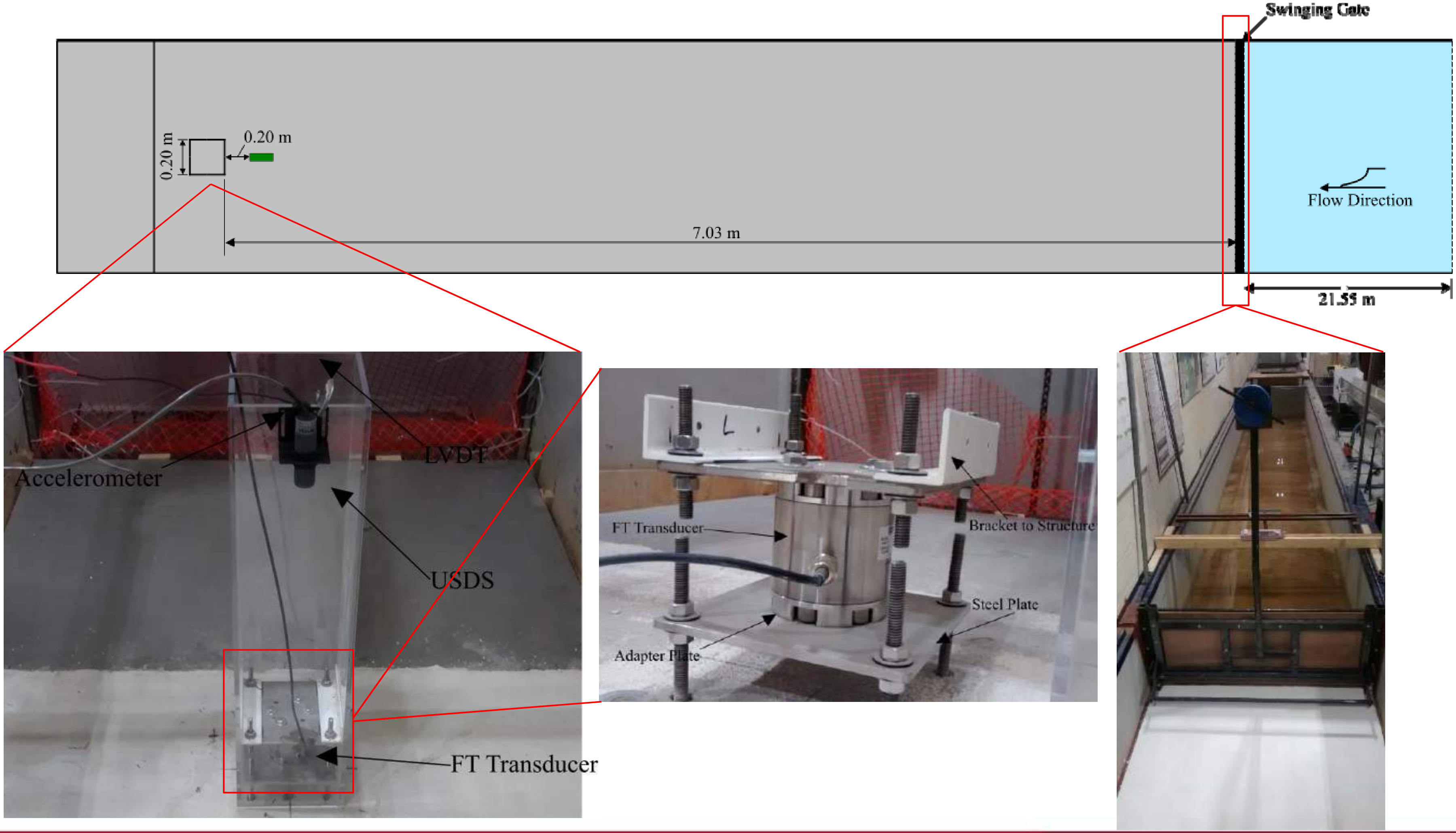
Optical Non-Intrusive Debris Tracking – Motion



Stolle *et al.*, 2016

Dam break test – University of Ottawa

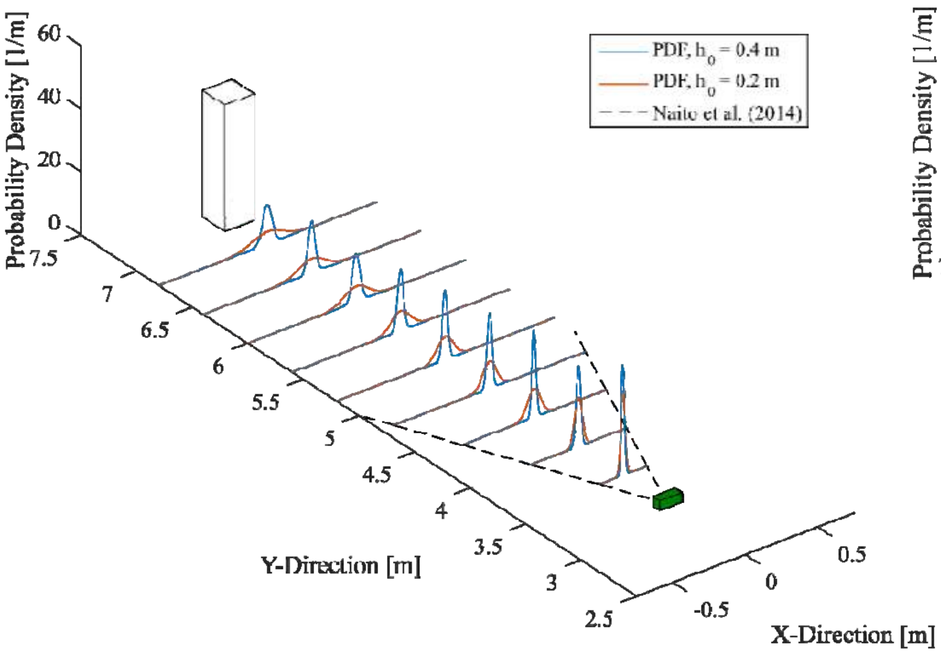
Comprehensive experimental program using multiple debris events

