Tsunami Loads on Skew Bridges

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- Working Group 1: Tsunami Hazard and Mapping
  - Members: Hong Kie Thio (co-Lead), Patrick Lynett (co-Lead)
- **Working Group 2: Tsunami Loading of Bridges**
  - Members: Michael Scott (Lead), Ian Buckle, Tom Murphy, Denis Istrati
- Working Group 3: Bridge Detailing for Tsunami Loads
  - Members: Tom Murphy (Lead)
- Working Group 4: Geotechnical Issues (Scour and drawdown induced liquefaction)
  - Members: Tom Shantz (Lead)
- Working Group 5: Guide Specifications for Bridge Design for Tsunami Hazard
  - Members: Tom Murphy (Lead), Ian Buckle

Background

- 2004 Indian Ocean EQ and Tsunami
- 2010 Chile EQ and Tsunami
- 2011 Tohoku EQ and Tsunami
- 2018 Sulawesi EQ and Tsunami

Many bridges were able to withstand the earthquake but were severly damaged due to the tsunami inundation.

81 bridges in Sumatra (Unjoh 2007)

252 bridges in Japan (Maruyama 2013)

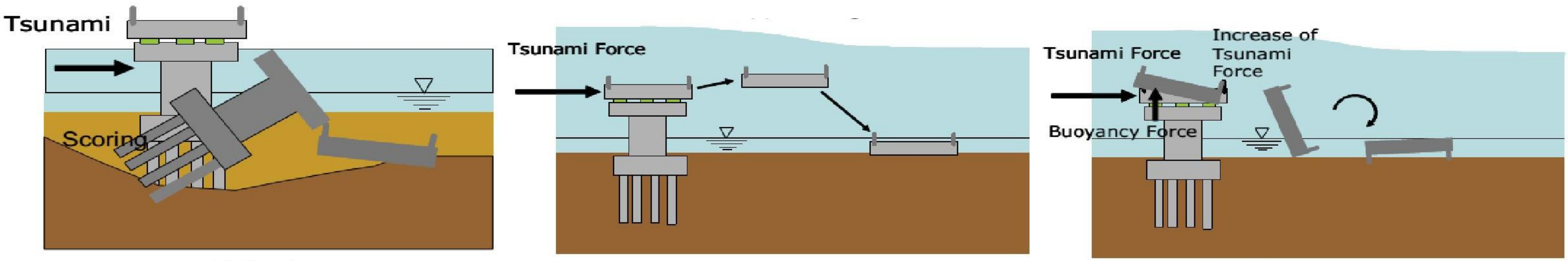
Damaged bridges in recent tsunamis [Source: Japan Media (top-left), I.G. Buckle (top-right), M. Yashinski (bottom)]

Typical Tsunami-Induced Failure Modes of Bridges

Scour of bridge piers and/or abutments

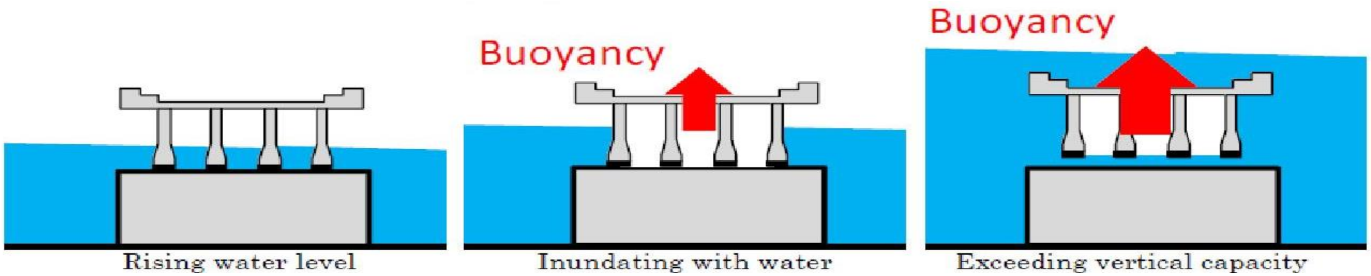
Transverse offset of bridge deck

Overturning of bridge deck



Failure modes (Kawashima et al)

Uplift of bridge deck

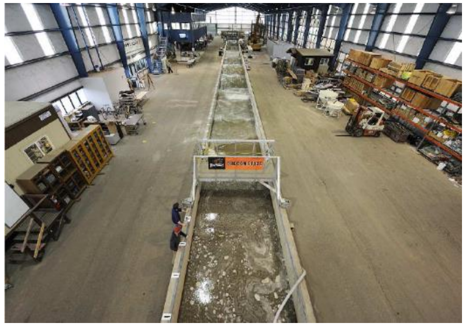


Failure mode (modified from Hoshikuma et al)

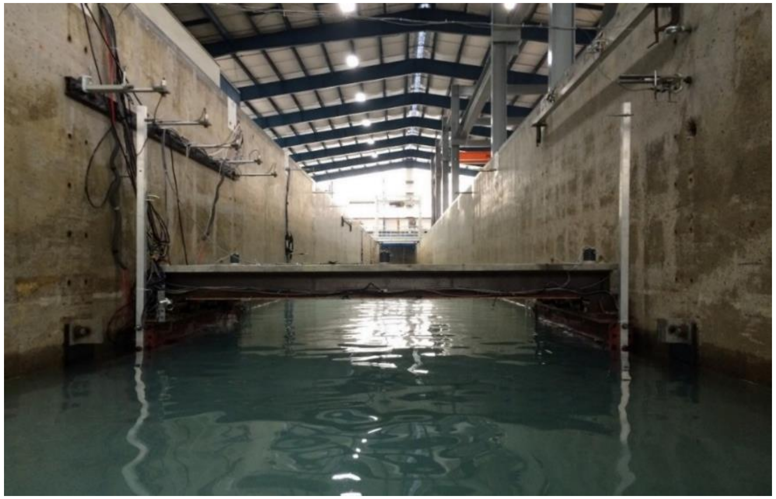
Representation of tsunami waves

Several approaches used in previous studies to represent tsunami-induced effects on bridges including:

(a) **Solitary waves**, (b) **Bores**, (c) **Rising water level**

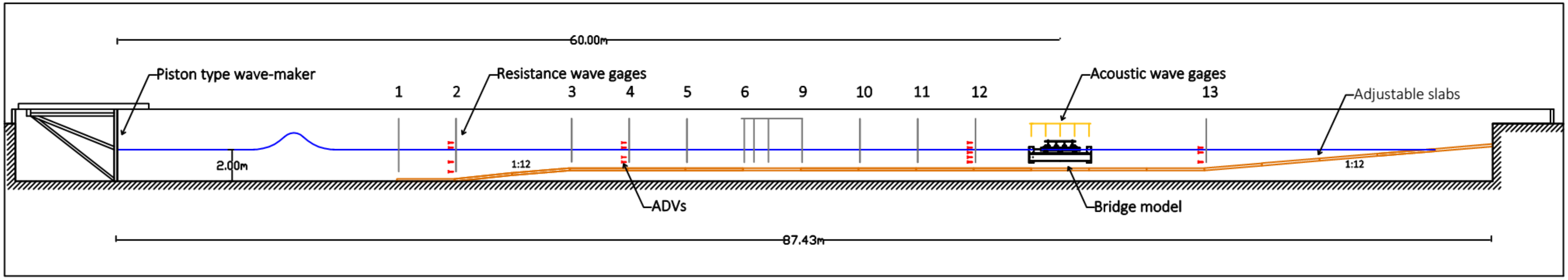


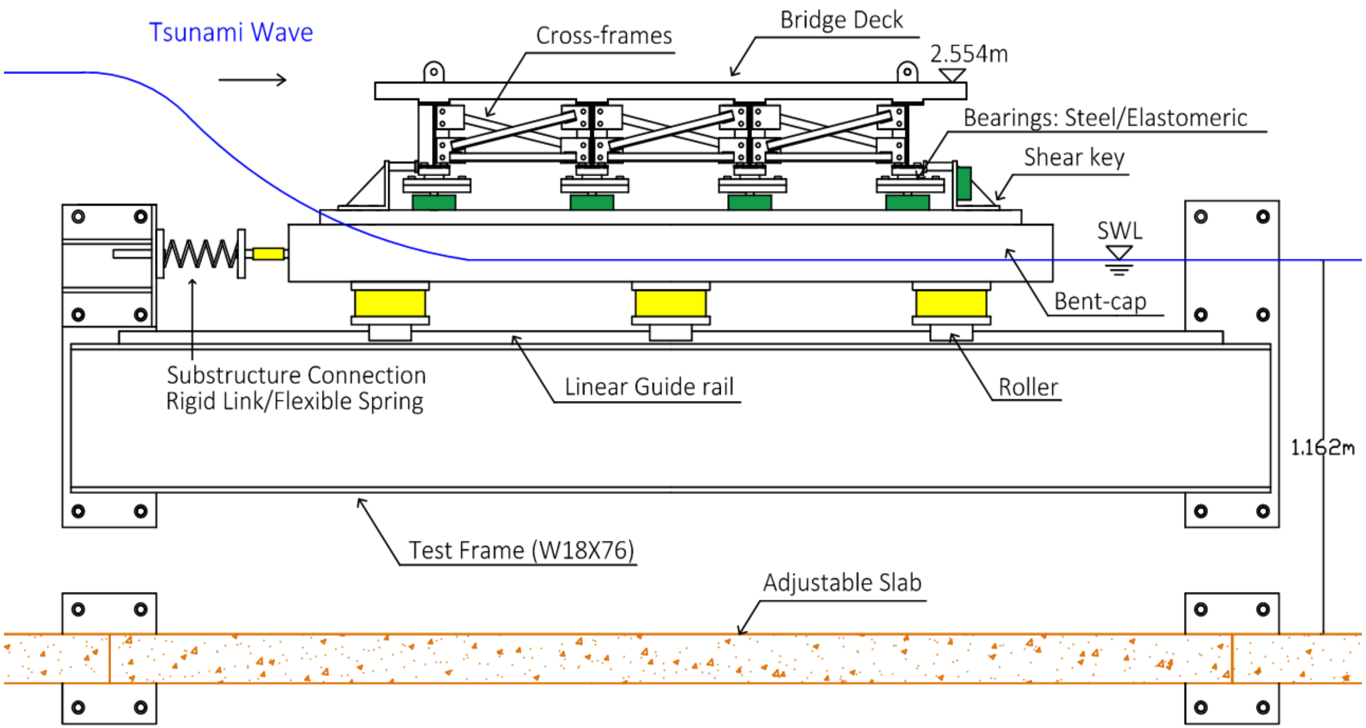
UNR conducted large-scale (1:5) hydrodynamic experiments at Oregon State University using both solitary waves and bores.



