Experimental study of connection forces in bridges during tsunami inundation

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Outline

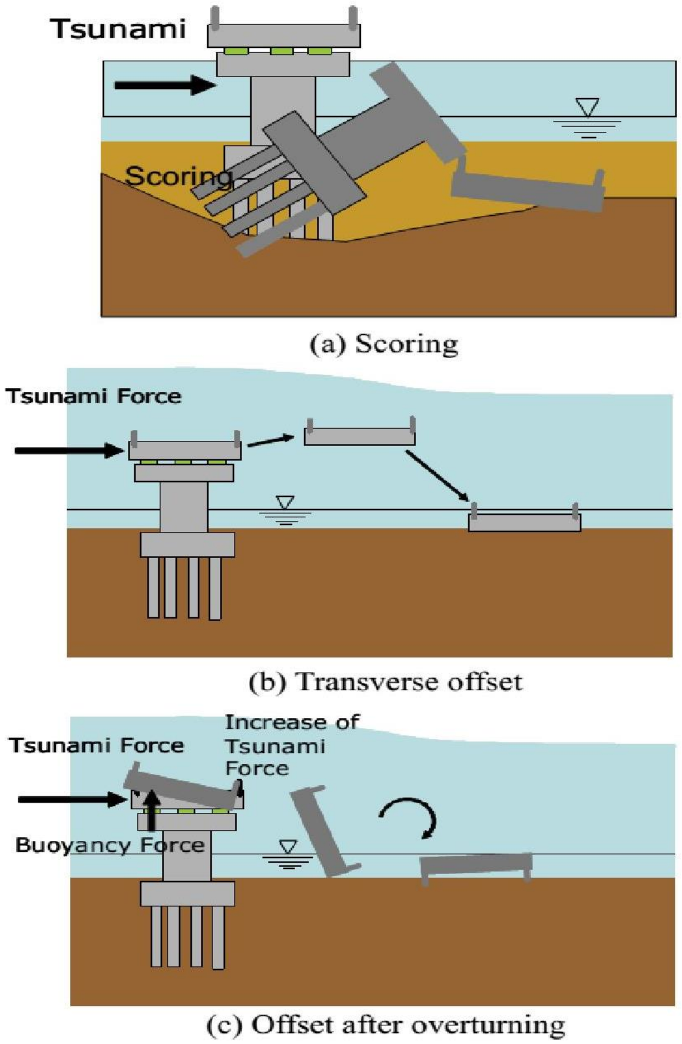
- Recent tsunamis and bridge failures
- Challenges in Fluid-Structure-Interaction (FSI)
- Large-scale experiments conducted in 100 m Wave Flume at Oregon State University
- Preliminary Results
- Conclusions

Recent Tsunamis and Bridge Failures

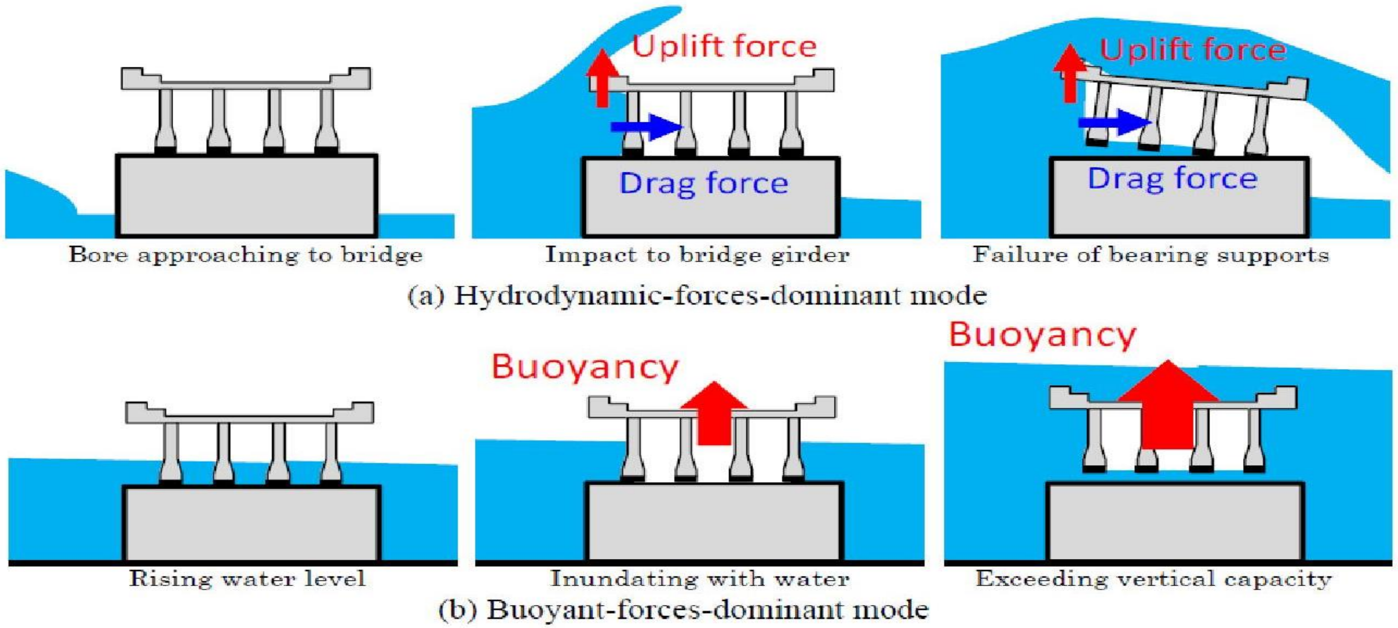
- 2004 Indian Ocean Earthquake and Tsunami
- 2010 Chile Earthquake and Tsunami
- 2011 Tohoku Earthquake and Tsunami

PHOTO OBTAINED FROM MARK YASHINSKI

Typical Failure Modes in Bridges due to Tsunami Inundation



- Scouring
- Transverse offset
- Overturning

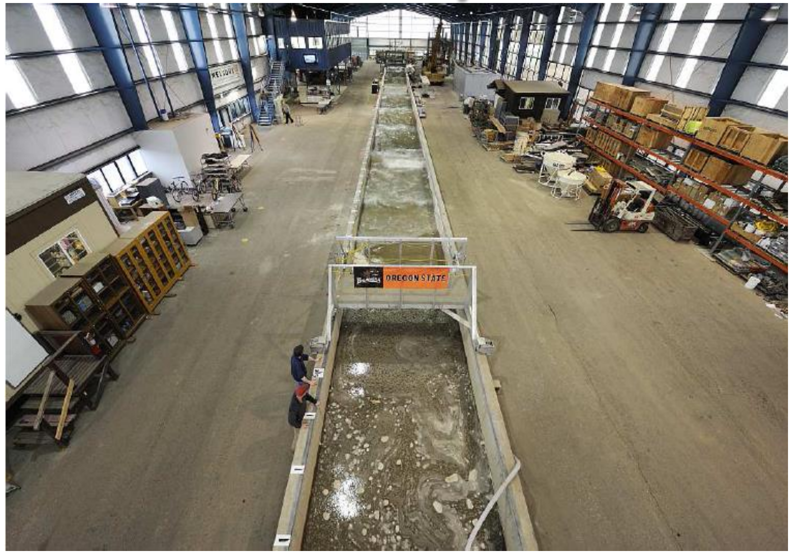


Challenging Issues

1. It is a multi-disciplinary topic. Cooperation between ocean engineers, hydraulic engineers and structural engineers is required. Multi-physics simulations are necessary.
2. Consistency does not exist in the way different researchers around the world simulate tsunami waves (solitary wave, unbroken, broken, bore type…).
3. Field of fluid-structure interaction is in its infancy and advanced FSI analyses require large computational resources. Realistic numerical modelling of the impact of tsunami waves on bridges is very challenging because it requires a multi-phase flow in combination with FSI. Only a few software tools have these capabilities, but none have been validated in experiments at reasonable scale.
4. Prescriptive design equations have been proposed for bridges based on empirical evidence, numerical analyses and small-scale experiments in flumes ignoring FSI (structures assumed to be rigid bodies). Individual connection forces not available.

Objective of Experiments at Oregon State University

- Construct ‘large-scale’ single-span bridge in 100 m wave flume, instrument flume and bridge, run family of solitary waves, record bridge response.
- Identify differences in the tsunami forces caused by broken and unbroken waves
- Understand the role of flexibility of the
  (a) bridge connections (bearings and shear keys) &
  (b) bridge substructure (columns and pier walls)
  on tsunami forces induced in these components.
- Determine not only total horizontal and vertical forces but also the distribution of these forces to connections and substructures



Objective of Experiments at Oregon State University

- Determine tsunami forces for different types of bridges (I-girder with cross-frames, I-girder with solid diaphragms, I-girder with soffit slab). Understand the role of air entrapment

- Examine the efficiency of venting in reducing the vertical (uplift) tsunami forces in bridges

- Investigate 3D flow effects by comparing performance of a straight bridge normal to flow to that of a skew bridge at 45^0 to the flow

- Validate software tools for simulating FSI for structures with significant inertia forces and displacements