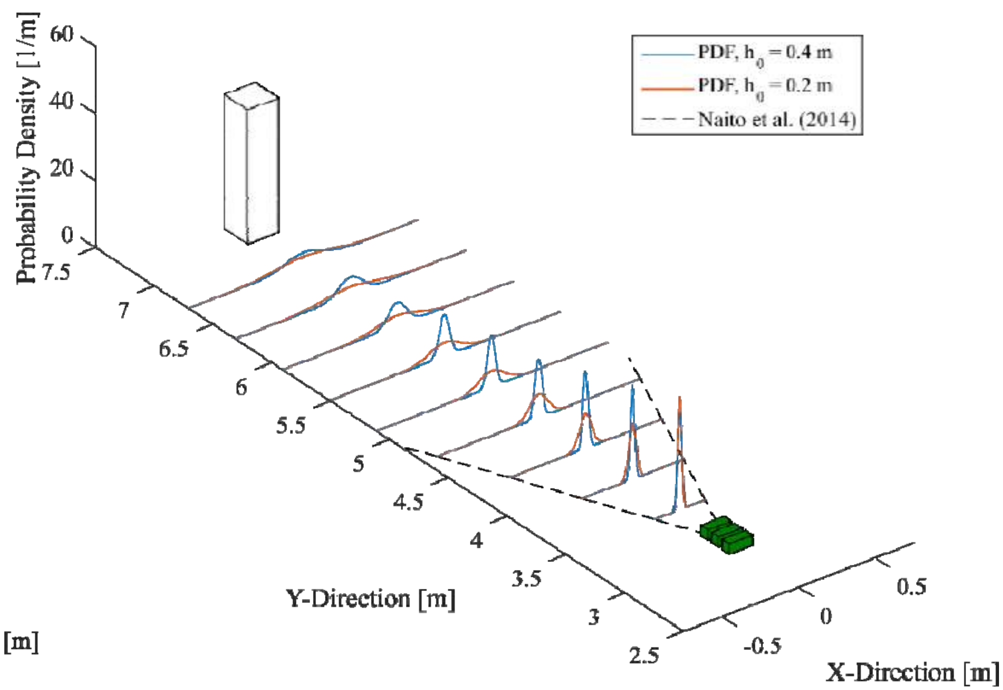


Optical Non-Intrusive Debris Tracking – Motion

- Examined a normal probability density function of the debris motion against longitudinal displacement

