THE UNIVERSITY OF AUCKLAND
Te Whare Wānanga o Tāmaki Makaurau
NEW ZEALAND

Infrastructure Component Fragility and Vulnerability for Tsunami Wave Impacts and Currents

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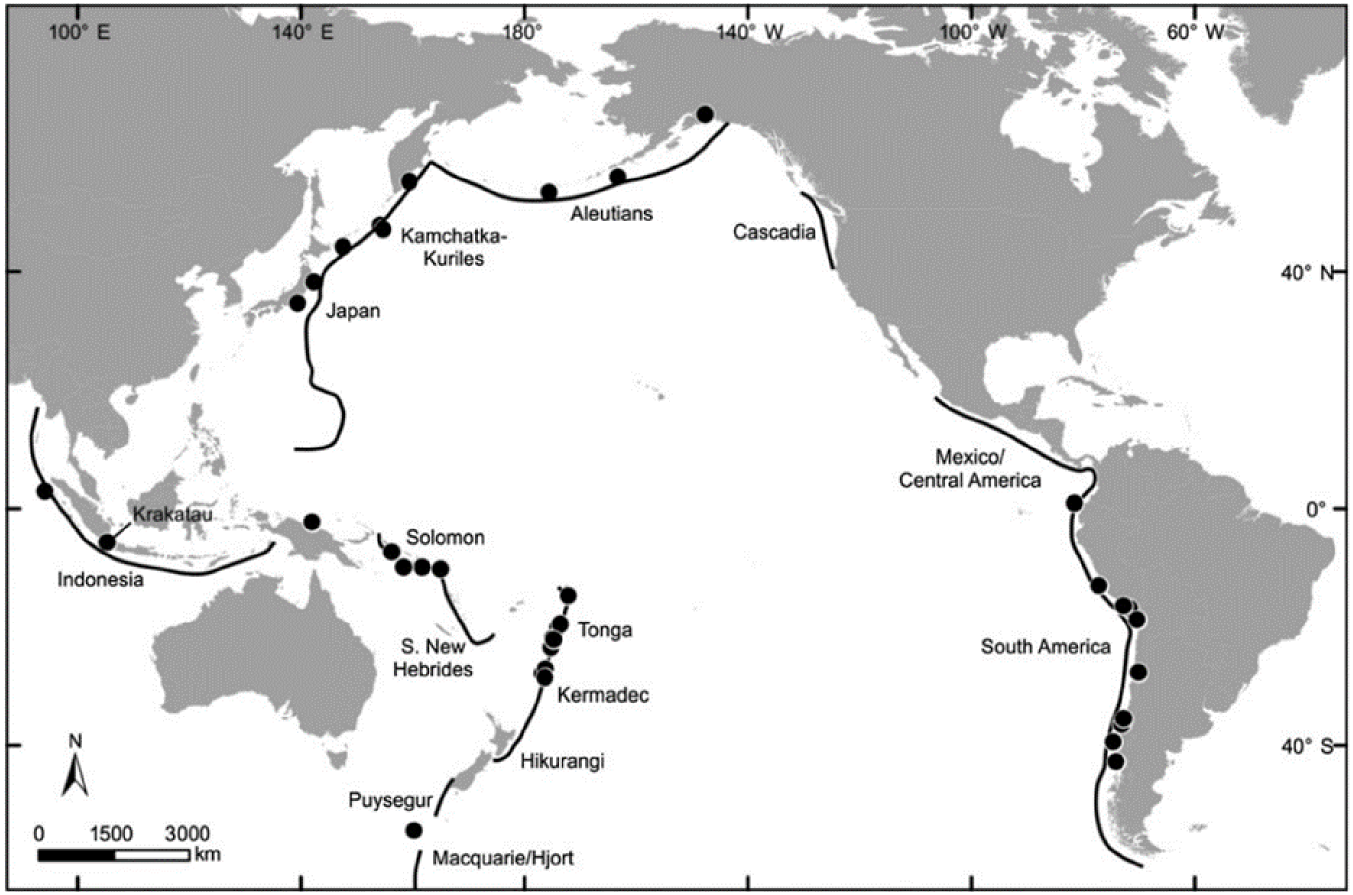
Agenda

- BACKGROUND
- OBJECTIVES & SCOPE
- METHODOLOGY
- CURRENT PROGRESS

Background

Exposure



Source: Downes et al., 2017

Geographical Relevance

- Pacific Ocean (Pacific Rim)
- Tectonic Boundaries (Earthquakes & Volcanoes)
- Astride Pacific and Australia Plate (Puysegur Trench, Southern Alps, Hikurangi Trench)
- 80% of Mw =8.0 Earthquakes on Pacific Rim

Sources

- **Distant**: South America, Central America, Aleutian Islands, Kamchatka Peninsula, Japan, Solomon Islands
- **Regional**: Southern New Hebrides, Southern Kermadec Subduction Zone, Hjort Trench
- **Local**: Hikurangi Trench, Australian Plate Rupture Faults, Wairarapa Fault, Puysegur Trench

Background

Historical Significant Tsunami

Year	Month	Source	Number of Observations	Maximum Intensity
1855	January	Wairarapa (earthquake)	26	X
1868	August	Southern Peru (earthquake)	88	X
1877	May	Northern Chile (earthquake)	51	VIII
1883	August	Krakatoa, Indonesia (volcano)	28	V
1895	July	Pigeon Bay, Canterbury (landslide)	1	VIII
1924	July	Chatham Islands (unknown source)	7	VIII–IX
1931	February	Hawke's Bay (earthquake and landslide)	5	VIII–IX
1947	March	Poverty Bay (tsunami earthquake)	30	X
1960	May	Chile (earthquake)	129	IX
1964	March	Alaska (earthquake)	35	V
2003	August	Charles Sound, Fiordland (earthquake and landslide)	2	VIII
2010	February	Chile (earthquake)	36	IV
2011	March	Japan (earthquake)	96	IV