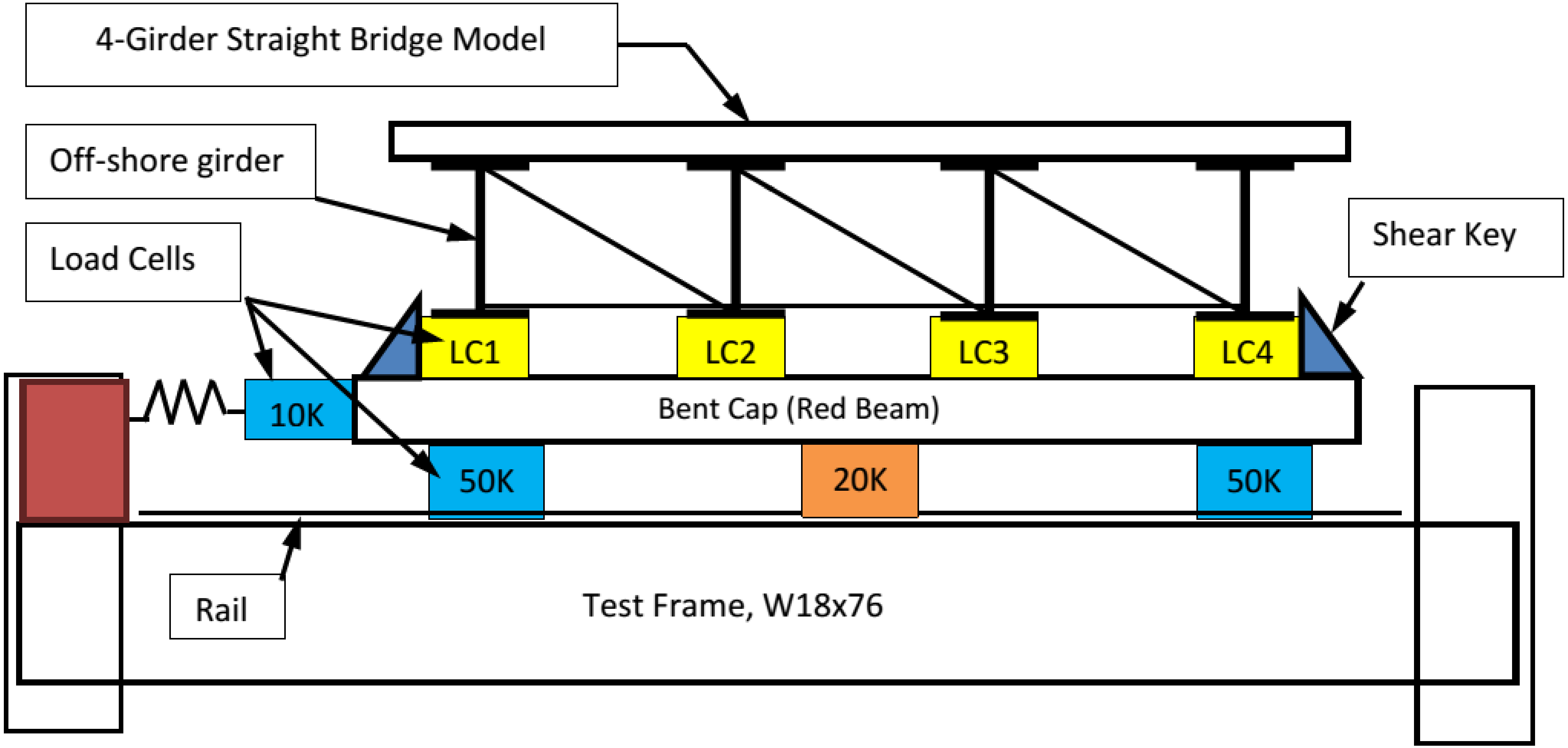
Bridge specimen

- Bridge and rest of components designed according to AASHTO LRFD
- Assumed to be located on the west coast in a Seismic Zone 3

- I-girder composite bridge with four steel girders, cross-frames, RC deck and steel shear keys
- Plain elastomeric bearing pads designed for thermal expansion

Test Cases: Straight Bridge

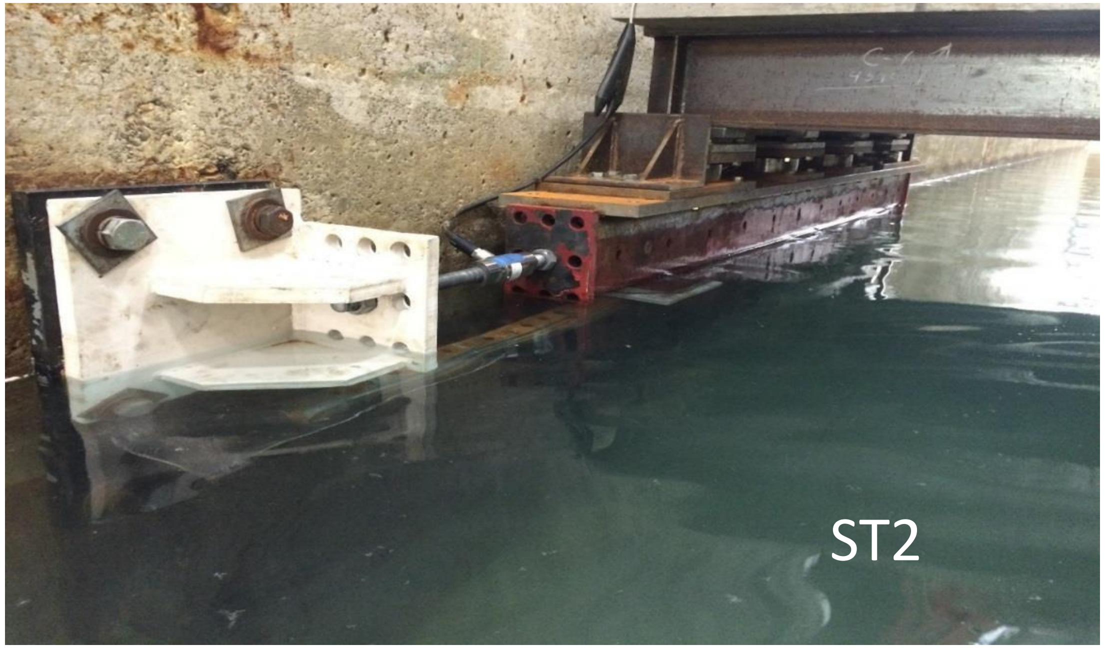
STRAIGHT	Substructure Stiffness			Connection Type		Shear Keys	Diaphragm	Soffit	Vent
	Rigid	Medium	Soft	Elastomeric Bearing	Steel Spacer				
ST1	•				•	•			
ST2	•			•		•			
ST3		•		•		•			
ST4			•	•		•			
ST5	•			•		•	•		
ST6	•			•		•	•	•	
ST7	•			•		•	•		A
ST8	•			•		•			A
ST9	•			•		•	•		B
ST10	•			•		•			B
ST11	•			•					

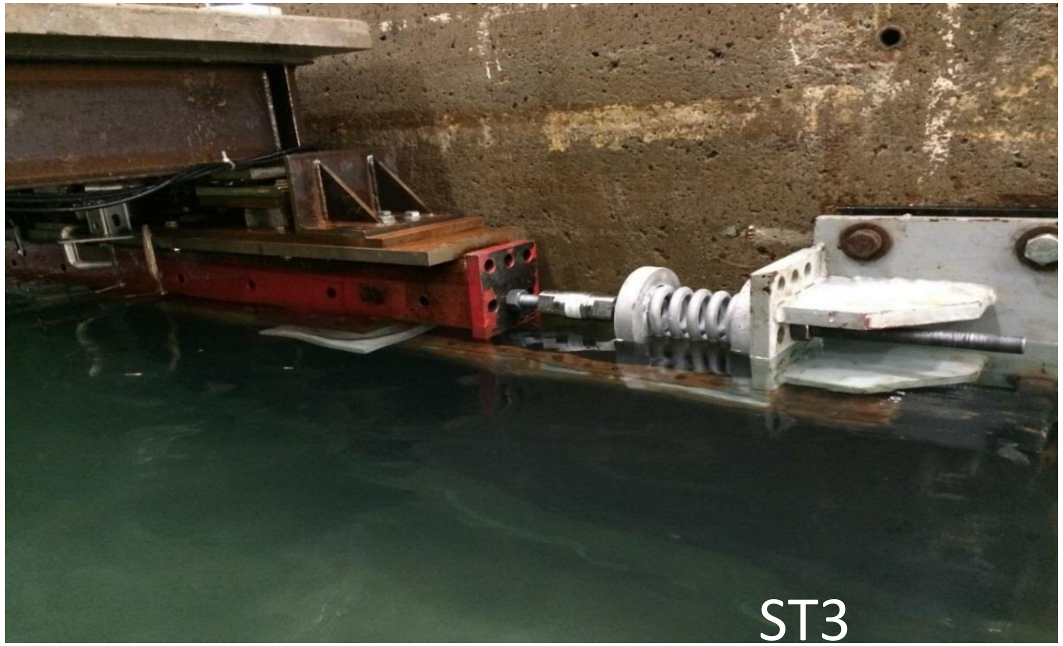


Load Cell Configuration Straight Bridge:

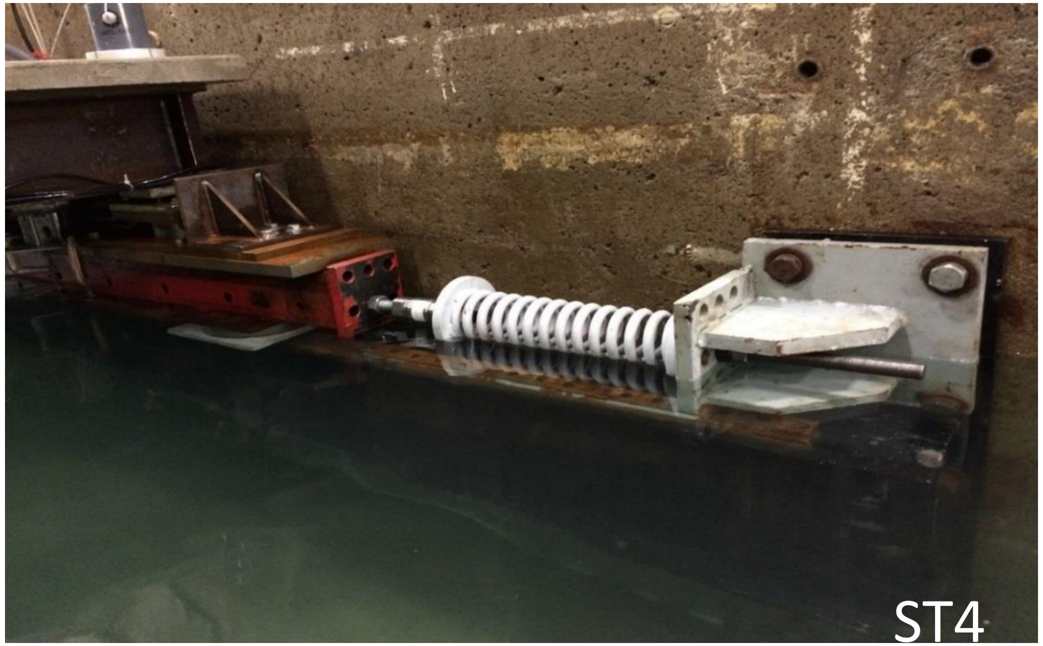

ST1

ST1

ST2

ST2



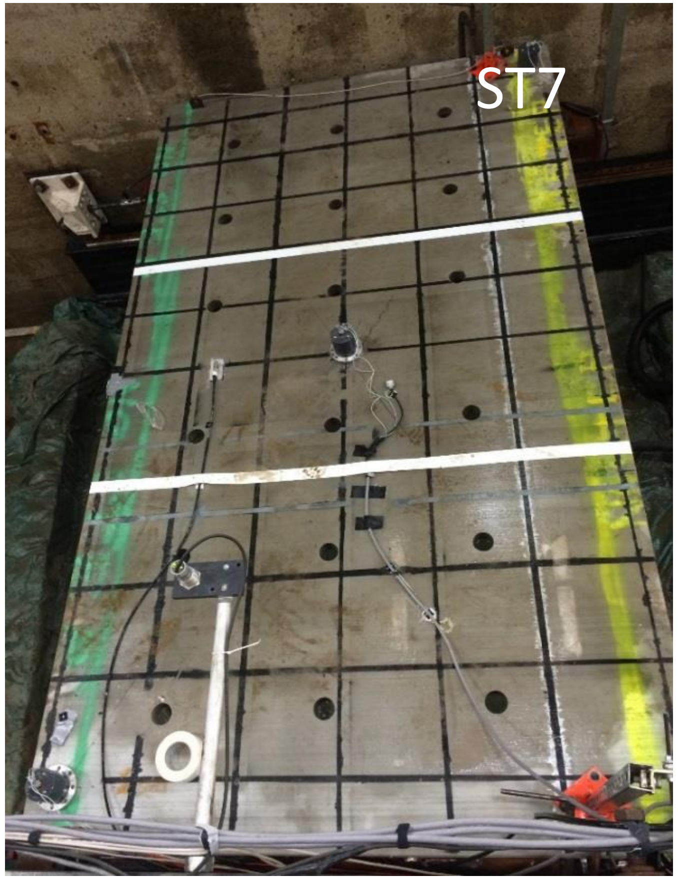
ST3



ST4

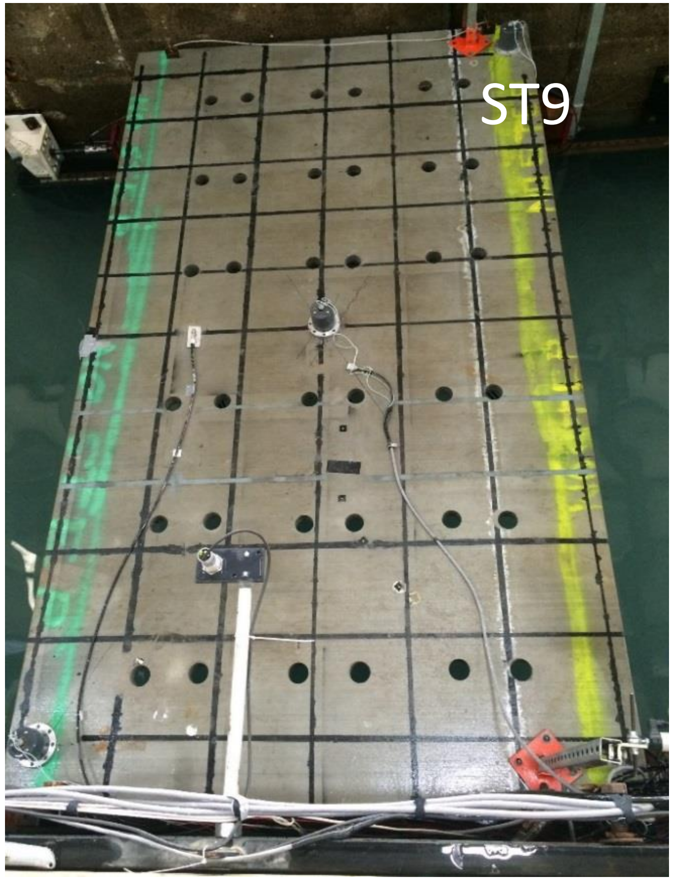
ST5

ST6



A. Deck with 18 x 2.5in diameter holes

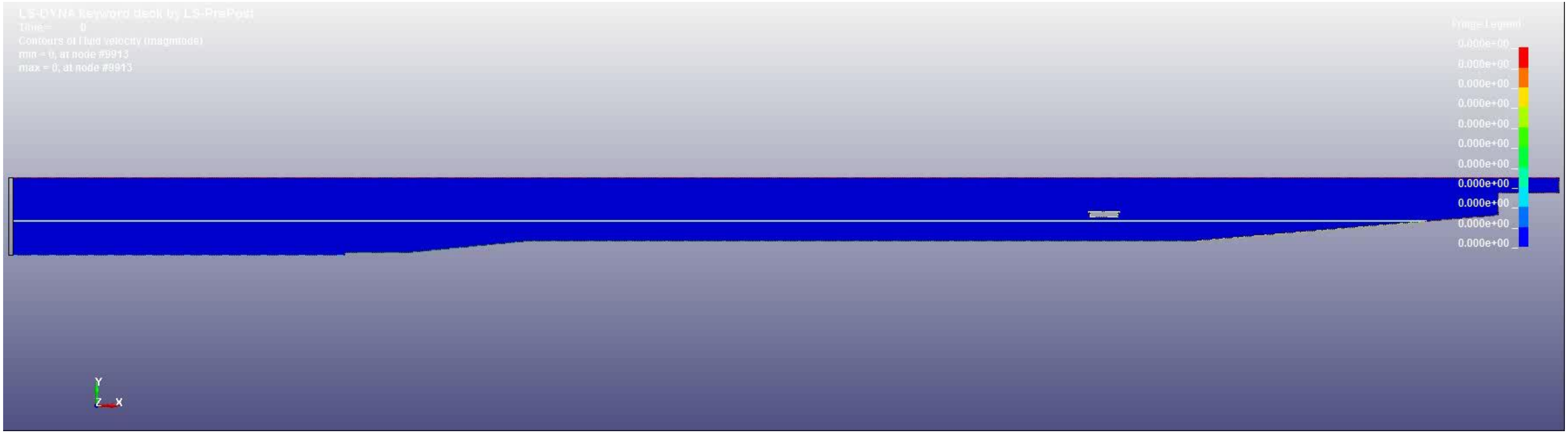
Vented area = 0.85% of total deck area



B. Deck with 36 x 2.5in diameter holes

Vented area = 1.7% of total deck area

Bathymetry



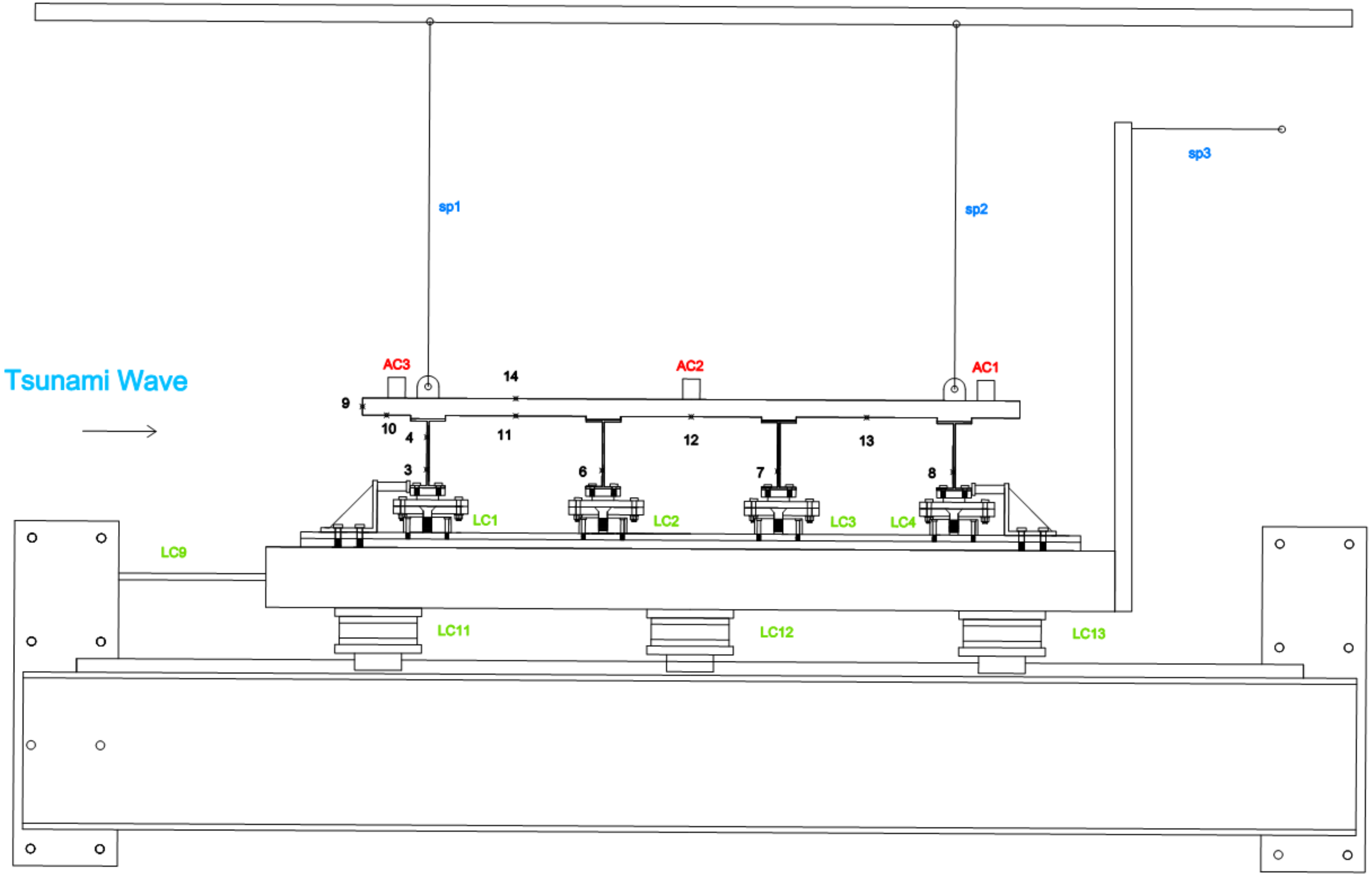
Preliminary CFD analyses of the whole flume were conducted in LS-DYNA in order to determine:

- The appropriate combination of slopes that will permit to test both unbroken and broken waves
- The best location of the bridge along the flume and its elevation that will allow for maximum inundation
- The required wave matrix that will be able to impact the bridge

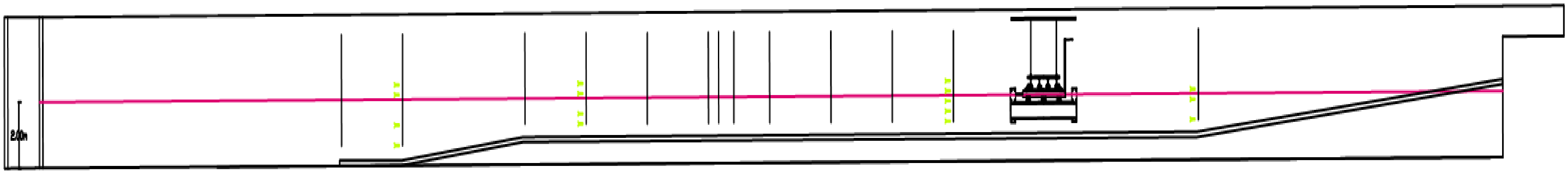
Wave Matrix and Bridge Instrumentation

Water Depth (m)	Wave height (m)
1.90	0.46 - 1.30
2.00	0.36 - 1.40

- ✓ 12 pressure gages on girders/deck
- ✓ 24 strain gages on cross-frames
- ✓ 16 load cells girders &bent caps
- ✓ 3 biaxial accelerometers on deck
- ✓ 4 string pots and 2 LWGs



Flume Instrumentation

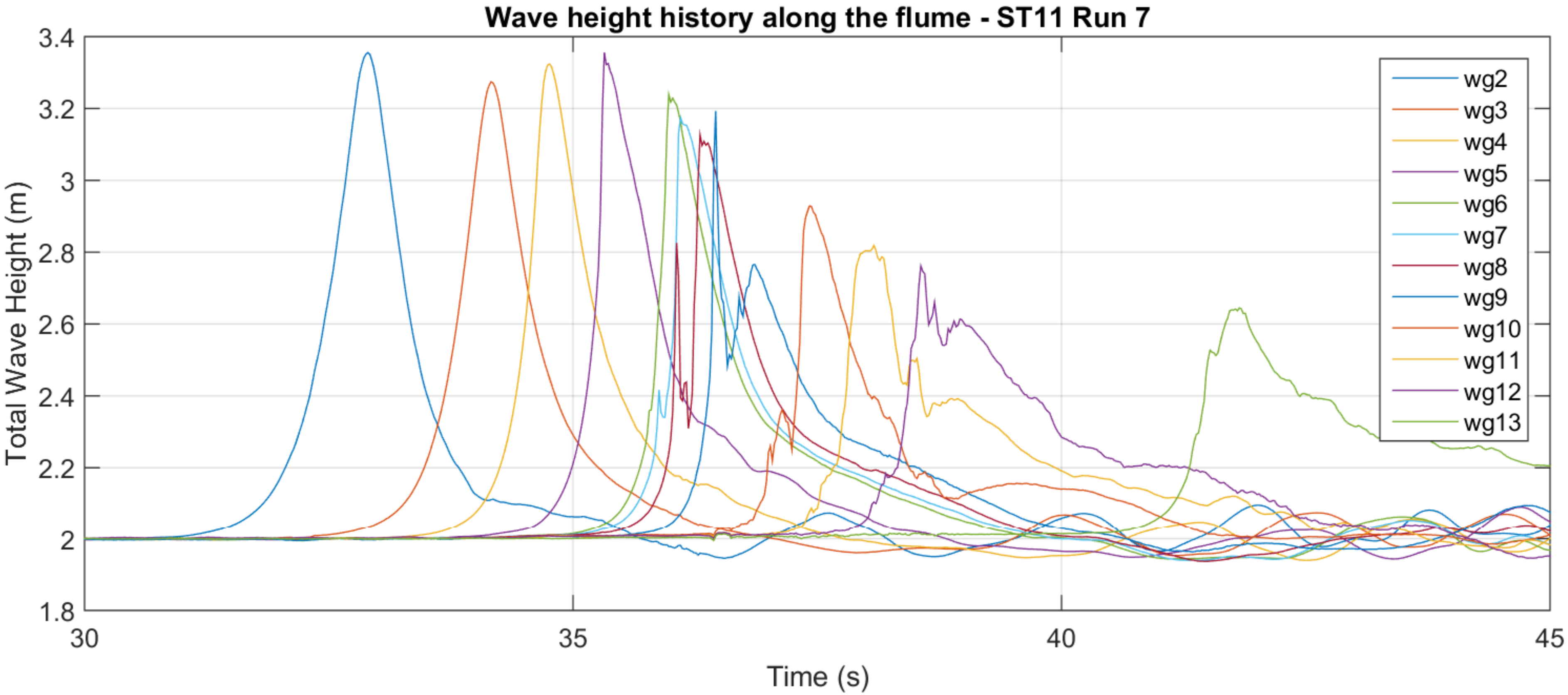


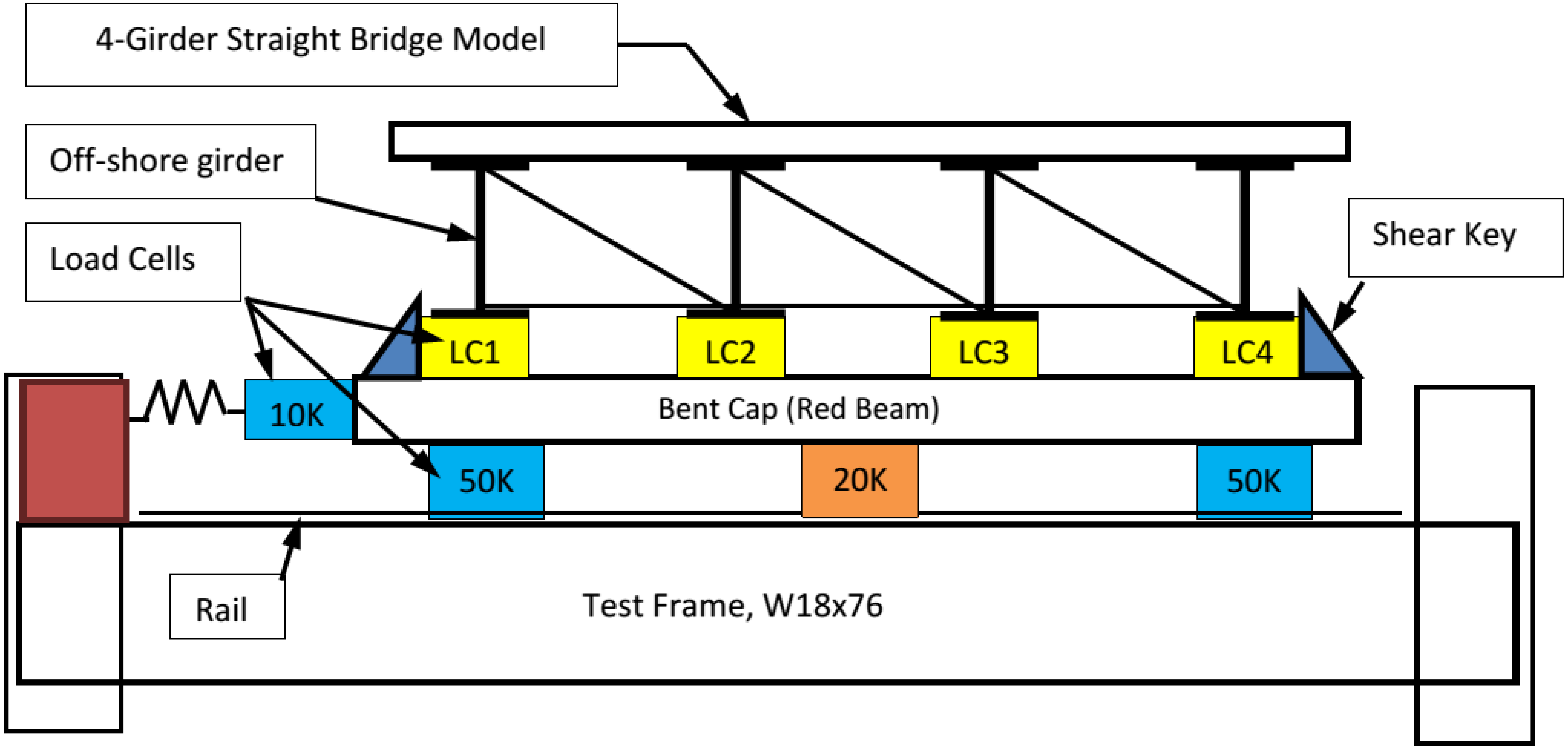
- ✓ 13 resistive-type wave gages to measure wave height and capture the evolution of the tsunami wave
- ✓ 5 ultrasound gages to track overtopping of the bridge
- ✓ 16 Vectrino-II ADVs to measure wave velocities at certain locations
- ✓ 2 pressure gages collocated with two velocity profiles