Stolle *et al.*, 2016





Within Naito et al. (2014) guidelines

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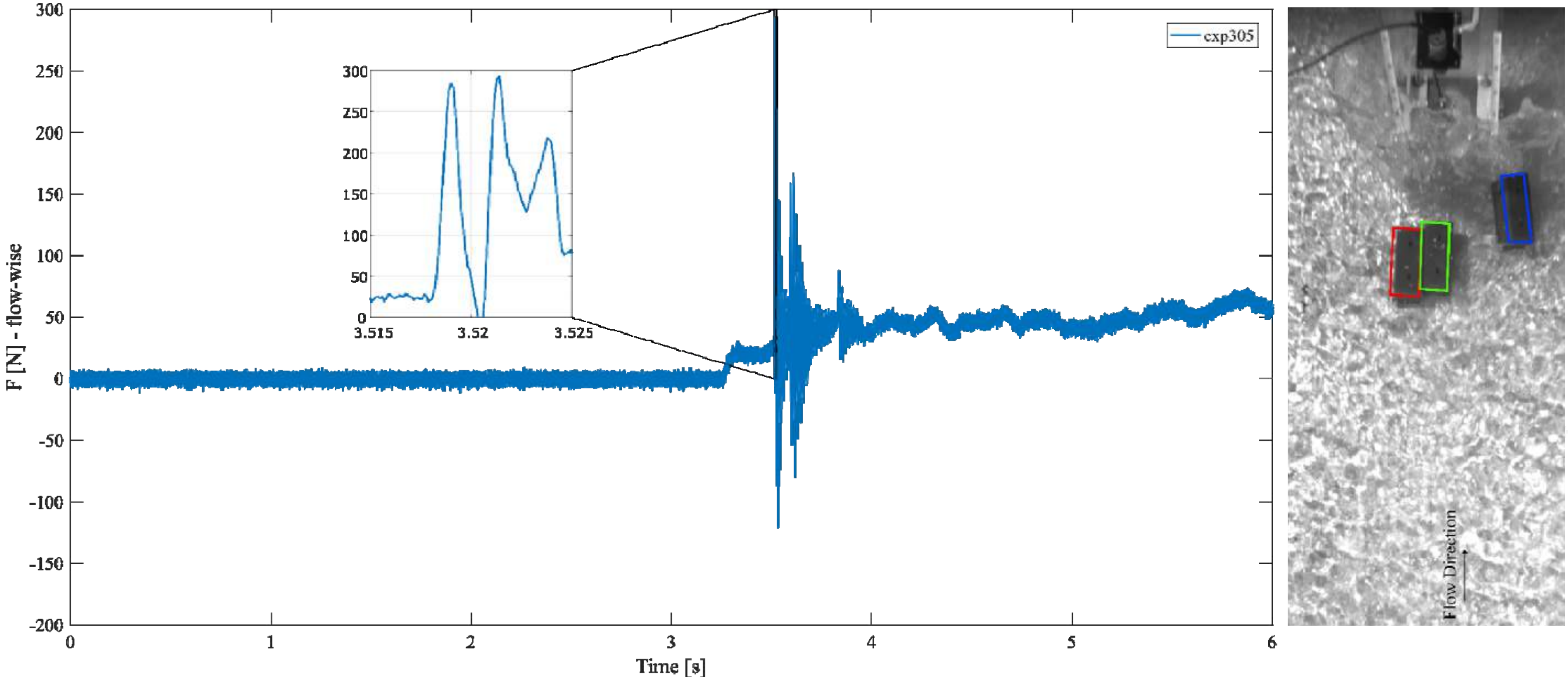
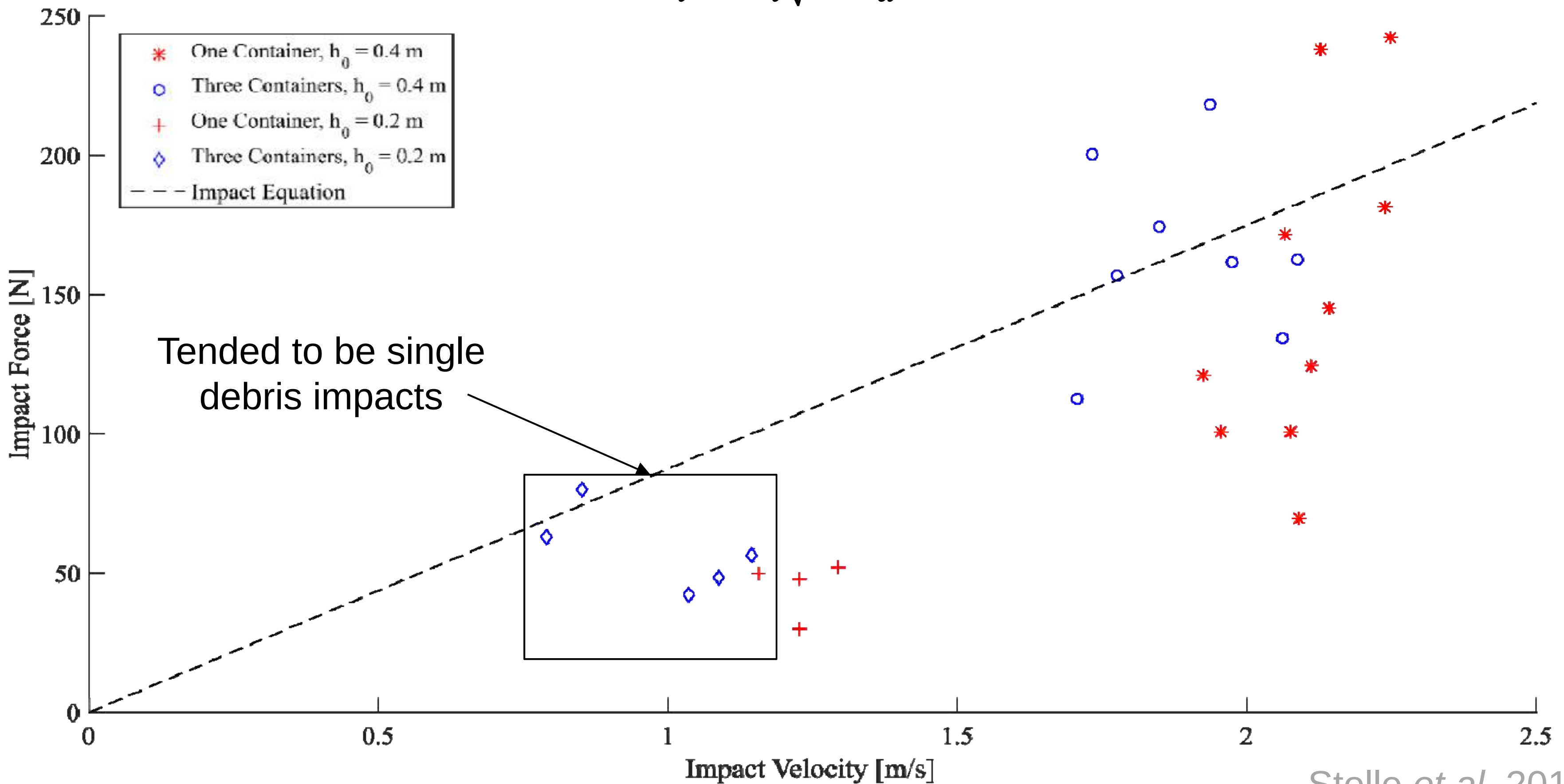
Optical Non-Intrusive Debris Tracking – Forces