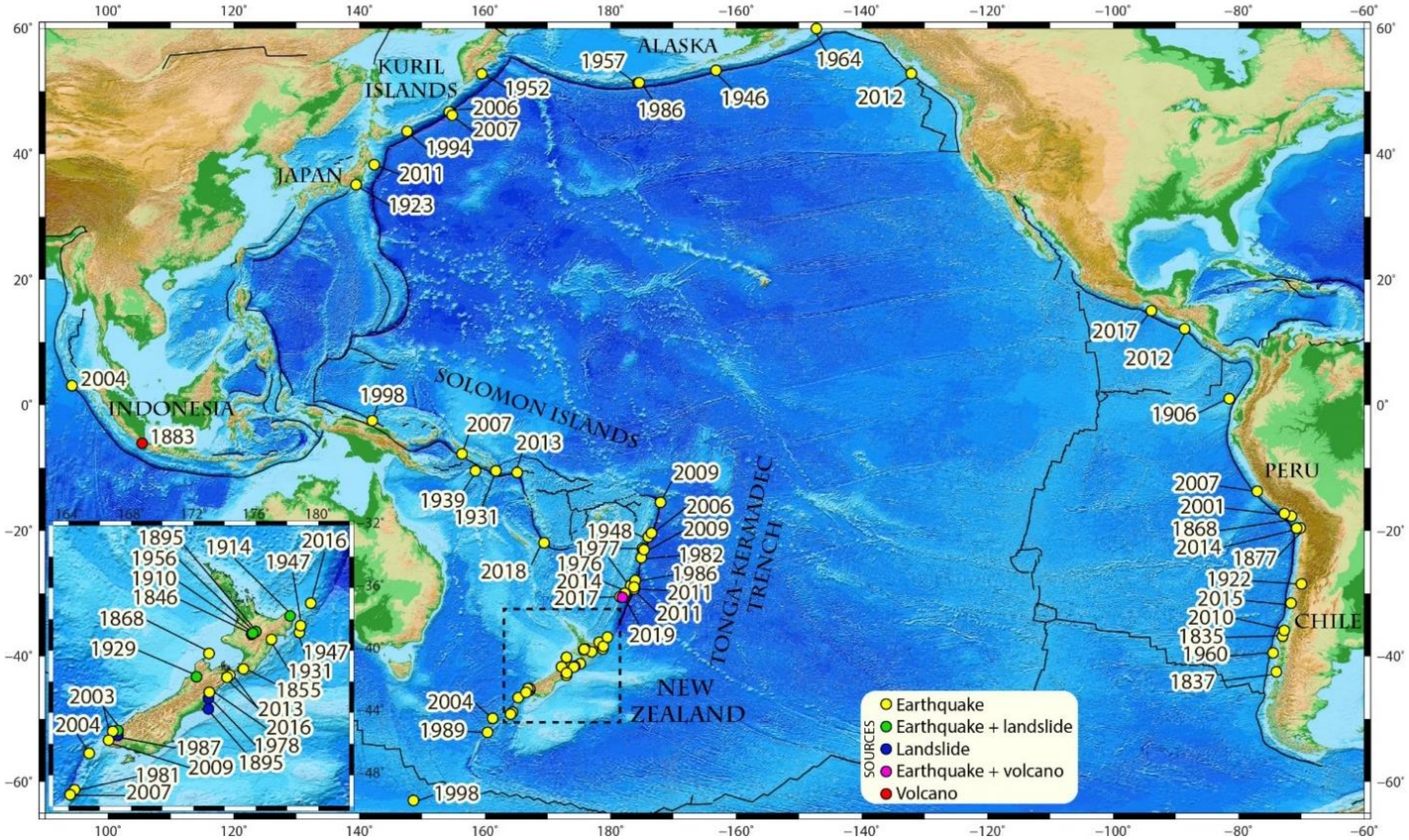
Significance here is defined according to the number of locations where impact was observed and their corresponding intensity. Criteria used for this selection were intensity ≥ 8 or observations ≥ 20.