Representation of tsunami waves

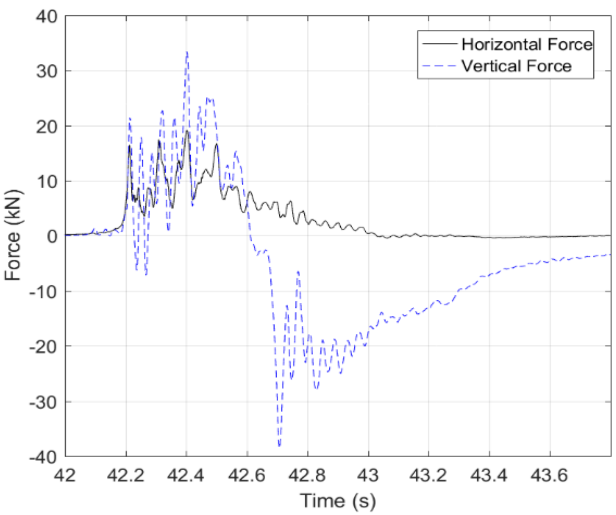
Tsunami loading on straight bridges



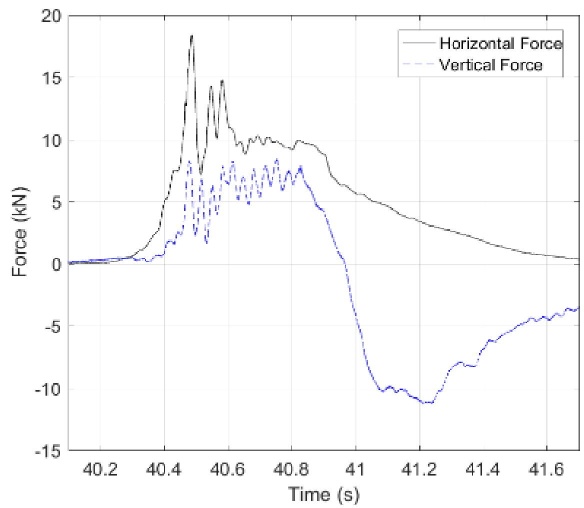


A. Total tsunami loading on straight bridges

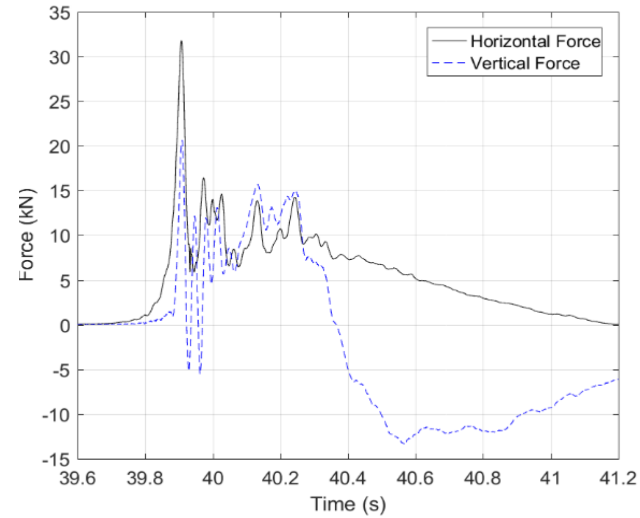
Solitary: H=0.70m

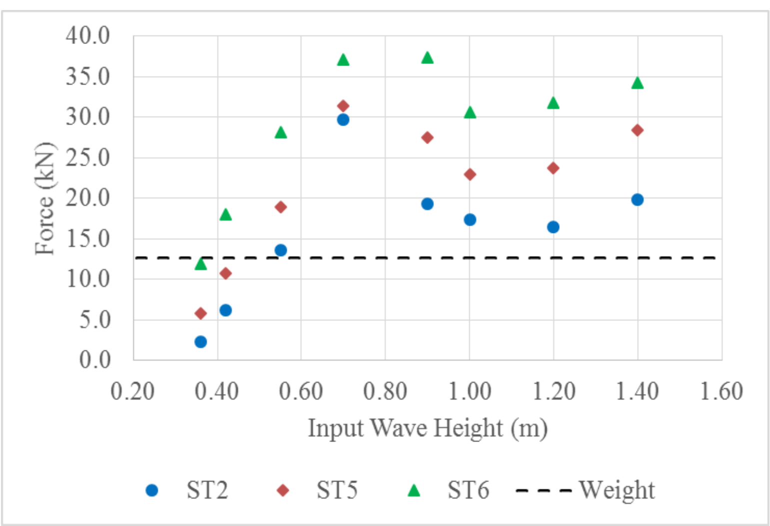


Bore: H=0.80m



Bore: H=1.20m