Experimental Results: Wave Passage

Total number of runs = 280

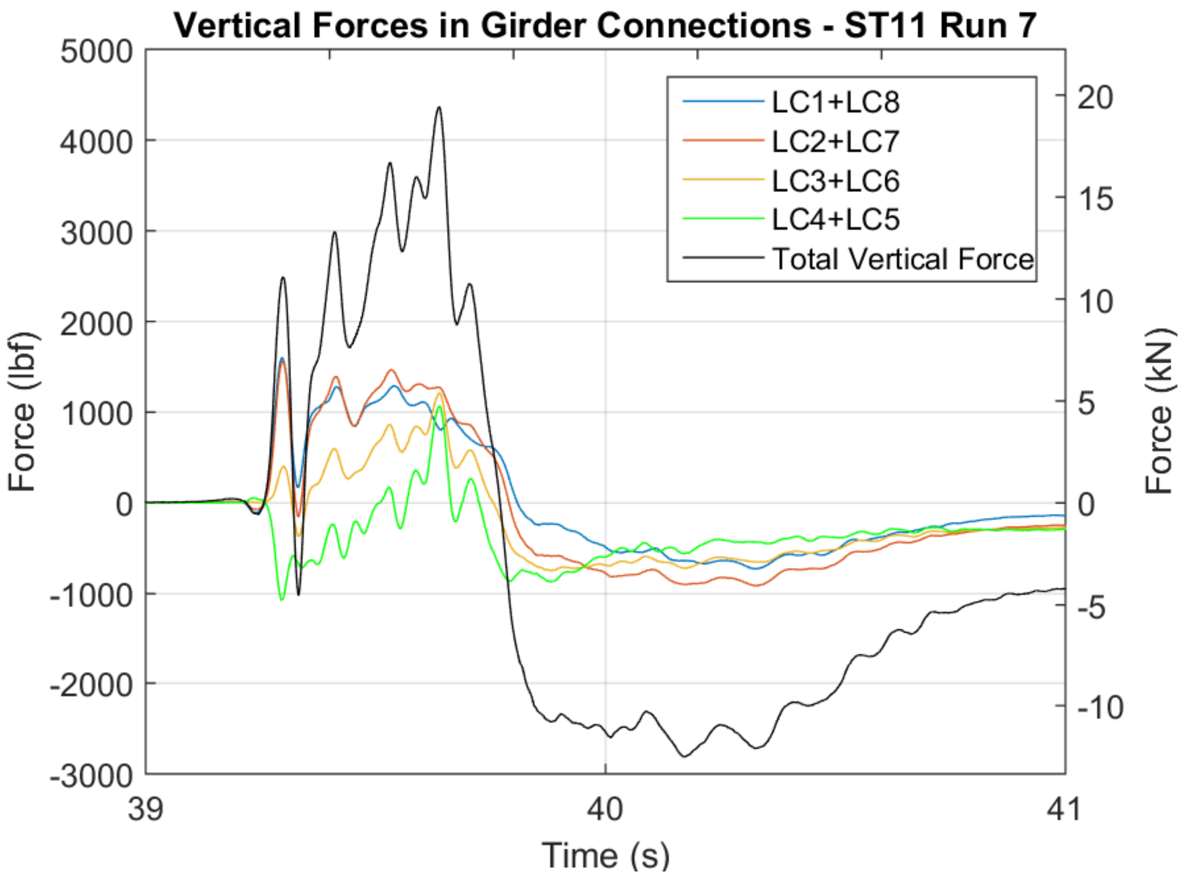
Figure below shows wave progression down flume for ST11, Run 7

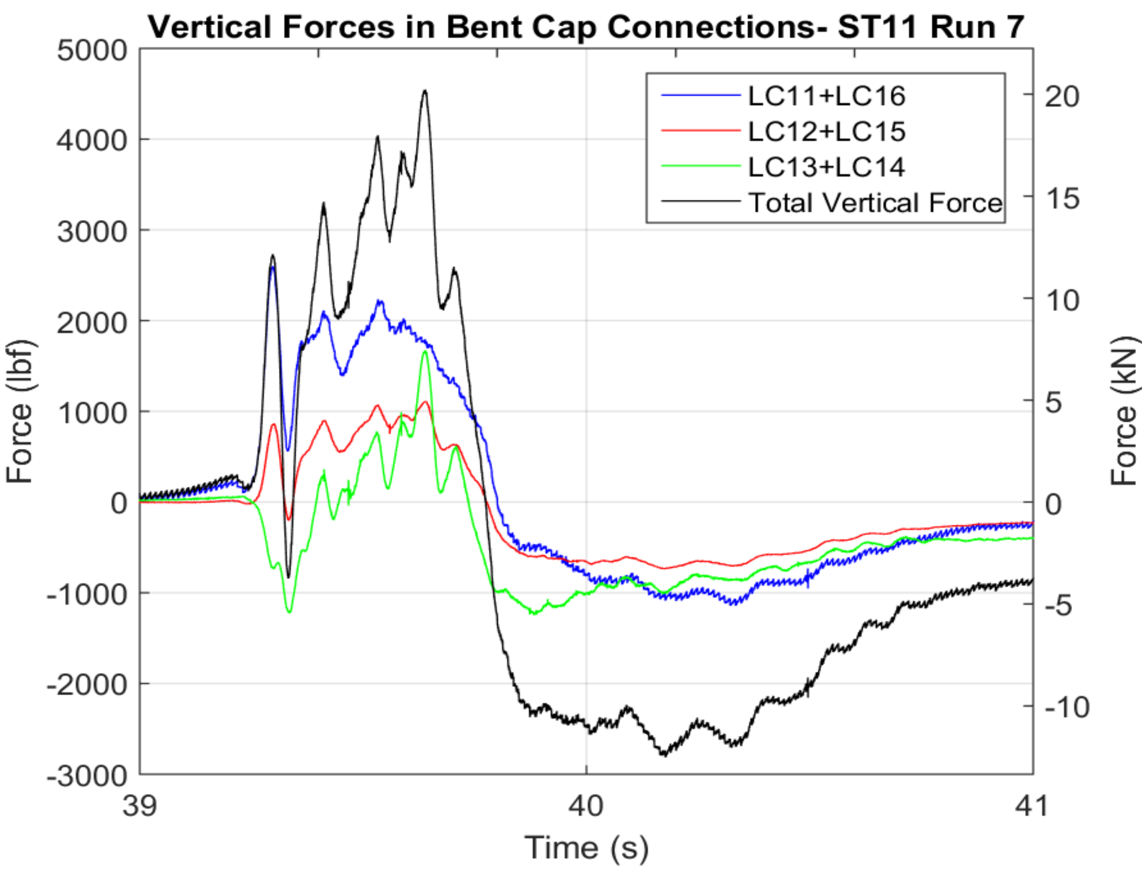




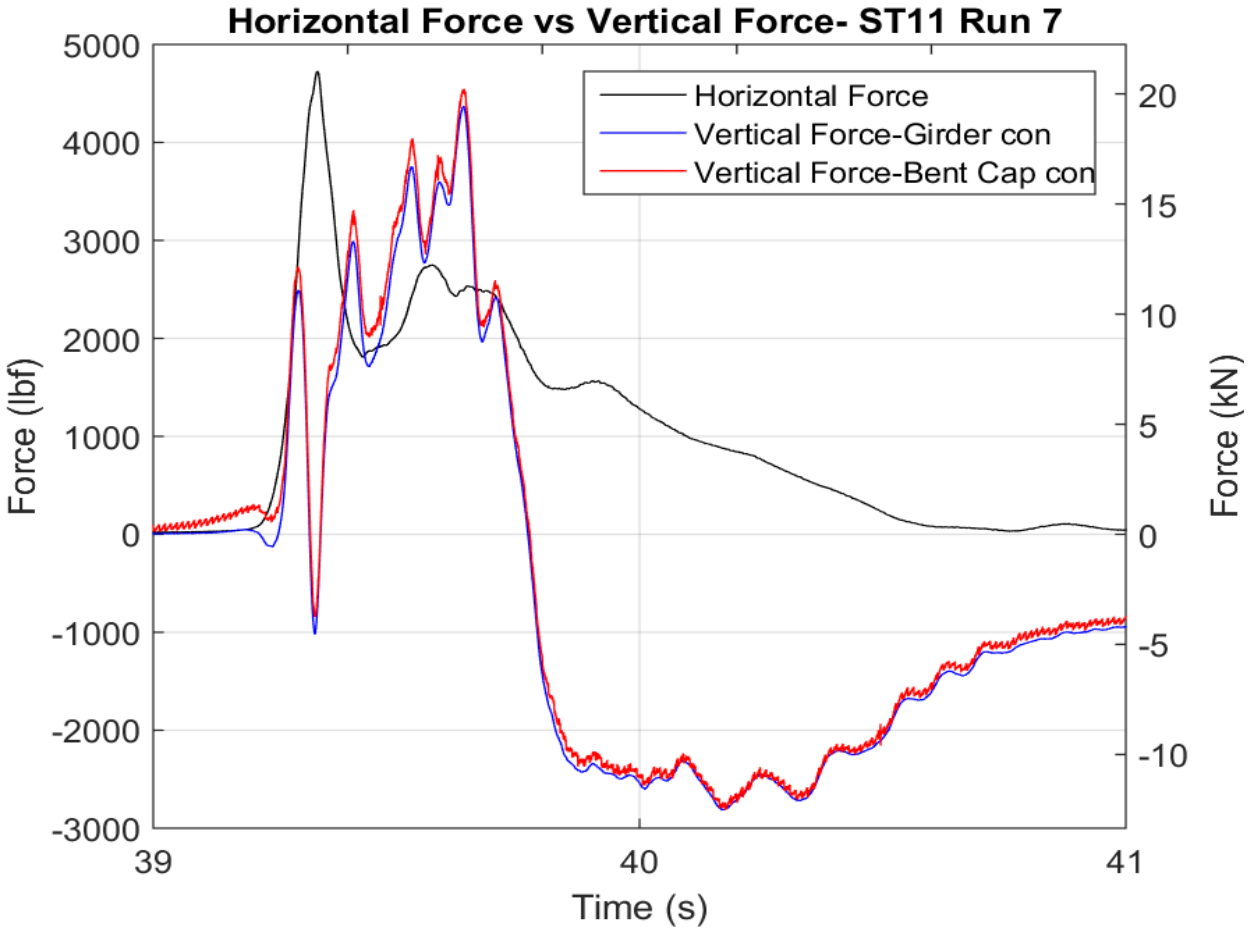
Load Cell Configuration Straight Bridge:

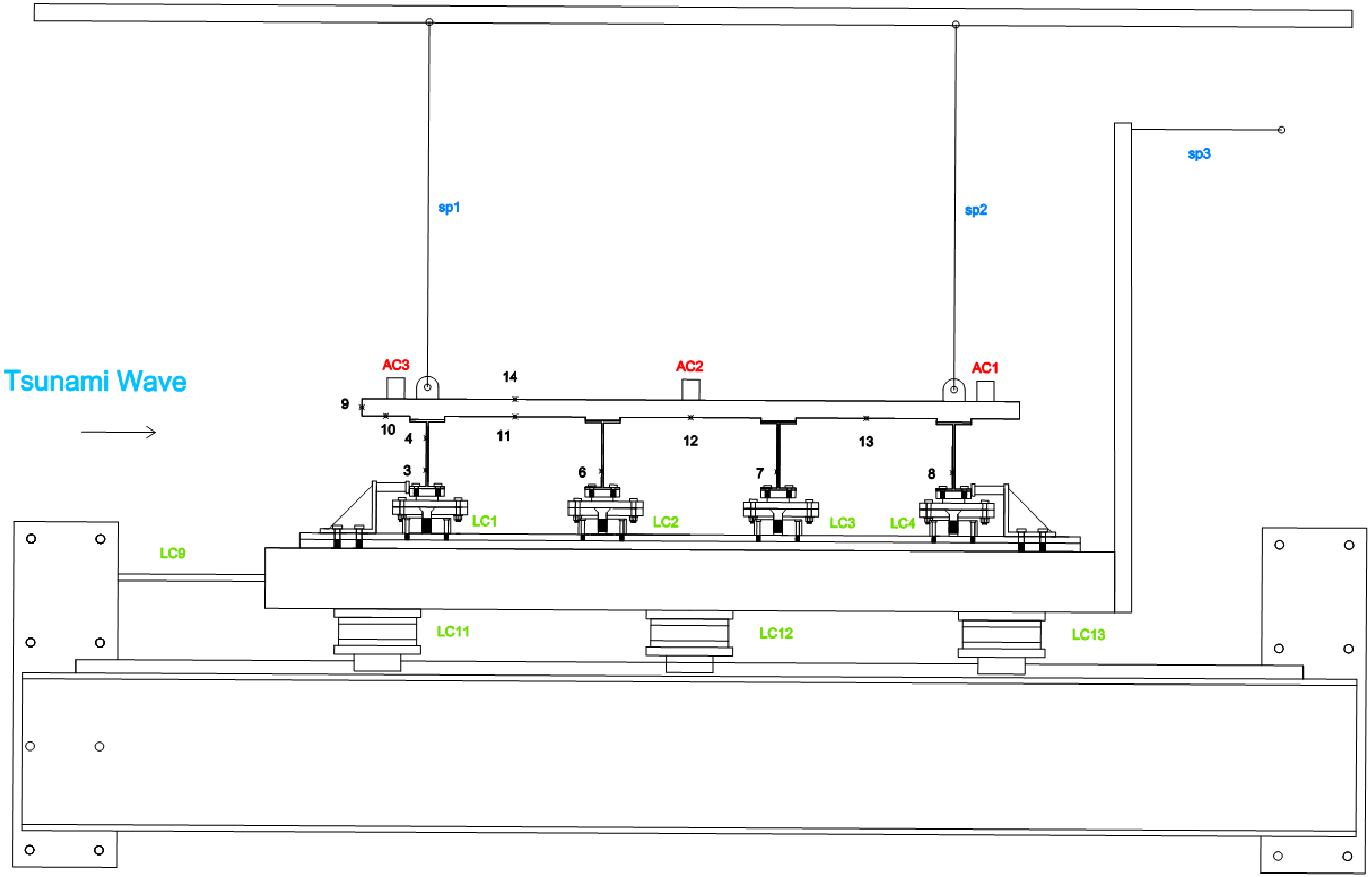
Experimental Results: Total Vertical Forces