Source: Downes et al., 2017

Background

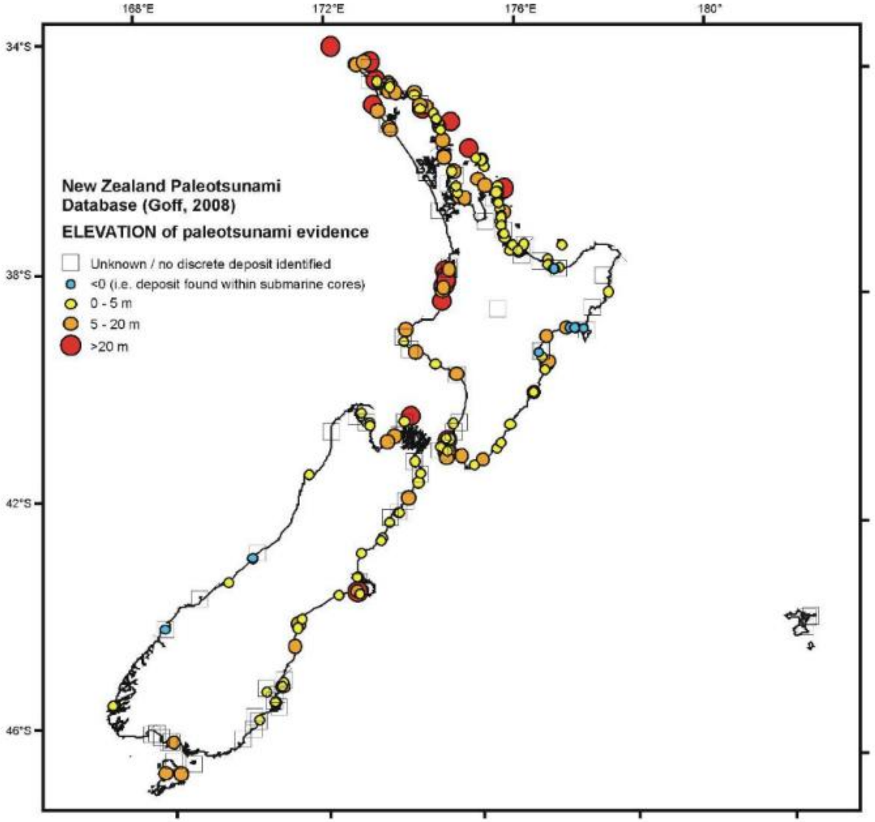
Historical Tsunami

Written History Tsunami Events



Source: Roger, 2020

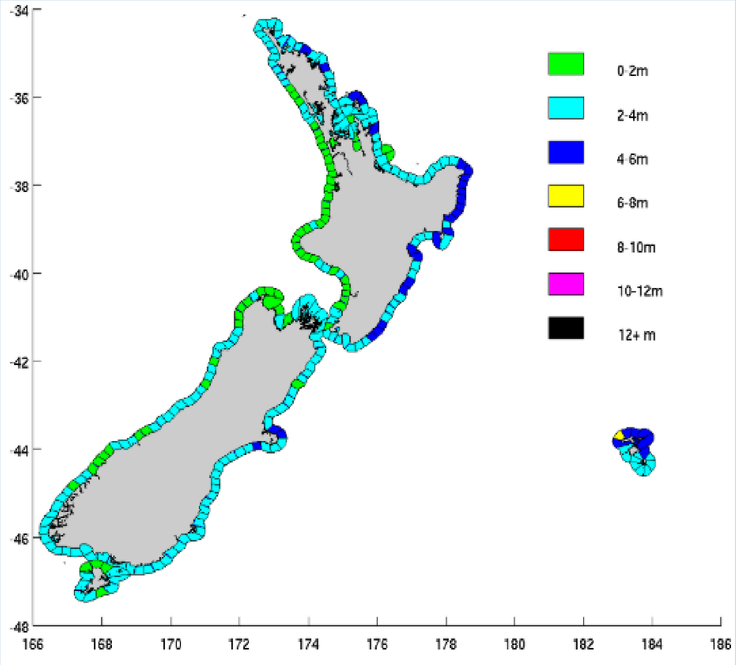
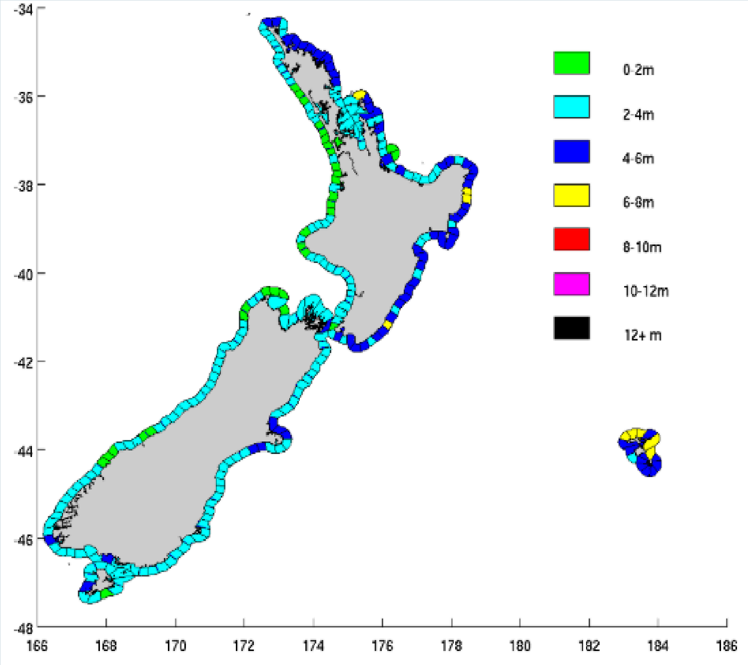
Paleotsunami Events



Source: Goff, 2008

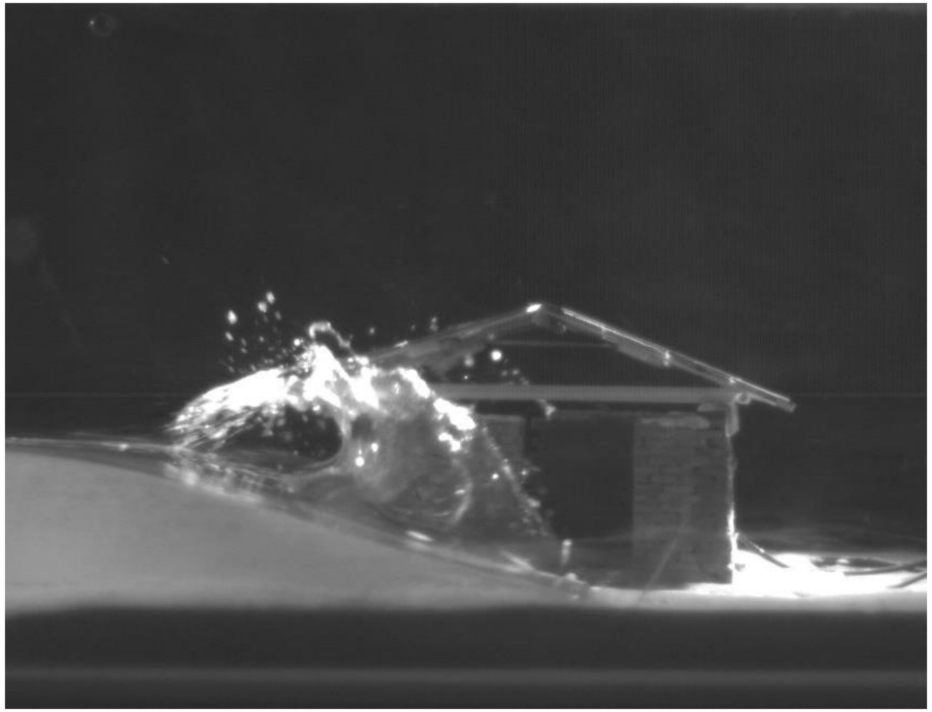
Background

Quantitative Tsunami Wave Height Estimates

Tsunami Height (Maximum Amplitude) in metres at 50th percentile at return period: 100	Tsunami Height (Maximum Amplitude) in metres at 84th percentile at return period: 100
	

Source: Power, 2013

Damage



https://www.flickr.com/photos/cambridgeuniversity-engineering/5533852339

Mechanisms

- Primary impacts
  - Drag, lift and inertia caused by the hydrostatic and hydrodynamic impacts
  - Depend on the shape and characteristics of the structure, the flow depth and the flow characteristics.
- Secondary impacts
  - Result from dragging of objects, debris impacts, contamination, and scour around foundations
  - Water contact detrimental to infrastructure components (e.g., insulation, internal lining, electrical systems)

Damage

Post-Tsunami Survey

- 2004 Indian Ocean, 2010 Chile, and the 2011 Japan Tsunami provide valuable empirical insight into the damage mechanisms and damage to infrastructure assets.
- Local Construction Standards

Source: PARI, 2009

Source: PARI, 2009

		Damage surveyed following past tsunami events
Transport	Bridges	• Scour and erosion of the fill around abutments, wing walls and piers • Minor-moderate damage to bridge superstructure, mostly from debris impacts • Complete washout of the bridge superstructure
	Ports & Harbours	• Damage to wharves from buoyancy and hydrodynamic forces • Scouring of piers and breakwaters • Debris impacts • Damage to vessels
	Rail	• Damage to rail tracks and ballast • Debris deposited on tracks • Damage to railway bridges • Damage to overhead lines • Damage to stations and facilities
	Roads	• Scouring, including peeling of the road surface • Debris Impacts