Stolle *et al*, 2016

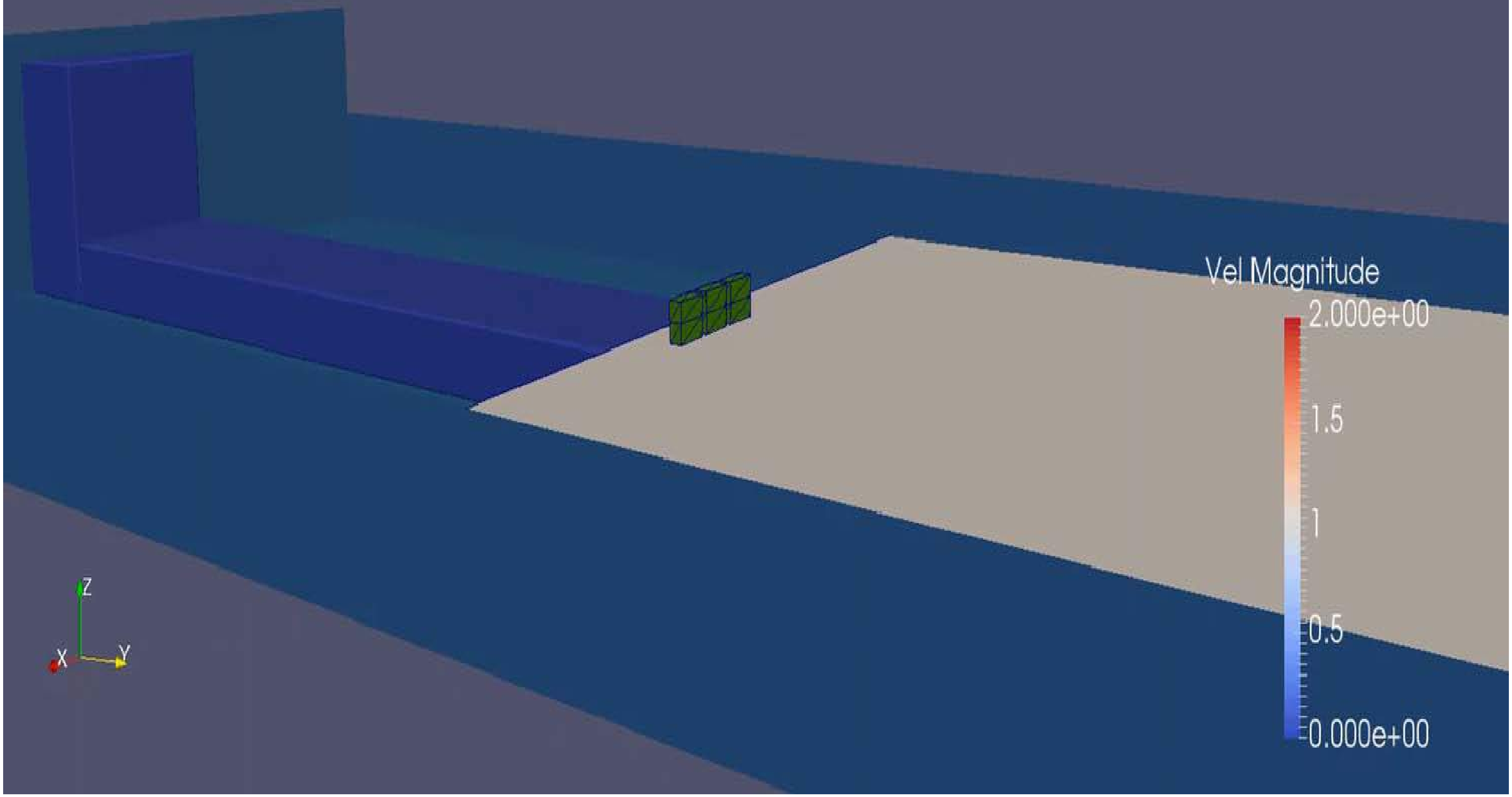
Optical Non-Intrusive Debris Tracking – Forces

$$F_i = u_i\sqrt{km_d}$$



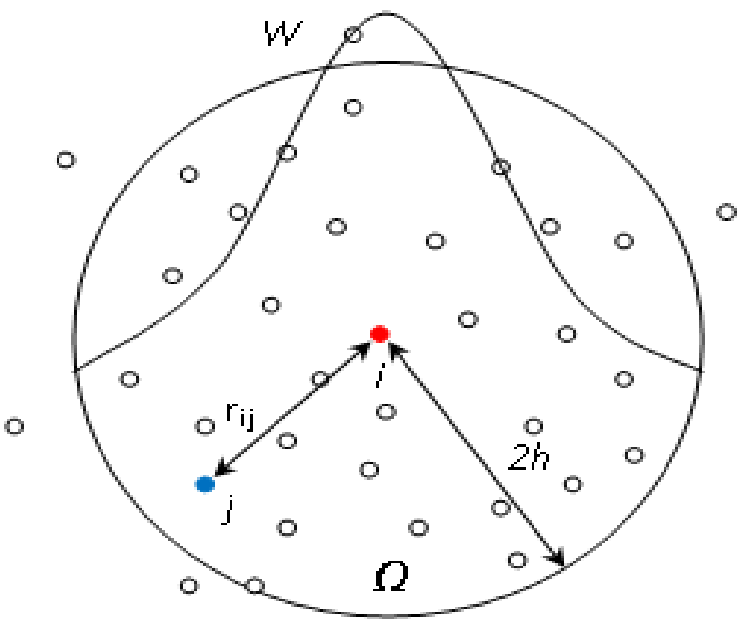
Stolle *et al*, 2016

Research Program
Numerical Modelling of Debris Motion



DualSPHyiscs Smoothed Particle Hydrodynamics

- Meshfree Lagrangian particle-based method
- Particles are represented by a set of arbitrarily distributed points