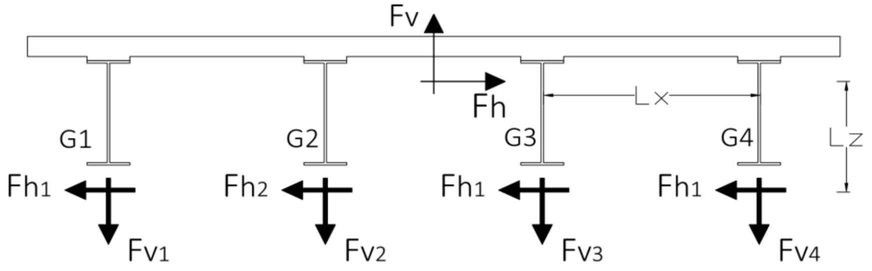




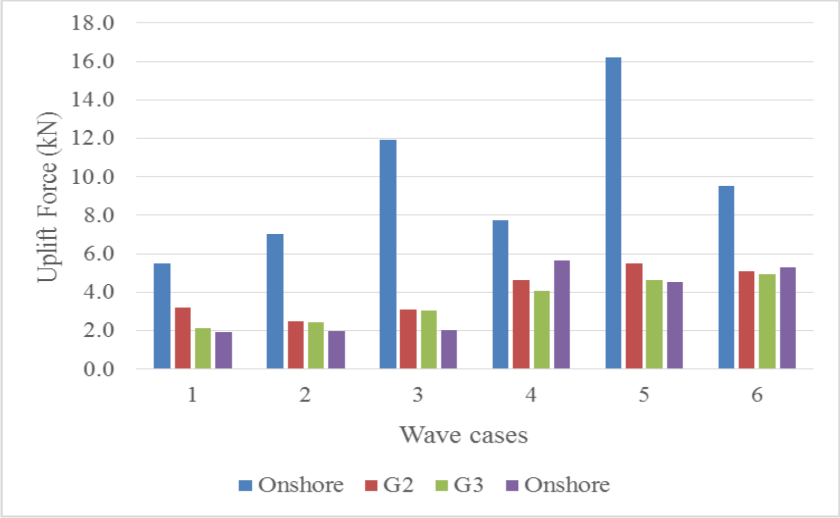
Tsunami-like waves introduce:

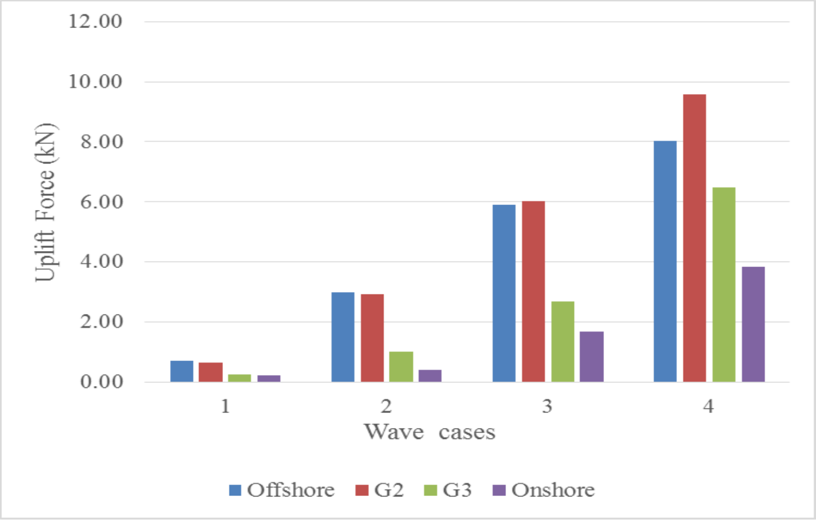
- Significant **impulsive loads** (especially in the horizontal direction), which could be **2-3 times** larger than the steady-state loads
- Large **uplift loads** that can exceed the weight of the bridge