Impact Assessment

Vulnerability Metrics

- **Damage Matrices**: Qualitative discrete damage approach measuring damage likelihood at various hazard intensities

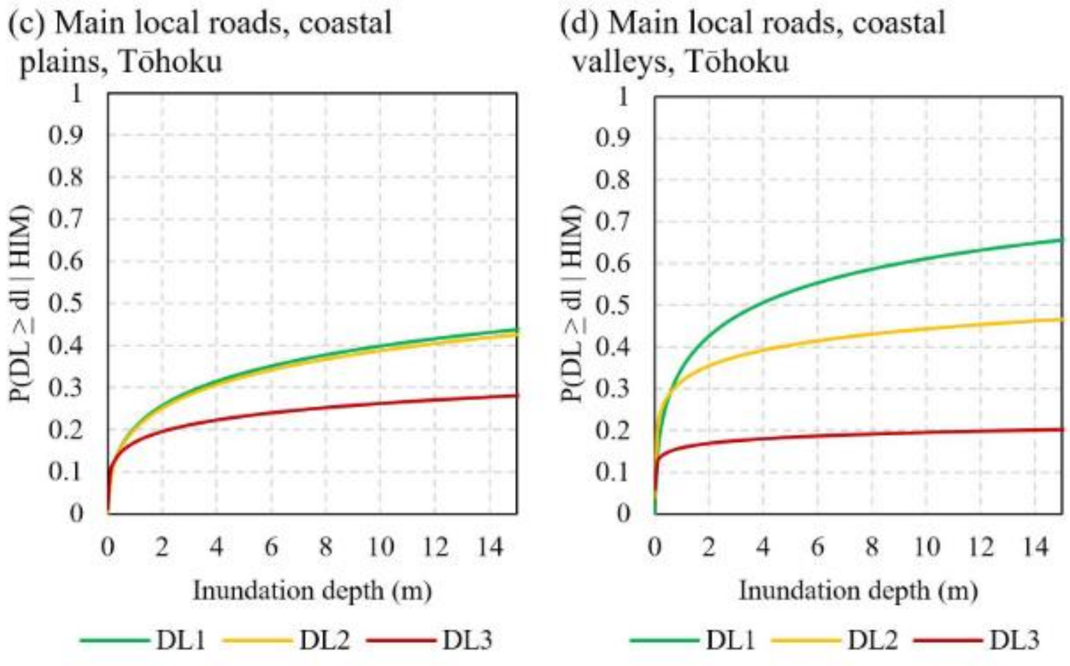
Infrastructural Asset	Flow Depth < 0.5m		Flow Depth 0.5m – 2m		Flow Depth >2m		Information Quality
	Probability of Damage	Damage Type	Probability of Damage	Damage Type	Probability of Damage	Damage Type	
Transportation Roads							
Pavement	Low	Silt and light debris coverage, ponding	Medium	Debris & sediment coverage, scour of weak base materials, removal of signage and markings, ponding	Medium-High	Debris strikes , scour of base materials, lifting of carriage-way, removal of barriers and signage, cracking of pavement, liquefaction of base materials, ponding, debris and sediment coverage	High
Bridges	Negligible-Low	Superficial debris strikes	Medium	Some bank erosion, superficial debris strikes , sediment deposition, scour of footings, corrosion, washout of light timber structures	High	Debris and sediment deposition, erosion of adjoining banks, loss of signage and markings, side barriers bent or sheared, debris strikes, scour of footings, aggradation of waterway, widening of waterway separation of deck from footings, lateral distortion of super structure, separation of girders, washout of superstructure, corrosion, loss of utilities across bridge	High

Source: Williams (2016)

Impact Assessment

Vulnerability Metrics

- **Fragility Functions**: Assesses the probability of incurring a level of damage based on an imposed hazard intensity. Collection of cumulative distribution functions, each portraying a certain level of damage (damage state).