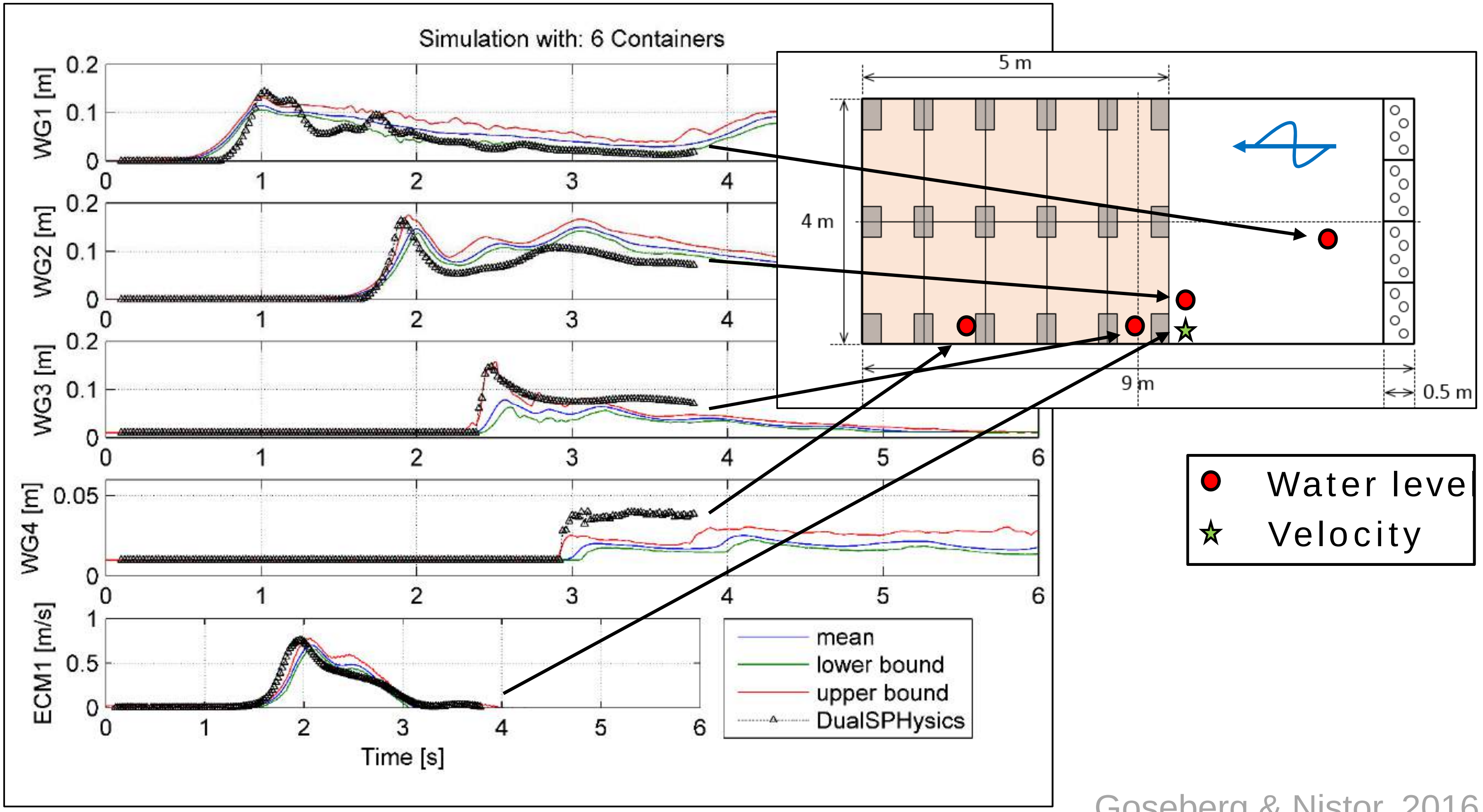


- The model uses a particle approximation to represent a function as the summation of all the particles within the influence domain

$$f(\boldsymbol{x}_i) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(\boldsymbol{x}_j) W(\boldsymbol{x}_i - \boldsymbol{x}_j, h)$$