B. Tsunami-induced uplift forces in bearings



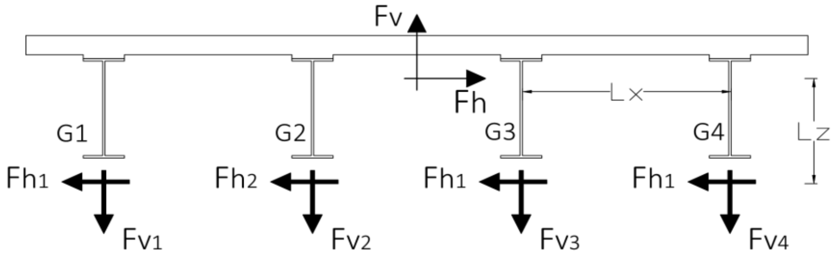
Steel bearings vs elastomeric bearings



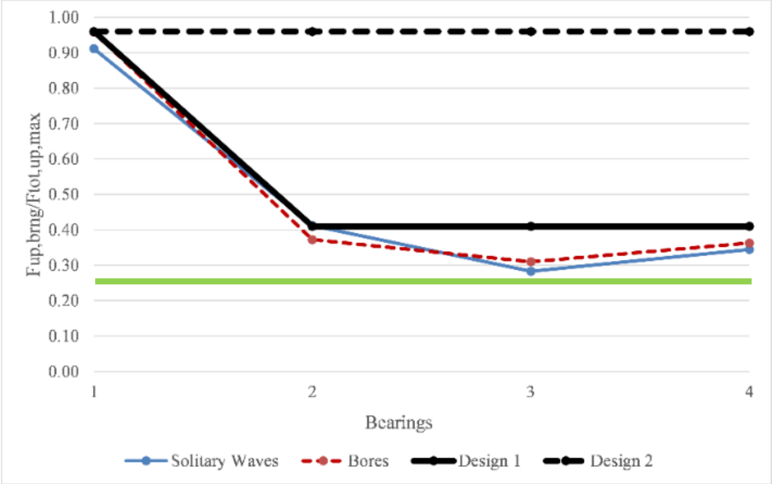


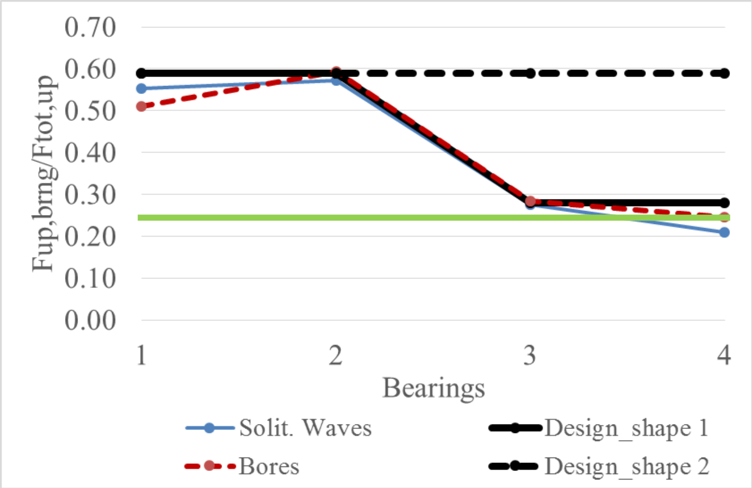
- Previous studies in the literature have assumed that the uplift load in **equally distributed to all the bearing connections**, which clearly is not the case!
- The offshore bearings consistently attract significantly larger uplift forces than the rest.

B. Uplift forces in bearings



Steel bearings vs elastomeric bearings: Normalized bearing forces





Typical assumption in previous studies:

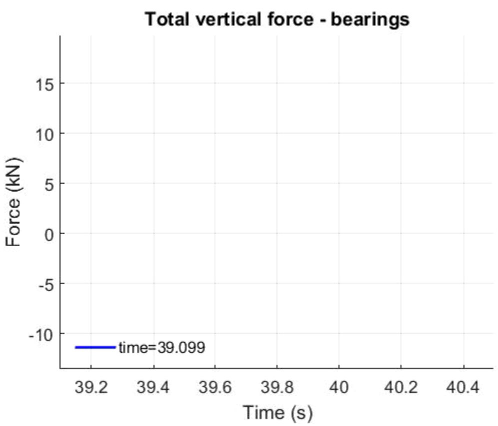
Equal distribution of uplift forces to all bearings, which would imply that the bearings of each girder will attract about **25%** of Fup,total (12.5% in individual bearing)

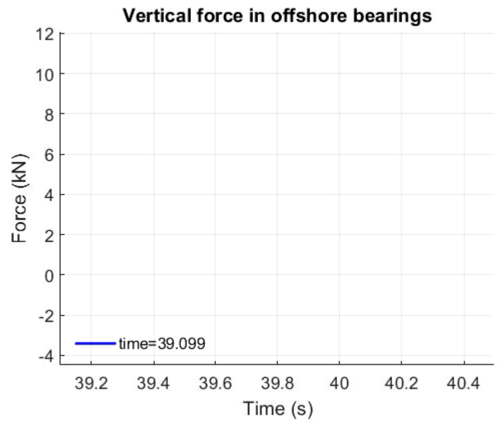
Recorded values:

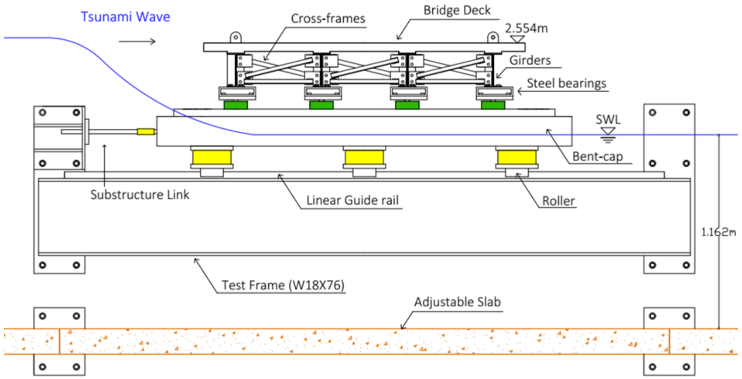
The offshore bearings have to withstand **95% and 60%** of **the total uplift** in the case of steel and elastomeric bearings. This is **3.8 and 2.4 times larger** than the equal distribution assumption.

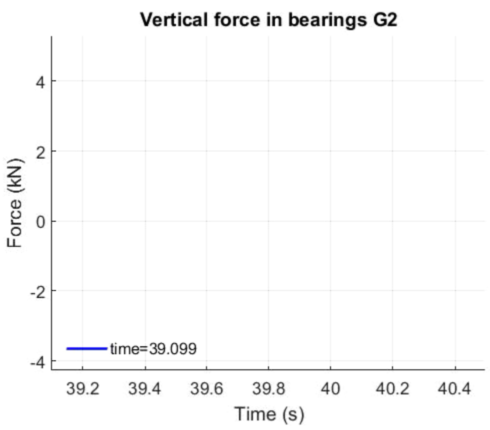
If the offshore bearings break, then that could lead to progressive collapse of the bridge deck.

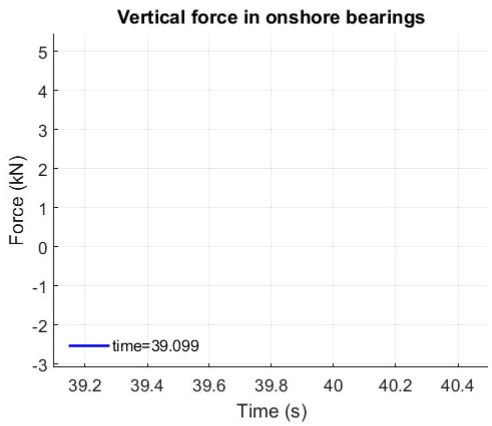
Tsunami-induced uplift forces in bearings