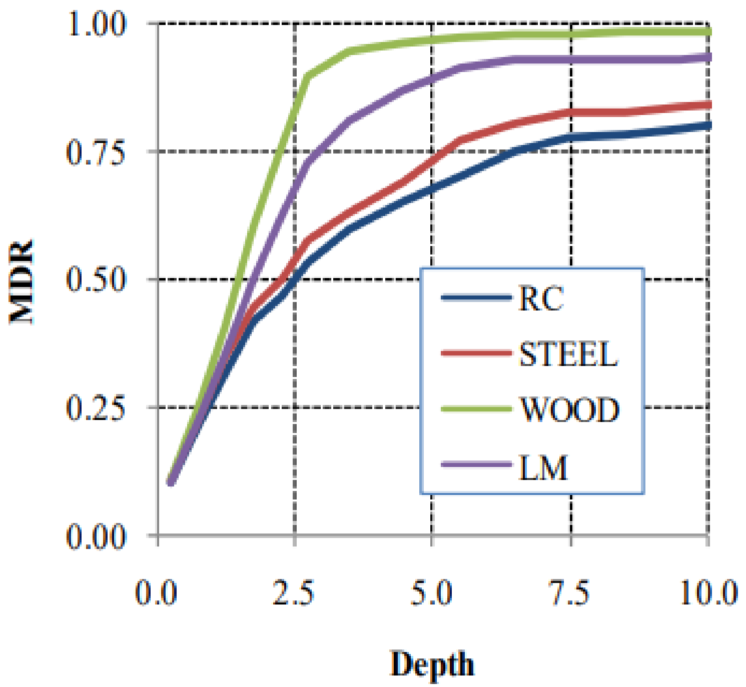
Source: Williams et al., 2020

Impact Assessment

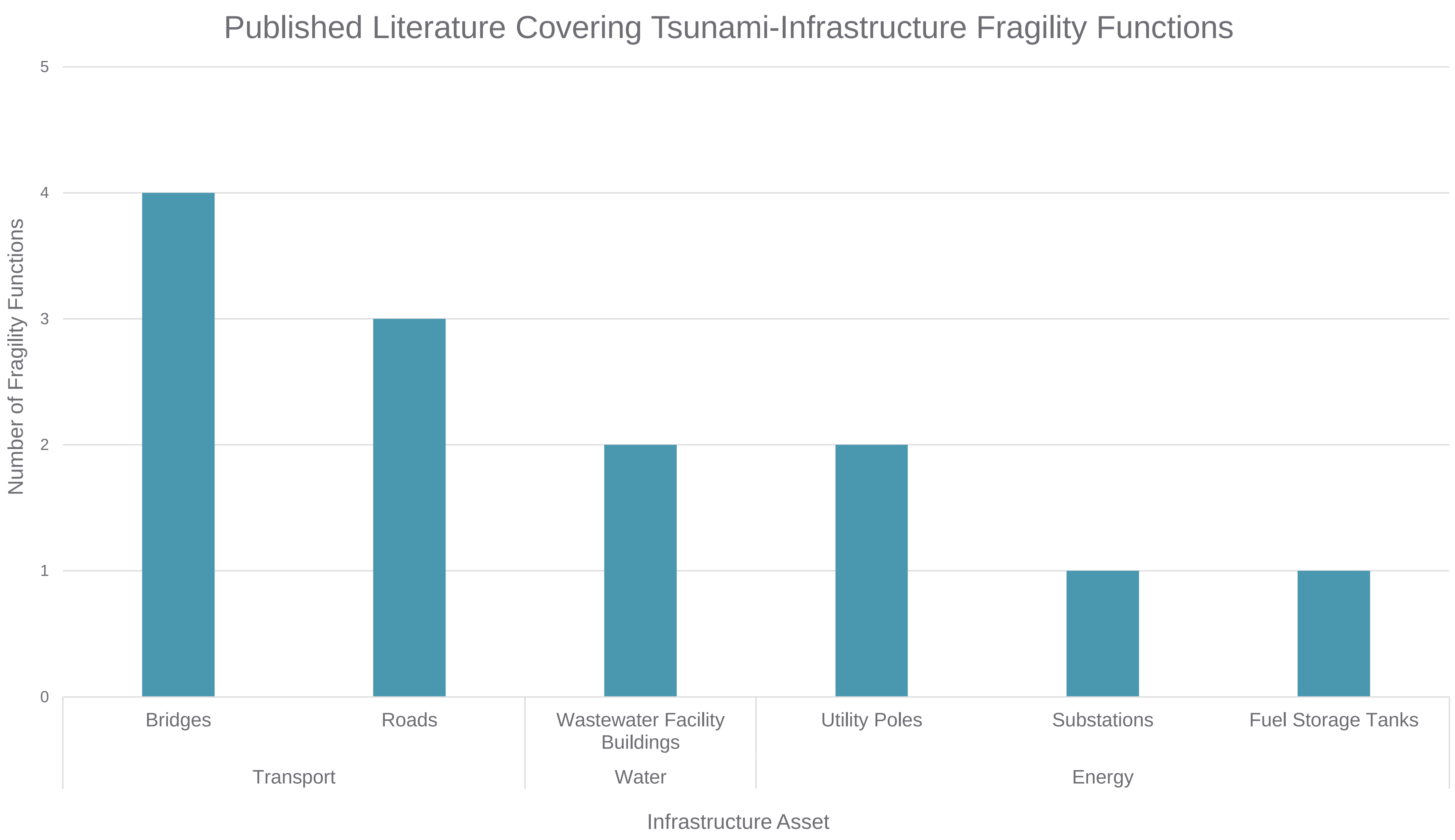
Vulnerability Metrics

- **Vulnerability Functions**: Relates the hazard intensity measure directly to the expected financial loss (proportional to degree of damage inflicted). Depicted as single cumulative distribution function.

Vulnerability Function for Building Material



Source: Masuda et al., 2012


Published Literature Covering Tsunami-Infrastructure Fragility Functions
Number of Fragility Functions
0
1
2
3
4
5
Bridges
Roads
Wastewater Facility Buildings
Utility Poles
Substations
Fuel Storage Tanks
Transport
Water
Energy
Infrastructure Asset

Infrastructure Asset	Attributes	Tsunami Hazard Intensity Measure (HIM)	Data Source	Tsunami Event	Reference
Transport					
Bridges	Construction type, 3 damage states	Inundation Depth (above the base of the deck)	Post-event damage survey	Indian Ocean, 2004	(Horspool & Fraser, 2016)
	3 damage states	Inundation Depth	Post-event damage survey	Tohoku, 2011	(Eguchi et al. 2013)
	3 damage states	Inundation Depth (above the base of the deck)	Damage Simulations	Tohoku, 2011	(Akiyama et al. 2013)
	6 damage states	Velocity, Inundation Depth, Momentum Flux, Moment of Momentum Flux	Damage Simulations	-	(Qeshta et al., 2021)
Roads	3 damage states	Inundation Depth	Post-event damage survey	Tohoku, 2011	(Horspool & Fraser, 2016)
	3 damage states	Inundation Depth, Distance from the coastline, Distance from landward inundation extent	Post-event damage survey	Multiple	(Williams et al., 2020a)
	3 damage states	Inundation Depth	Post-event damage survey	Palu, 2018	(Williams et al., 2020b)
Water					
Wastewater Facility Buildings	1 damage state	Inundation Depth	Post-event damage survey	Tohoku, 2011	(Horspool & Fraser, 2016)
	2 damage states	Inundation Depth	Post-event damage survey	Tohoku, 2011	(Eguchi et al. 2013)
Energy					
Utility Poles	Construction type, 2 damage states	Inundation Depth (as a ratio to pole height)	Expert judgment	Multiple	(Horspool & Fraser, 2016)
	3 damage states	Inundation Depth	Post-event damage survey	Palu, 2018	(Williams et al., 2020b)
Substations	Indoor/outdoor components, 3 damage states	Inundation Depth	Expert judgment	Multiple	(Horspool & Fraser, 2016)
Fuel Storage Tanks	Probability of damage	Inundation Depth	Post-event damage survey	Tohoku, 2011	(Hatayama, 2014)

Fragility Function Gaps

- **Post-Tsunami Surveys**
  - Sensitive to infrastructure constructions standards
  - Sensitive to local topographic/bathymetric and tsunami characteristics

- **Hazard Intensity Measures (HIMs)**
  - Common use of Inundation Depth due to easy identification during survey
  - Forced based HIMs (e.g., momentum flux) have more significant contribution to damage
  - HIMs used in tsunami-building fragility functions:
    - *Inundation Depth*
    - *Peak Velocity*
    - *Froude Number*
    - *Momentum Flux*
    - *Quasi-Steady State Tsunami Force*

- **Infrastructure Components**
  - Few infrastructure components represented in fragility functions
    - *Transit — Roads, railways, and bridges*
    - *Power & Communications — Transmission facilities, electric lines, fiber optics*
    - *Subterranean — Pipelines, sewer, waterlines*

Literature Review Recap

- New Zealand is in an exposed location and significant tsunami are predicted to occur within a 100-yr return period
- Infrastructure can become severely damaged from primary and secondary tsunami effects
- The current coverage of tsunami impact assessments applicable to New Zealand are very limited
- Current physical and numerical modelling is limited for tsunami impacts and currents on a wide range of infrastructure components.