Debris motion – SPH model

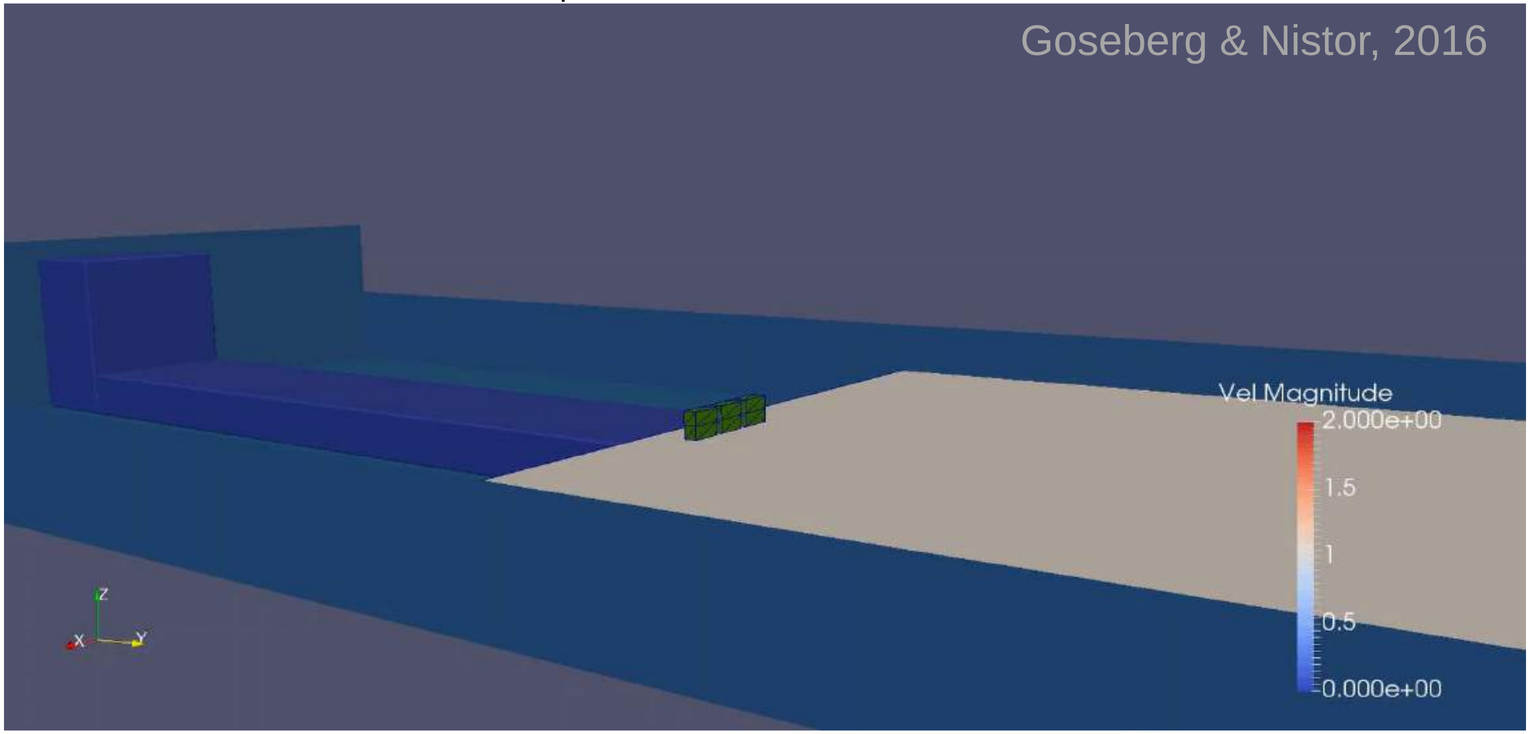
Validation of water levels and velocity with experimental data



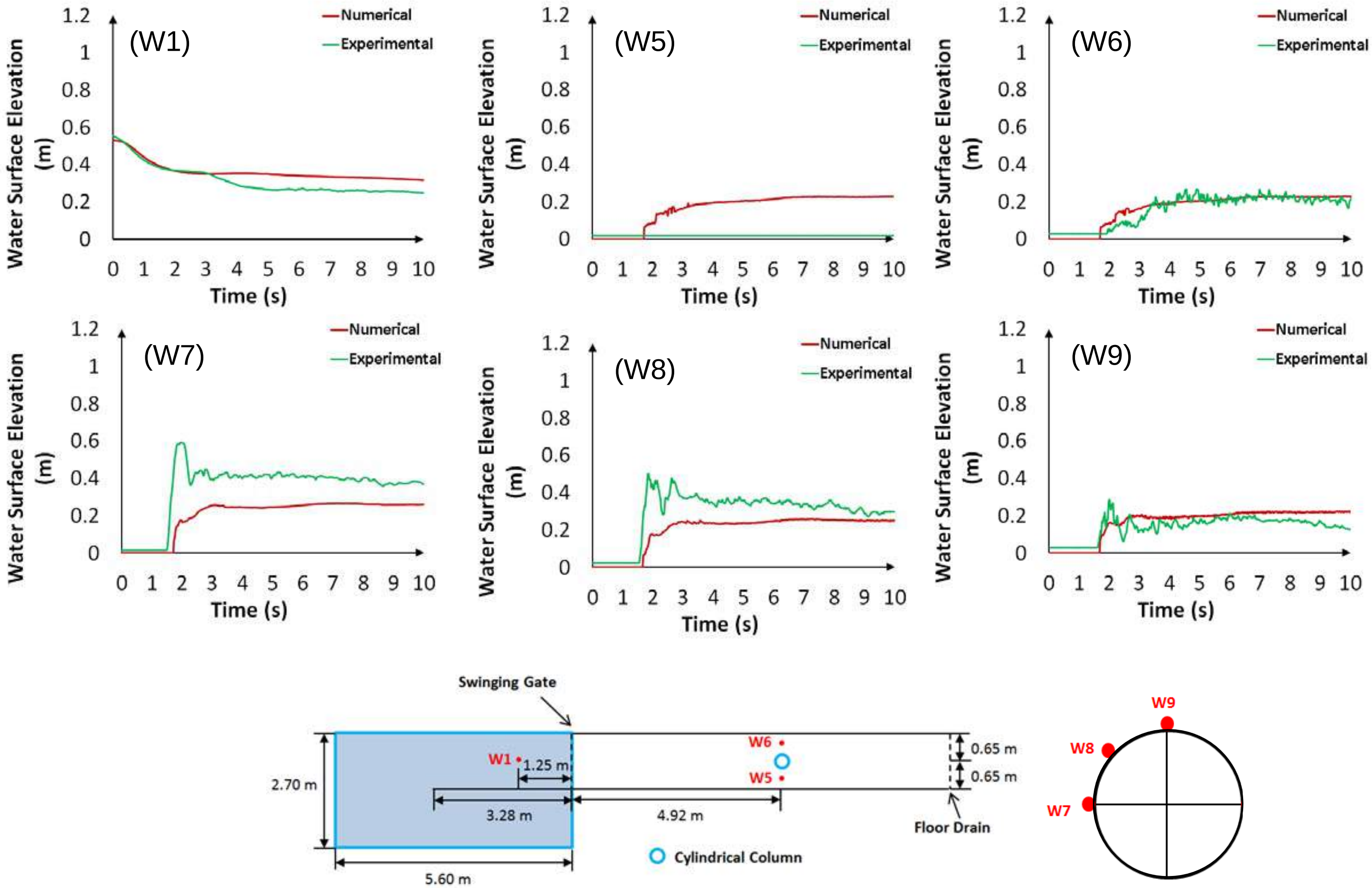
Goseberg & Nistor, 2016

Debris motion – SPH model

- Simulating debris dynamics on a harbor apron
- 6 shipping containers, 3x2 side-by-side arrangement
- Model parameters:
  - 9,788,181 particles
  - Initial particle spacing d_p = 0.5 mm