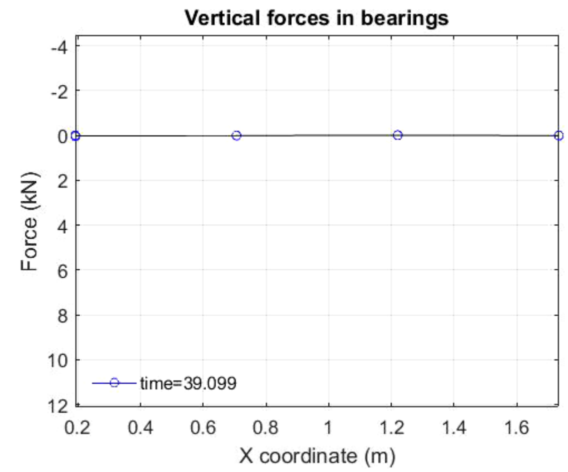




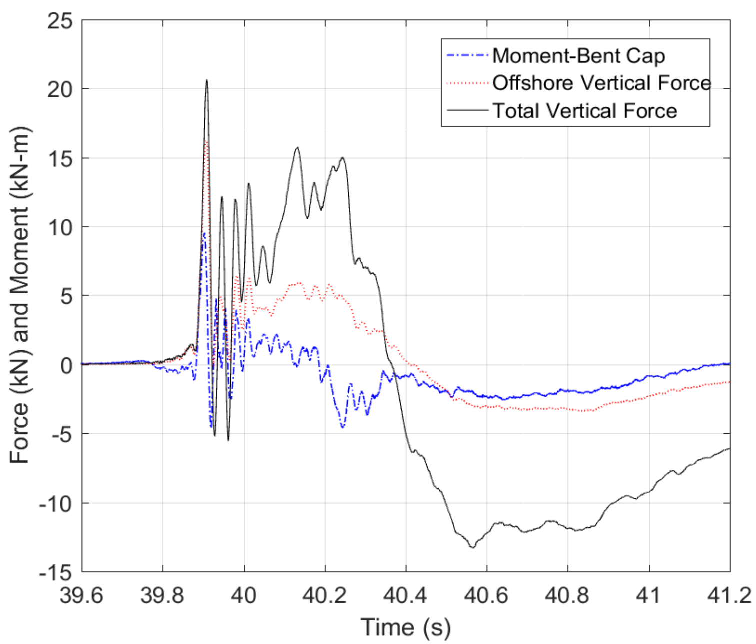


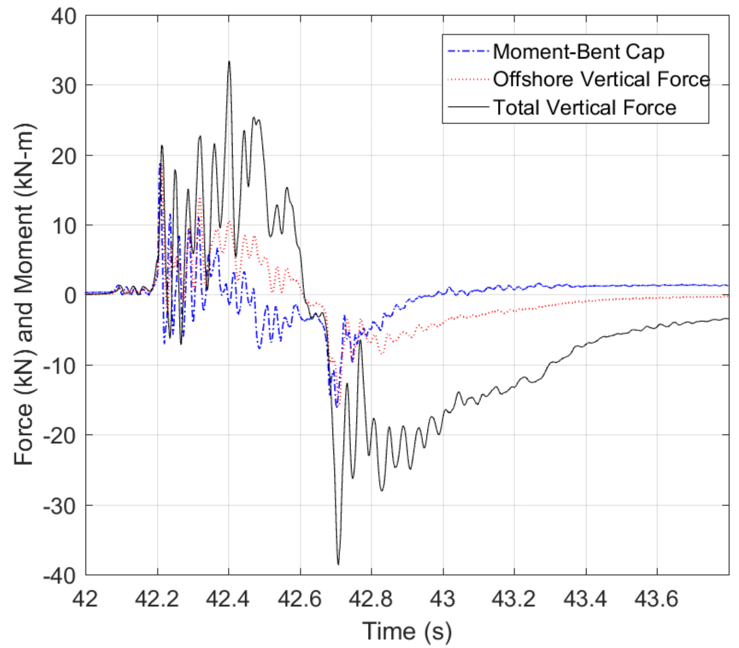


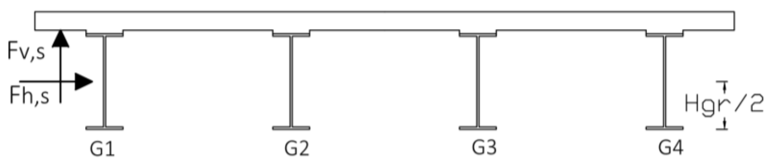




Overturning moment





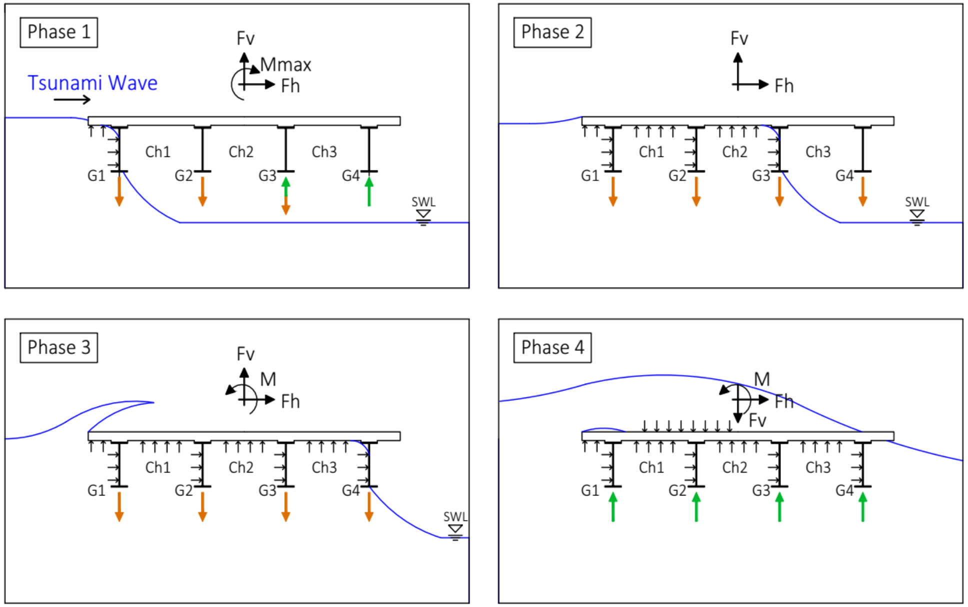


Reason behind the large uplift forces in the bearings and connections located offshore of the CM:

Significant overturning moment is generated by the impulsive tsunami forces applied on the offshore girder and below the offshore overhang!

Why do straight bridges get damaged by tsunamis?

Inundation mechanism of straight open-girder bridges

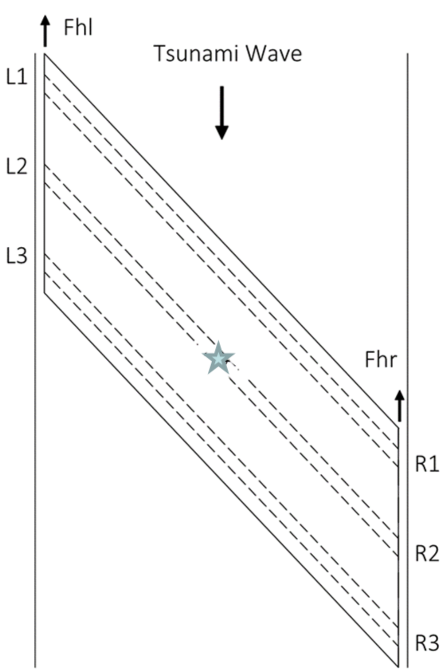


Tsunamis can be damaging for bridges because they introduce:

- **Large impulsive loads**, several times higher than the steady-state
- **Uplift loads,** which can exceed the bridge weight
- **Overturning moment** that has a major effect on offshore connections, bearings and columns, leading to non-uniform distribution of the demand.
- **A complex inundation mechanism and hydrodynamic loading**, which changes both spatially and temporally.

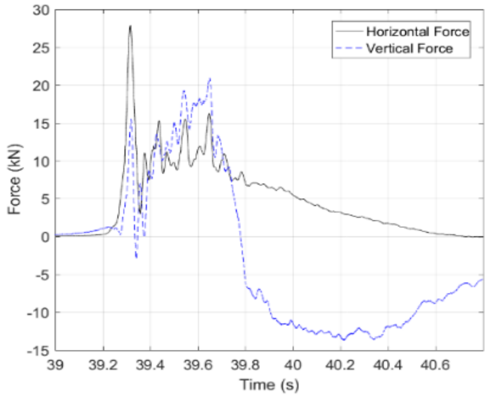
Tsunami impact on skew bridges

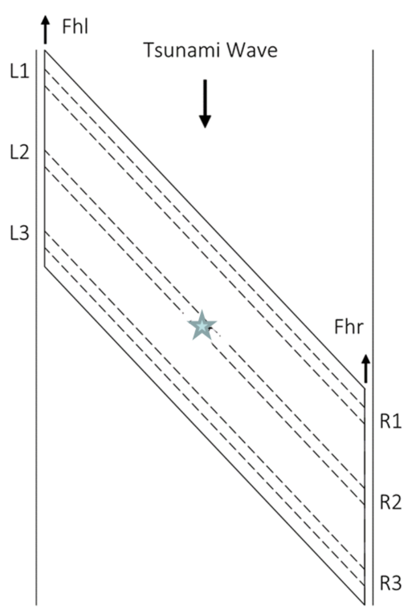
Conducted experimental tests of a skew bridge with a 45deg skew angle



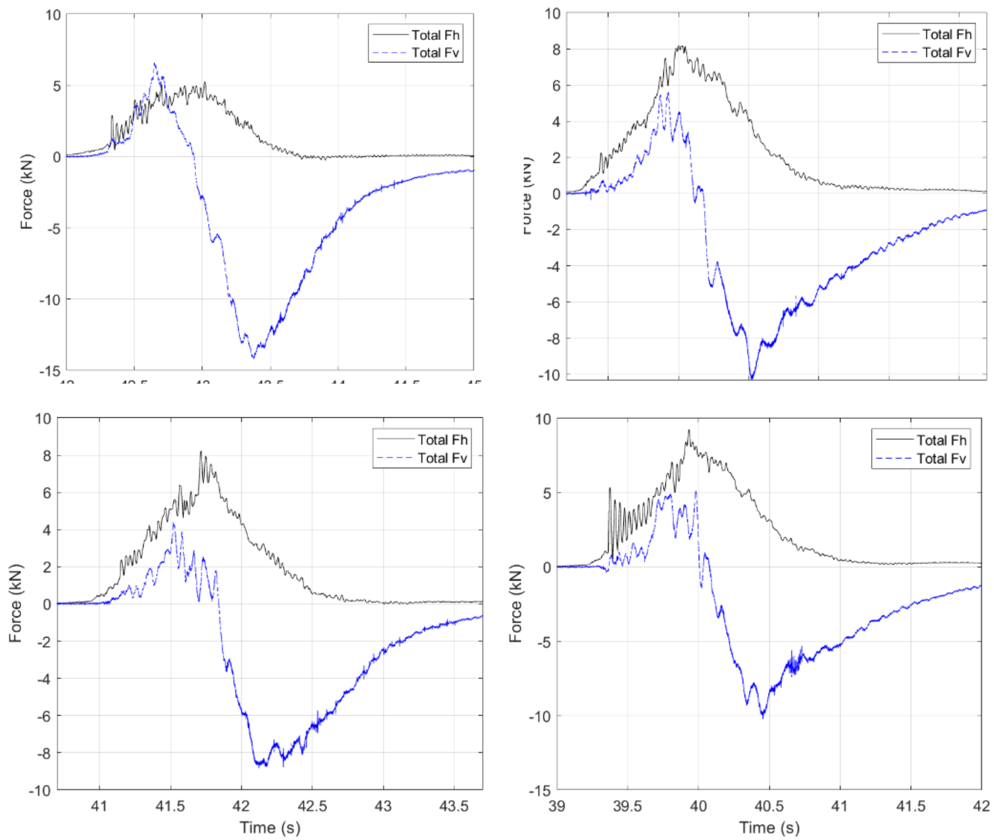
A. Total tsunami loads on a skew bridge with θ=45deg