Experimental Results: Total Horizontal Forces in Link Beam

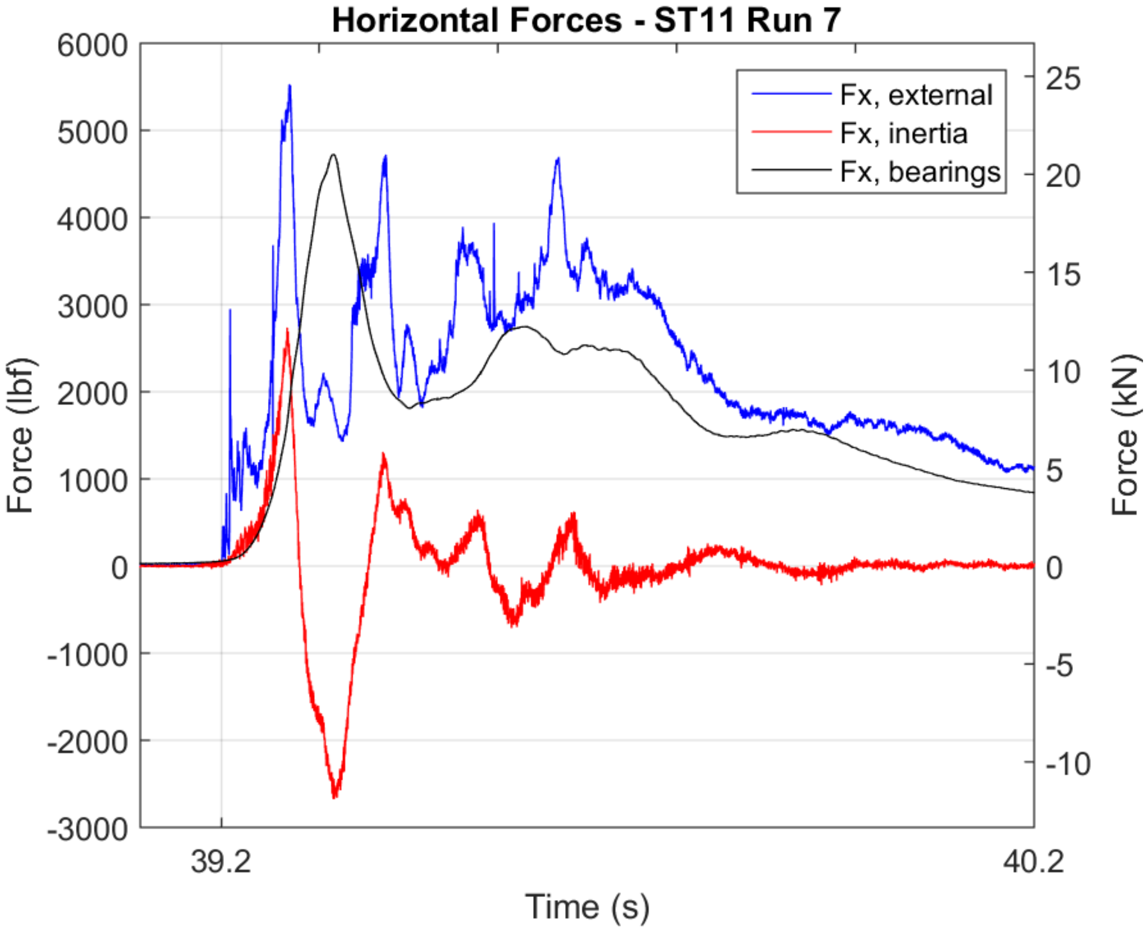


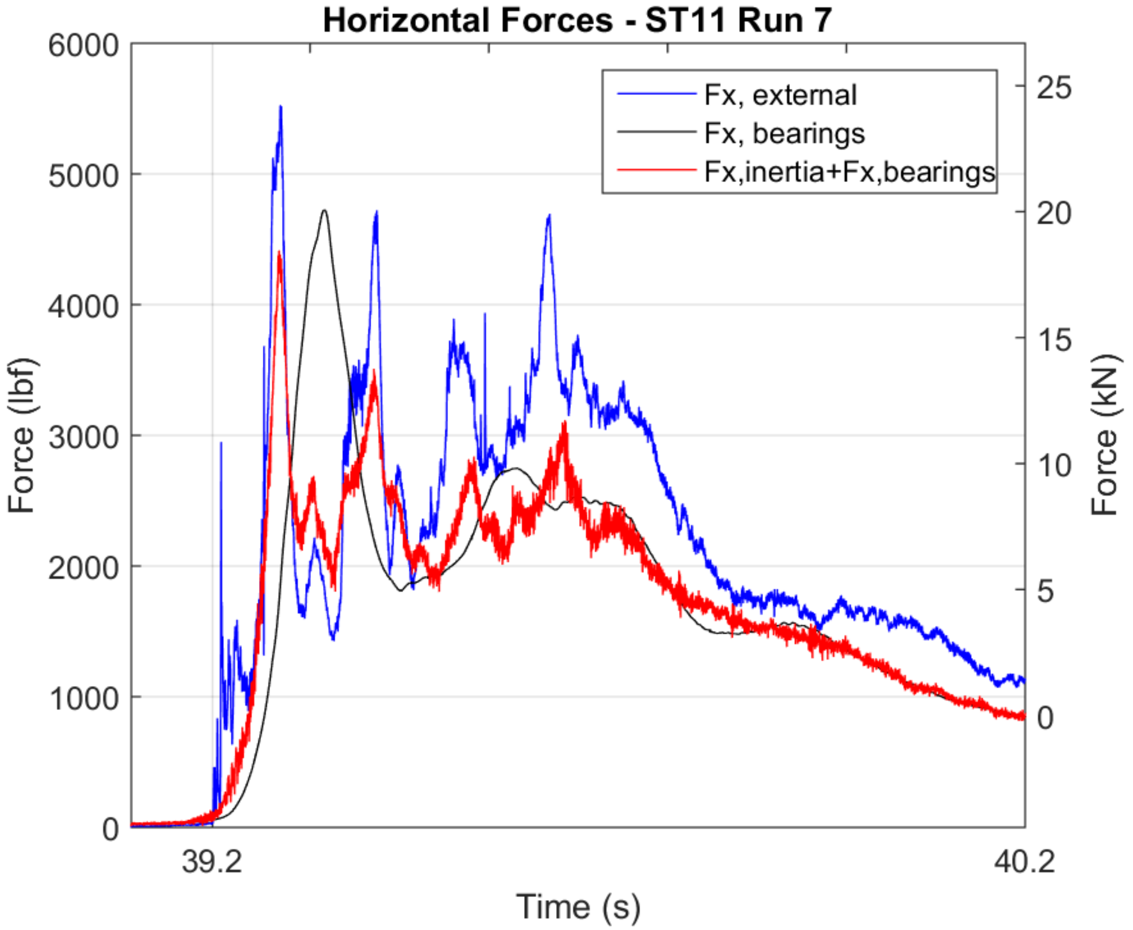


Tsunami Wave
sp1
sp2
sp3
AC3
AC2
AC1
14
9
10
4
11
12
13
3
6
7
8
LC1
LC2
LC3
LC4
LC9
LC11
LC12
LC13

Experimental Results: Role of Flexibility and Inertia Forces

Horizontal equilibrium requires: Fx-external = Fx-bearings + Fx-inertia





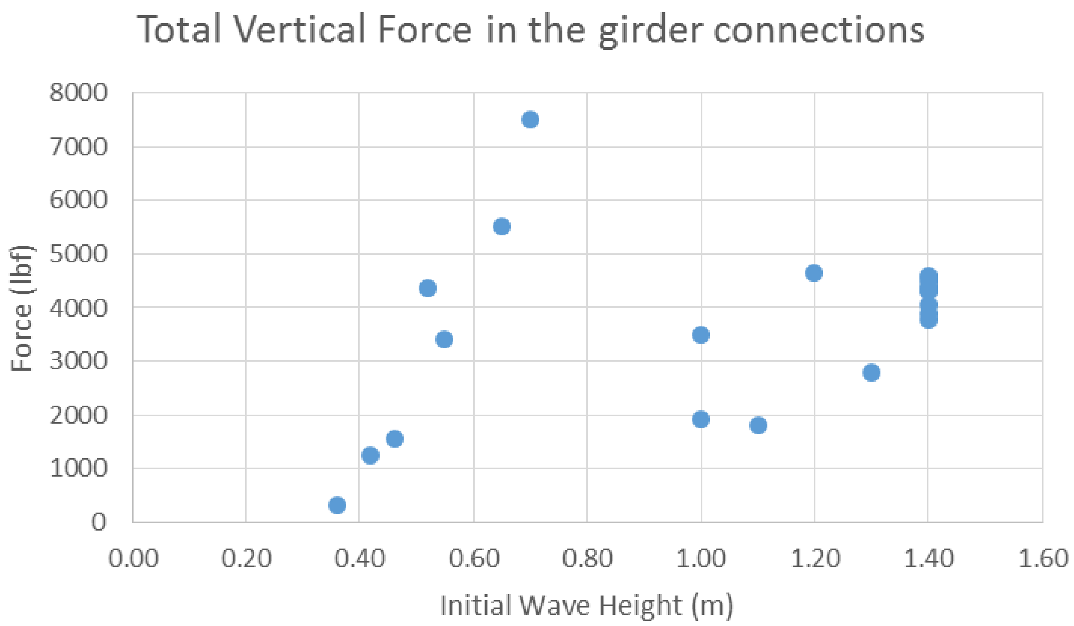
Repeatability

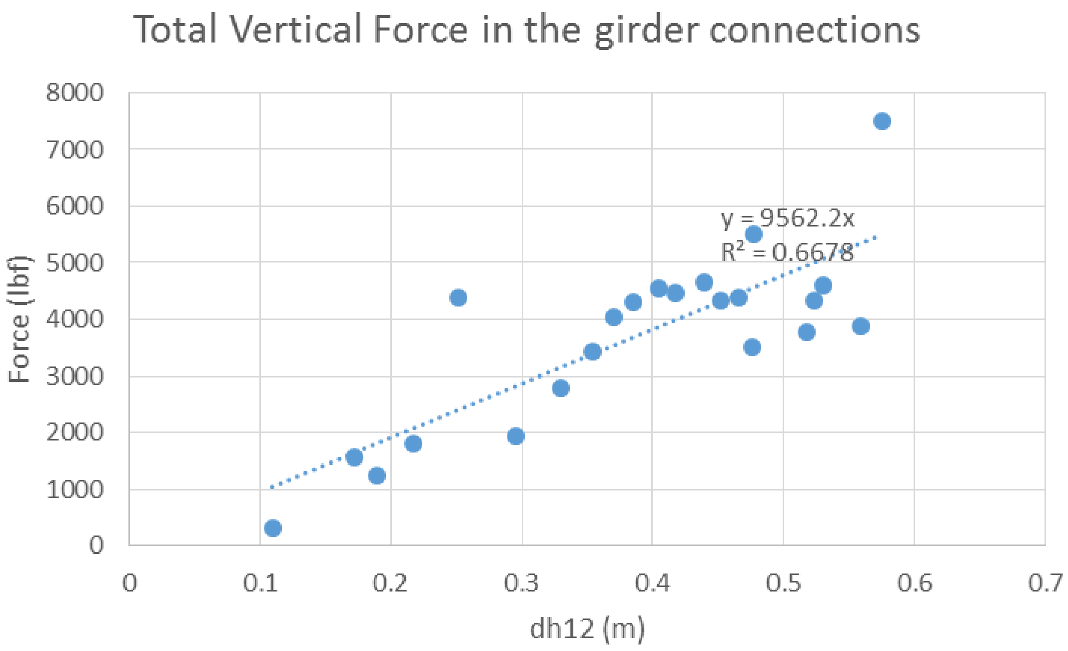
ST2	Total Forces (lbf)	
Wave height (m)	**Vertical**	**Horizontal**
1.40	4892	3756
1.40	4451	4718
1.40	3768	4807
1.40	4701	6074
1.40	4589	7754
Average	4480	5422
St. Deviation	384	1379

ST3	Total Forces (lbf)	
Wave height (m)	**Vertical**	**Horizontal**
1.40	4710	4919
1.40	4044	4480
1.40	4487	5097
1.40	4809	4660
1.40	4377	4628
Average	4485	4757
St. Deviation	269	221

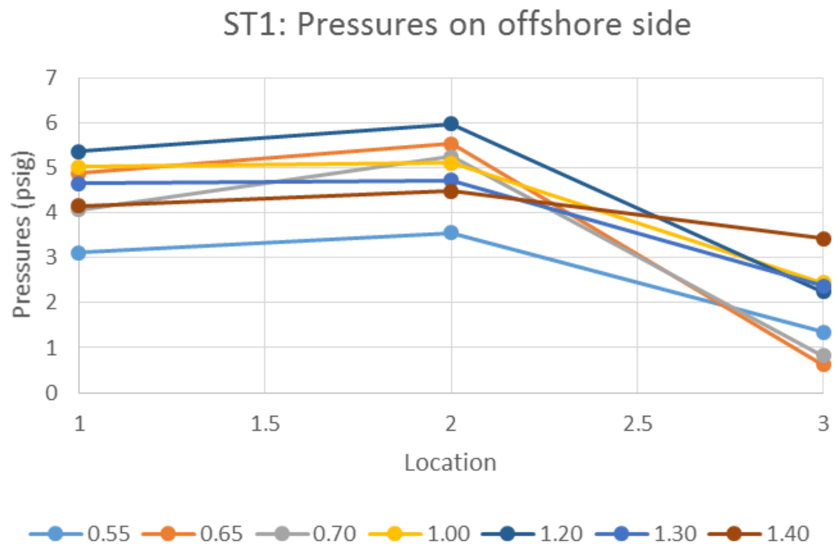
- ✓ The bridge specimen with rigid substructure demonstrated a better repeatability of vertical tsunami forces than of horizontal ones
- ✓ The bridge specimen with flexible substructure has a very good repeatability in both the vertical and horizontal forces, and this deviation is smaller than in the case of the rigid substructure