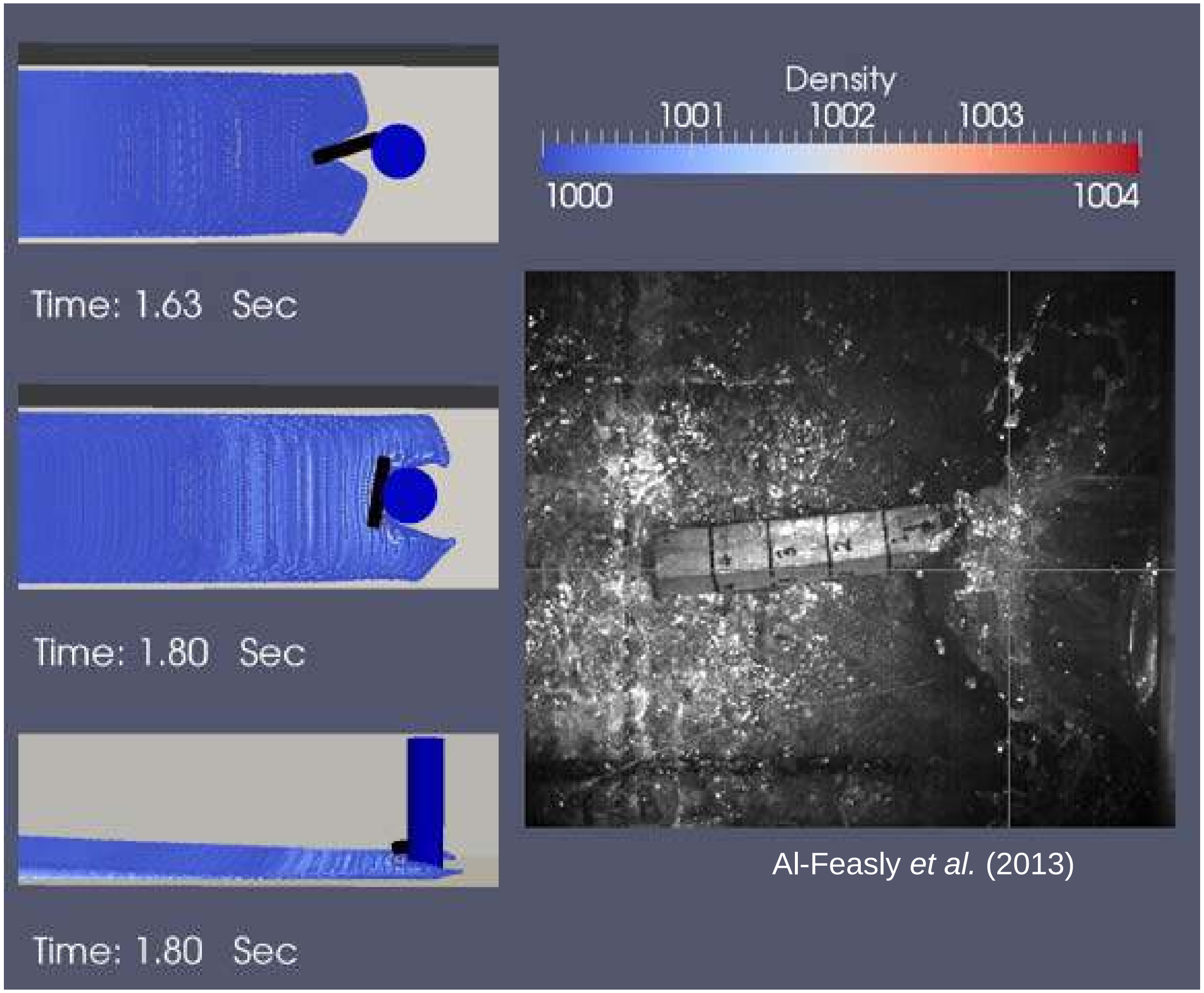


SPH Debris Impact – Ottawa U. (2014)



Piche *et al*, 2014

Debris Impact – SPH model



Piche *et al*, 2014

Conclusions

- Current design documents for the estimation of tsunami impacts show deficiencies
- Tsunami field surveys provide unmatched opportunities for data collection to verify and improve existing formulations
- Debris accumulation occurs rapidly once structures are encountered. Design loads must consider debris damming and blockage
- Debris spreading appears to be dependent on the number of debris and its hydrodynamic condition
- Physical models showed that the increasing the amount of debris increased their spreading angle and decreased the length of their longitudinal displacement
- The presence of obstacles reduced the longitudinal displacement of the debris but did not impact the spreading angle

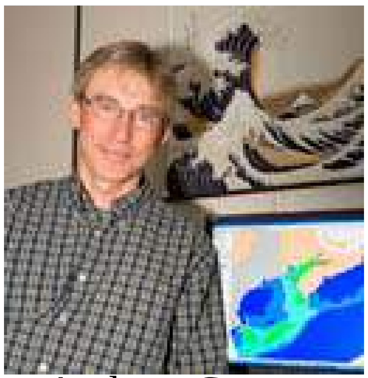
Acknowledgements

Dan Palermo
Ottawa U.