Objective

Understand the fragility of New Zealand's coastal lifeline infrastructure to tsunami attack, and hence provide component level mitigation measures to better protect our infrastructure assets

1. **Geospatial Identification of Vulnerable Components**
2. **Development of Component-level Fragility Functions**
3. **Design of Localised Mitigation Measures**

Task 1: Geospatial Identification of Vulnerable Infrastructure Components

Steps:

Identify relevant geospatial databases of infrastructure assets (consider transportation, water, telecommunications and energy)

Develop inundation models: 1) Bathtub inundation model, 2) Runup inundation model

Using QGIS and Geopandas coding methods identify the most vulnerable infrastructure components in the most exposed locations.

Task 2: Development of Component-level Fragility Functions

Steps:

Perform physical experiments and numerical modelling to determine damage on components when subject to tsunami impacts, extreme currents and secondary effects such as debris impacts.

Numerical modelling will complement the physical modelling to better understand phenomena that is harder to achieve in physical modelling due to scale effects.

Generate new component-level fragility functions that can be imported into different risk modelling packages.

Task 3: Design of Localised Mitigation Measures

Steps:

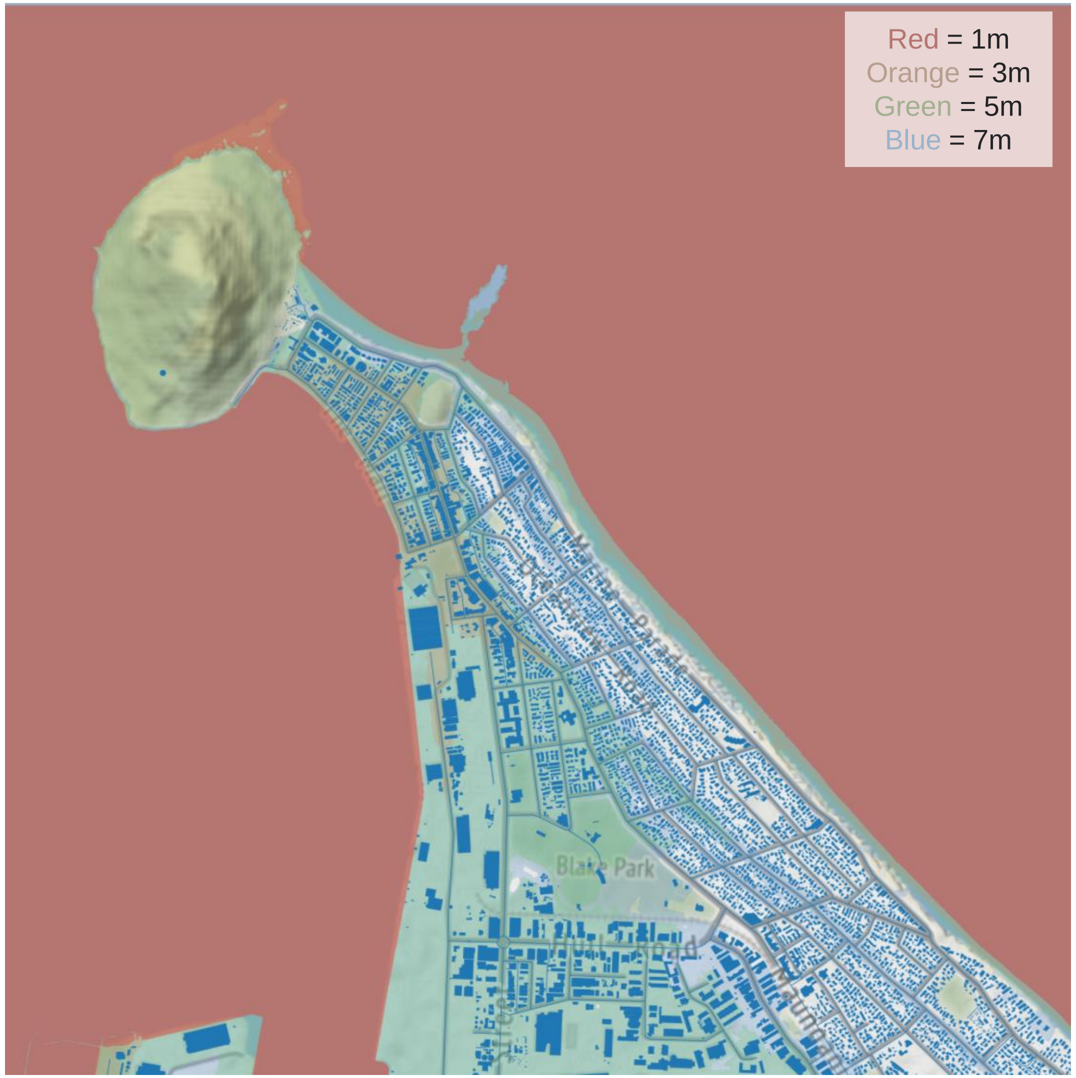
Explore possible mitigation measures (predominantly at the component level) to protect infrastructure assets from tsunami attack more effectively.

Tested both physically and numerically to determine whether improvements have been made.

Produce design recommendations at the component level.