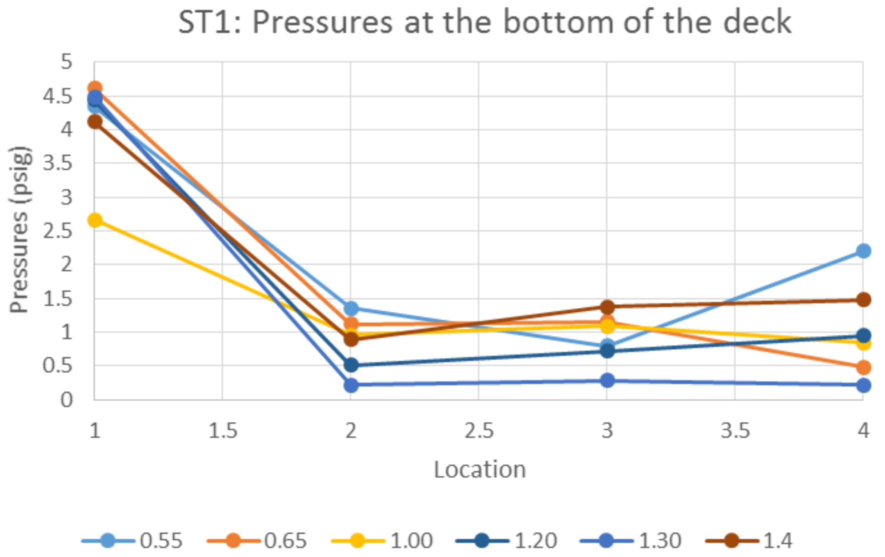
Experimental Results: Case ST1

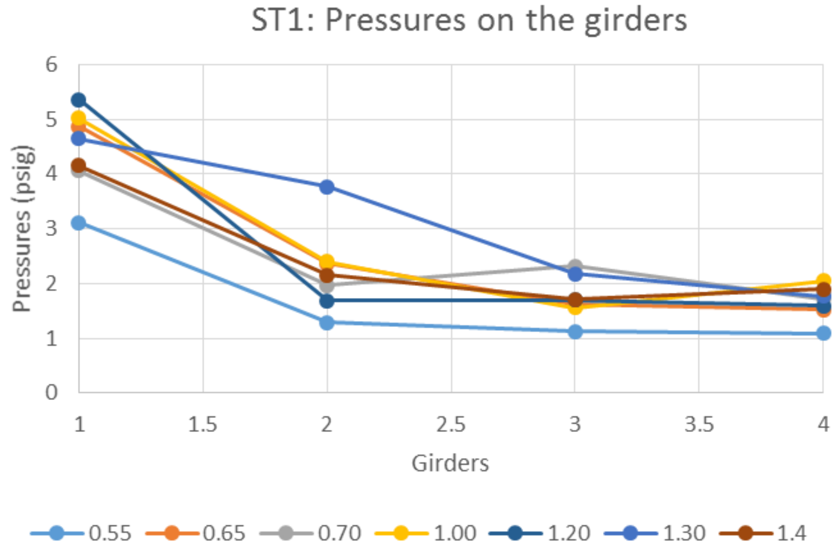




Experimental Results: Case ST1

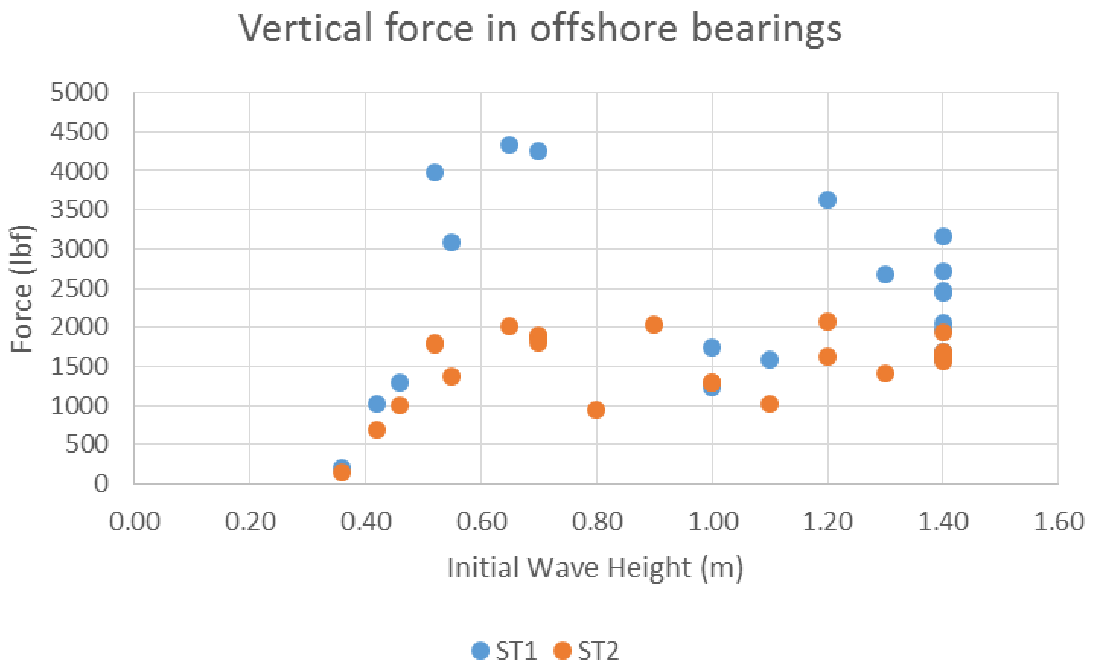


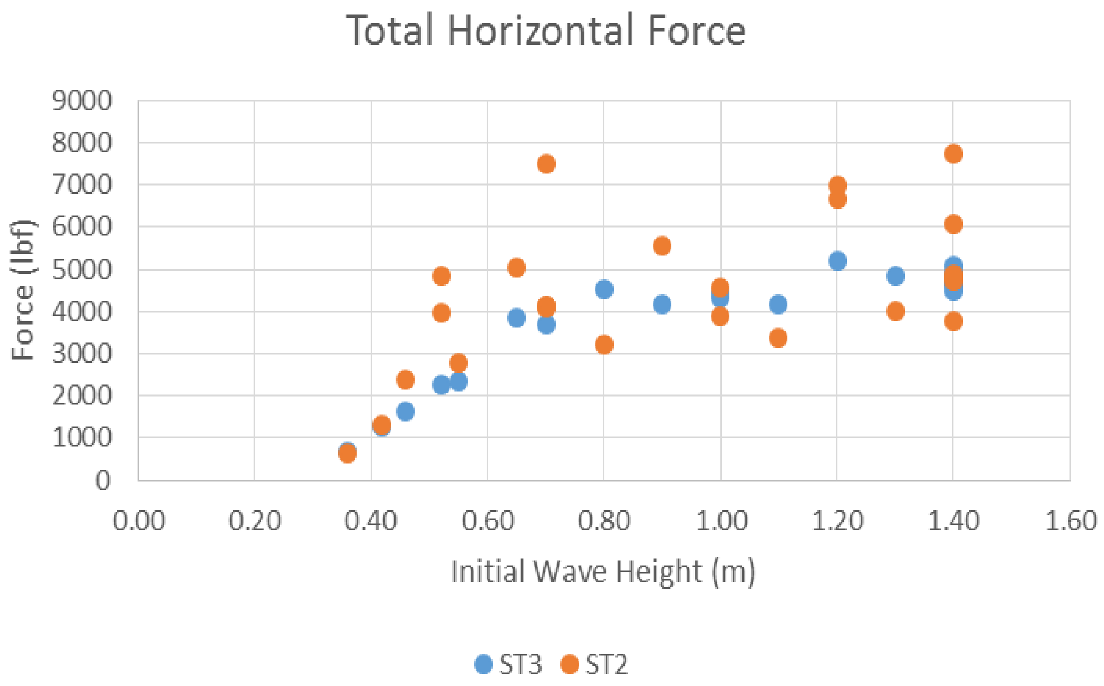




- Small changes in max pressures along the height of the girder
- Offshore girder is witnessing the largest pressure among the girders which can be up to 3 times larger than the pressure on the onshore girder
- Max Pressure at the bottom of the overhang is significantly larger than the pressures on the three bays

Experimental Results: Role of flexibility





Some Conclusions

1. Total horizontal and vertical forces substantially exceed weight of bridge, but do not occur simultaneously (about 0.5 sec apart). Maximum horizontal forces occur close to the initial impact while maximum vertical forces occur later when the wave is reaching the middle or onshore chamber
2. Four different Phases seem to exist in the vertical force histories, including a distinct rotational bridge mode in Phase 1 which occurs at the time of the first impact
3. Maximum total vertical connection forces and maximum tension in the offshore bearings occur at different times. The former occurs in Phase 1 and the latter in Phase 3

Some Conclusions (continued)

4. Equilibrium can only be satisfied when inertia forces are included in calculation (have been ignored to date). Inertia have a significant role in dynamic fluid-structure interaction
5. The offshore girder and the overhang are witnessing the largest pressures, which are several times larger than the pressures of internal girders and chambers respectively
6. The flexibility of the connections modeled in case ST2, reduced the tension in the offshore bearings by up to 56% for certain waves compared to the steel connections
7. The substructure flexibility reduced the horizontal forces for most waves with a maximum reduction of 49%

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