Tomoya Shibayama
Waseda U, Japan

Tad Murty
Ottawa U.

Murat Saatcioglu
Ottawa U.



Andrew Cornett
Ottawa U. & NRC

Nils Goseberg
Ottawa U. & Hannover U.

Graduate students at Ottawa U.

Philippe St-Germain, MASc
Stephanie Piche, PhD
Steven Douglas, PhD
Taofiq Al-Faesly, PhD
Jacob Stole, PhD
Younes Nouri, MASc
Safinaz El-Sohl, MASc

Thank you!

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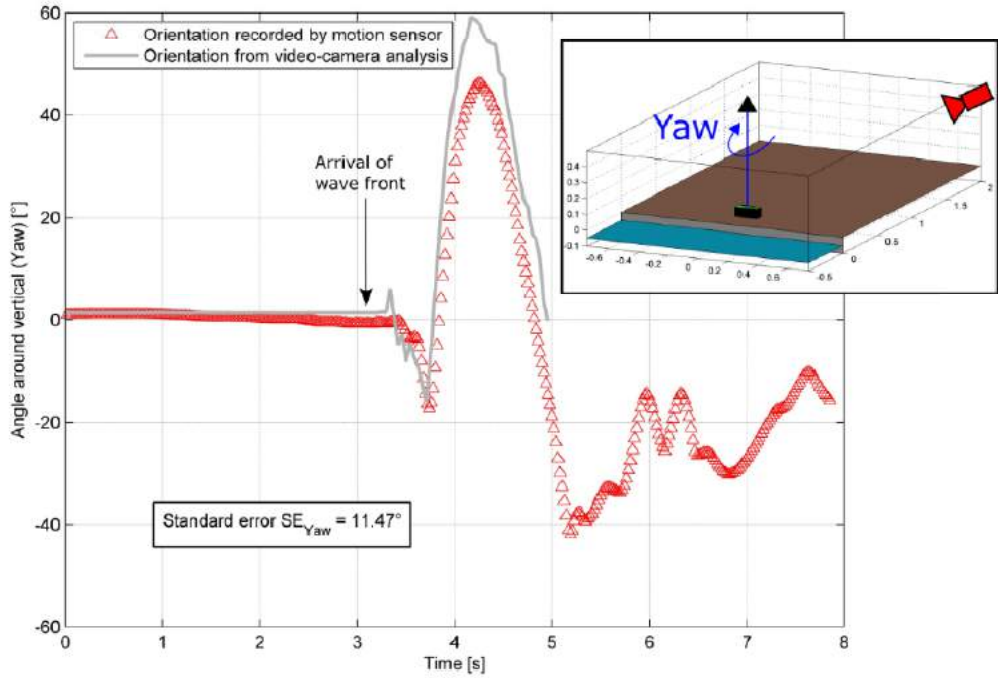
Non-Intrusive Debris Tracking – "Smart" Debris



- ***"smart" debris* in action**
  - Accurate tracking positions of 9 shipping containers in a wave basin simultaneously
  - Tracking container rotation along vertical axis during flow
- **Impact and potential future application**
  - Application to various other disciplines beyond civil engineering
    - Tracking of floating objects (e.g. plastics, large wood debris) in rivers
    - Automated tracking of coastal armour layers (e.g. tetrapods)
    - Monitoring of transport user behaviour (e.g. pedestrians)
    - Profiling of riparian fauna (e.g. in ecologic studies)

Goseberg et al. (2016) *Journal of Hydraulic Engineering*

Development of a new Tsunami Loads and Effects Design Standard by ASCE

- **No standard for engineering design for tsunami effects written in mandatory language exists.** There is no comprehensive construction standard comparable to seismic or wind building codes for structures.
- **The Tsunami Loads and Effects Subcommittee (TLESC)** was established in **February 2011** – Chair: Gary CHOCK
- The of the ASCE/SEI 7 Standards Committee is developing a new **Chapter 6 - Tsunami Loads and Effects**, with Commentary, for the March **2016 Edition of the ASCE 7 Standard**.
- **Review** by ASCE 7 Main Committee in 2014-2015
- Tsunami Provisions would then be referenced in the **International Building Code IBC 2018**

Outline of the New Design Method

- Probabilistic tsunami hazard analysis based criteria
- Energy-based methodology for calculating tsunami inundation depth and velocity at a site
- Structural loadings derived from research and validated
- Analysis techniques for determining building performance
- Multi-hazard performance-based approach for regions governed by local subduction earthquakes
- The proposed ASCE 7 provisions for Tsunami Loads and Effects are consistent with tsunami physics and performance based engineering, with substantial load validation from post-tsunami case studies of structures.

Principal Tsunami Design Strategies
Chapter 6 - Tsunami Loads and Effects

- Select a site appropriate and necessary for the building
- Select an appropriate structural system and perform seismic design first
- Determine flow depth and velocities at the site based on the tsunami design zone map
- Check robustness of expected strength within the inundation height to resist hydrodynamic forces
- Check resistance of lower elements for hydrodynamic pressures and debris impacts to avoid progressive collapse
- Foundations to resist scour at the perimeter of the building
- Elevate critical equipment as necessary