Current Progress

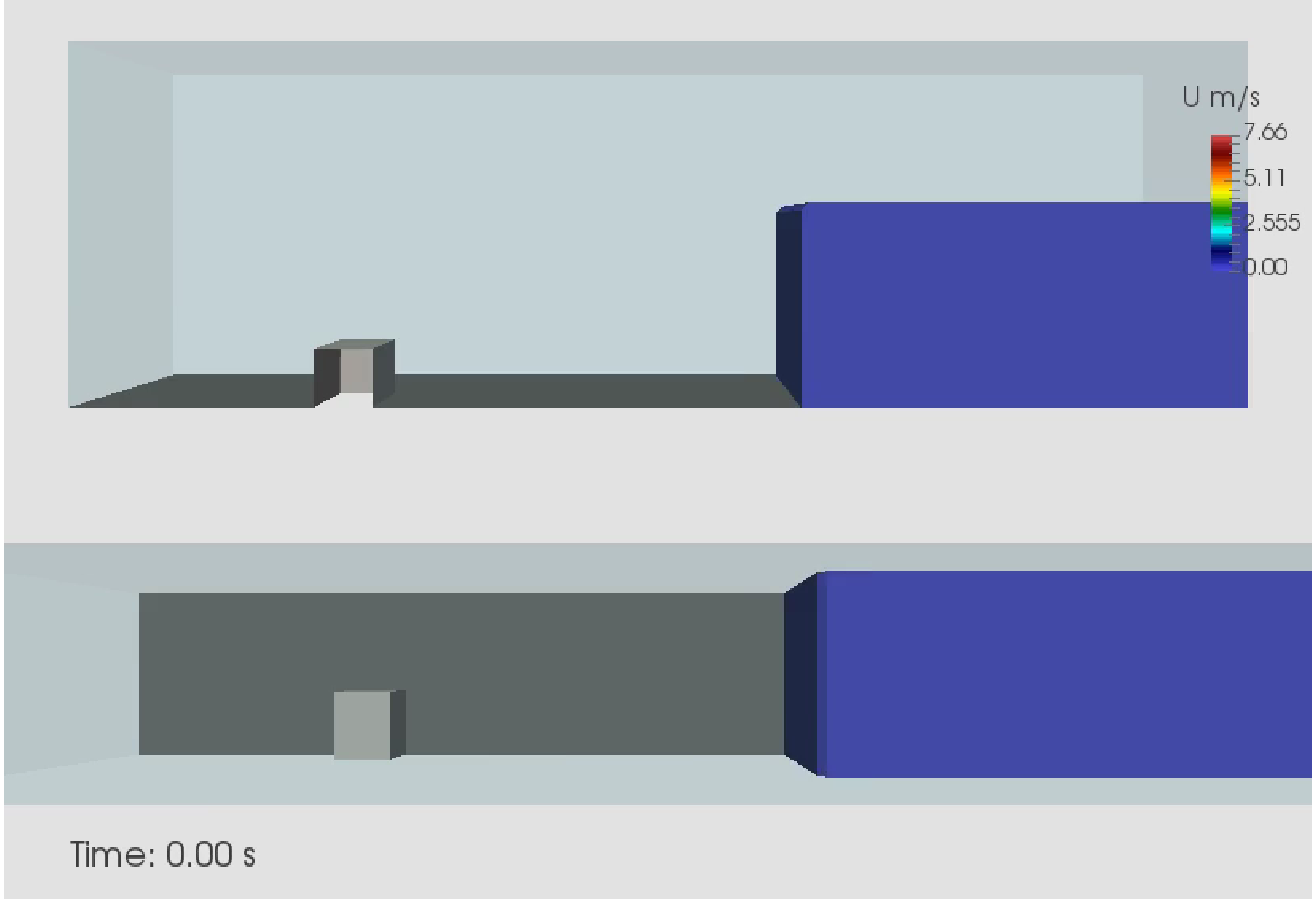
Geospatial Identification of Vulnerable Infrastructure Components

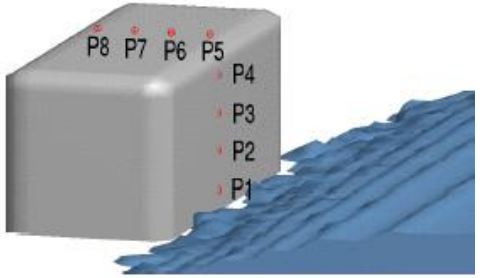


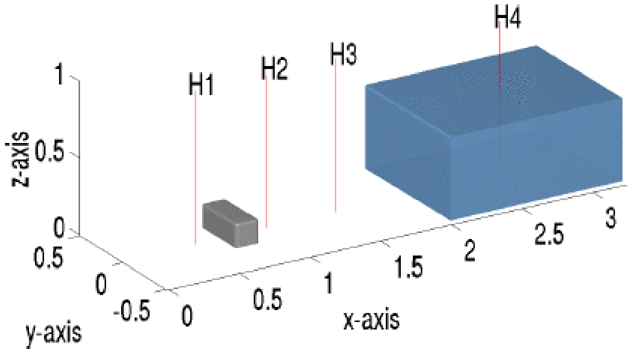
Bathtub	Number of Buildings	Total Length of Roads (km)
1	*0*	*0*
2	*129*	*2.23*
3	*390*	*7.52*
4	*1006*	*19.02*
5	*1456*	*25.65*
6	*1812*	*29.96*
7	*2333*	*35.01*
8	*3590*	*45.39*

Current Progress

Numerical Model Validation

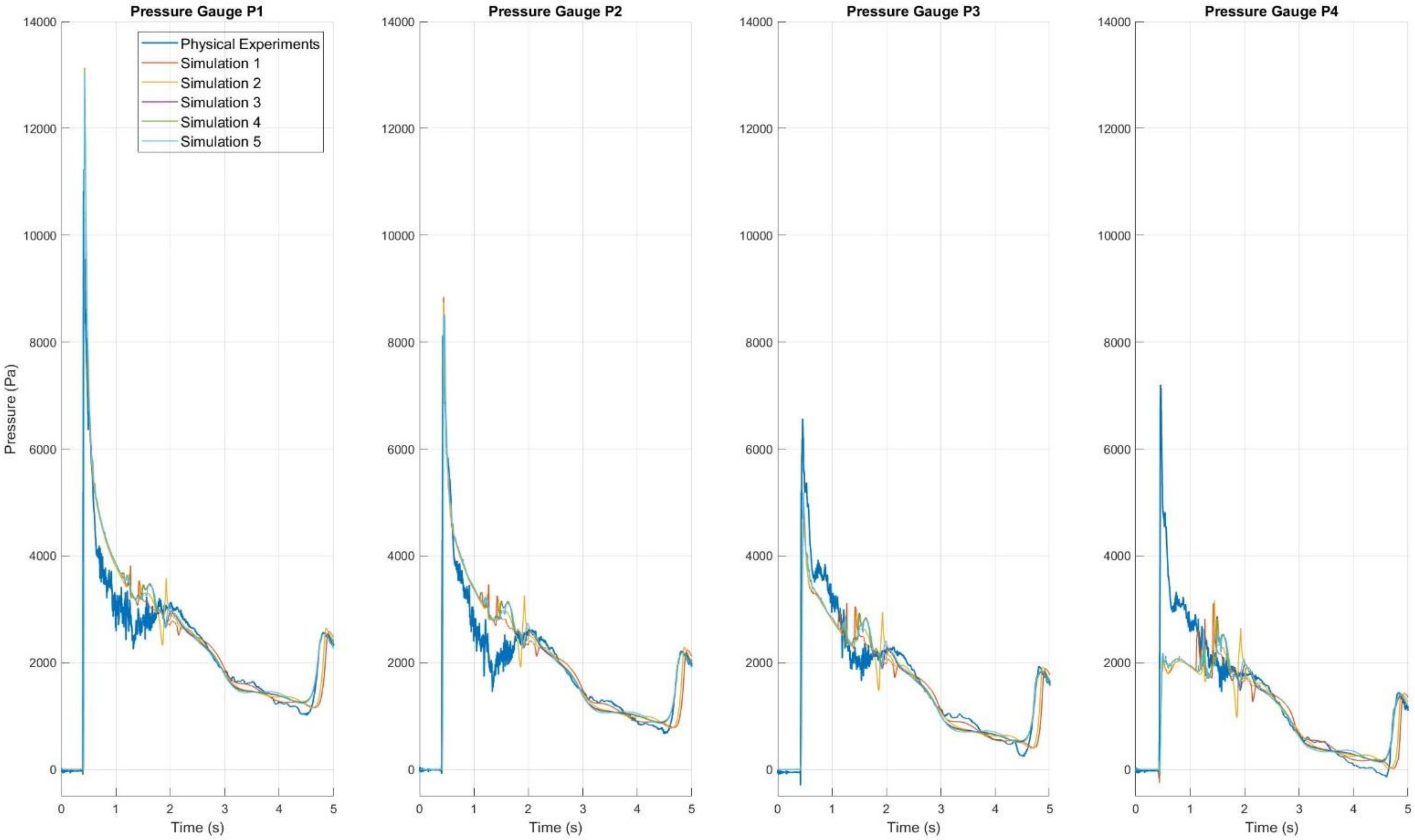






Current Progress

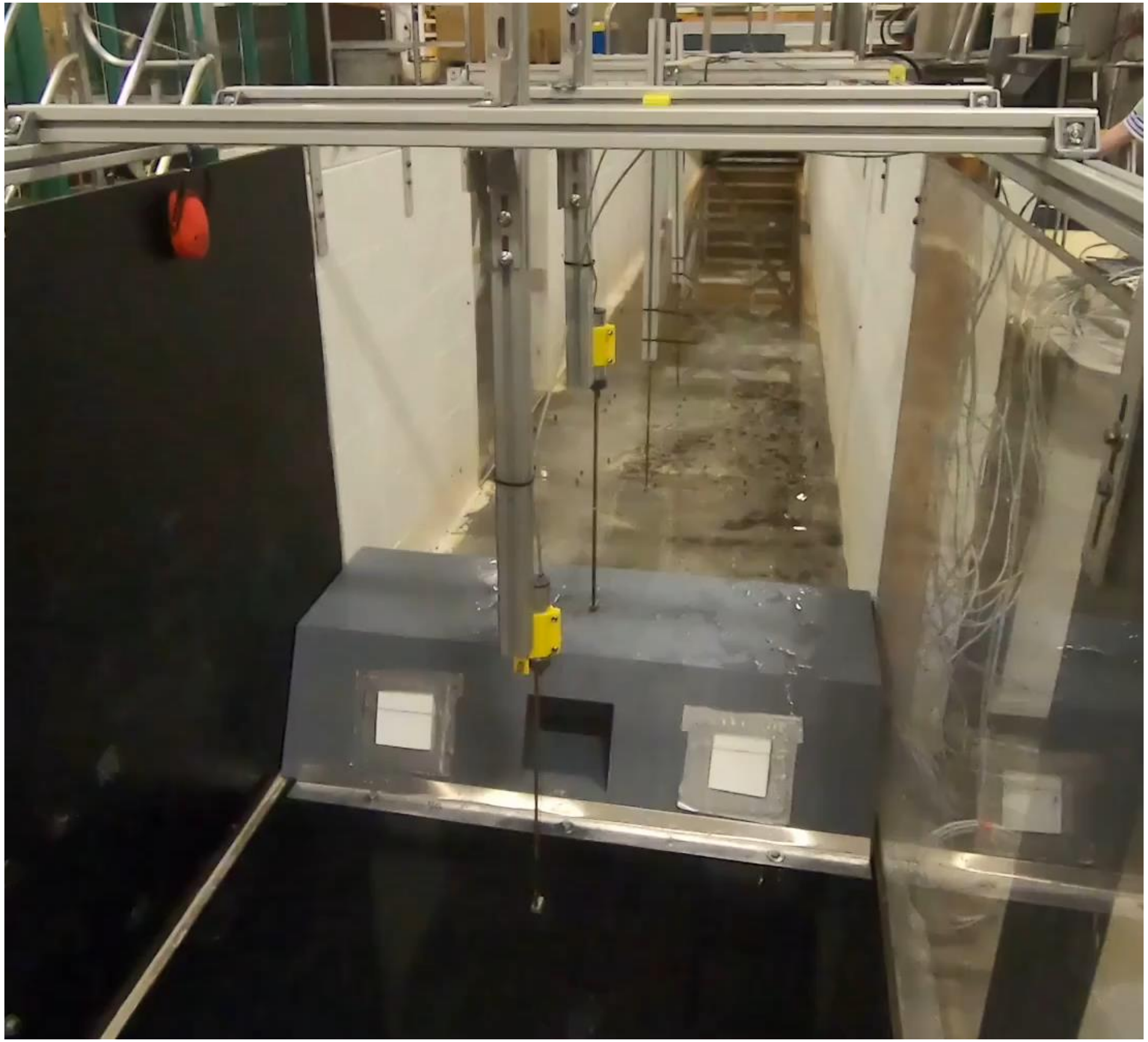
Numerical Model Validation



Current Progress

Numerical Model Validation

	Simulation	Cell Size	Courant Number	Mesh Size	Phase Shift of Time Series
Pressure Gauges	*5*	*1 cm x 1 cm*	*0.25*	*Symmetrical*	*-0.016*
Surface Elevation Gauges	*3*	*2 cm x 2 cm*	*0.25*	*Full*	*0*
Overall	*1*	*2 cm x 2 cm*	*0.15*	*Symmetrical*	*-0.016*



Physical Modelling

Culverts

References

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THANK YOU

QUESTIONS?