Straight Bridge



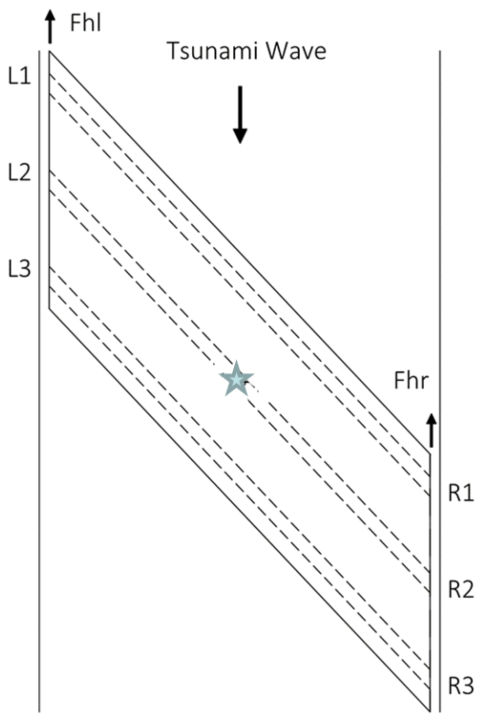


Skew Bridge

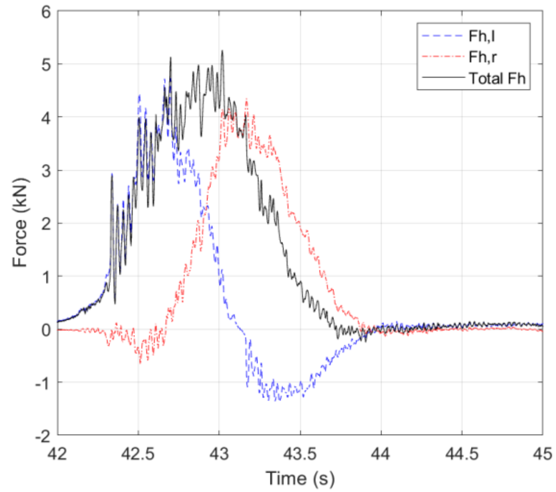


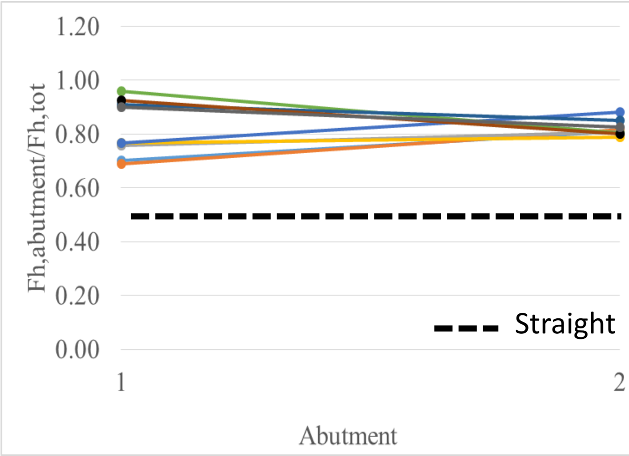
The **magnitude of the impulsive horizontal and vertical** loads is **significantly reduced** for a 45deg skew angle, and the demand is governed by a longer duration load.

B. Horizontal tsunami forces in bridge abutments

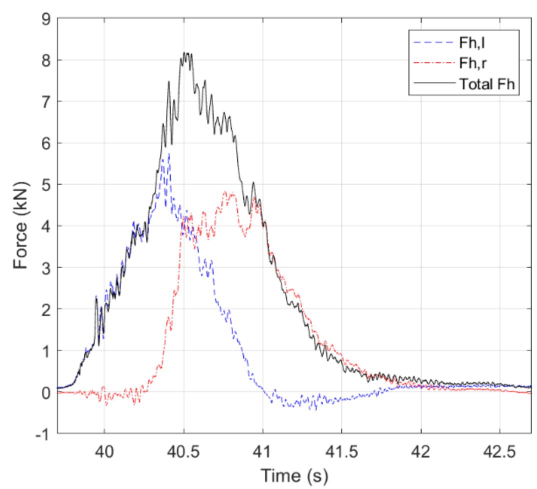


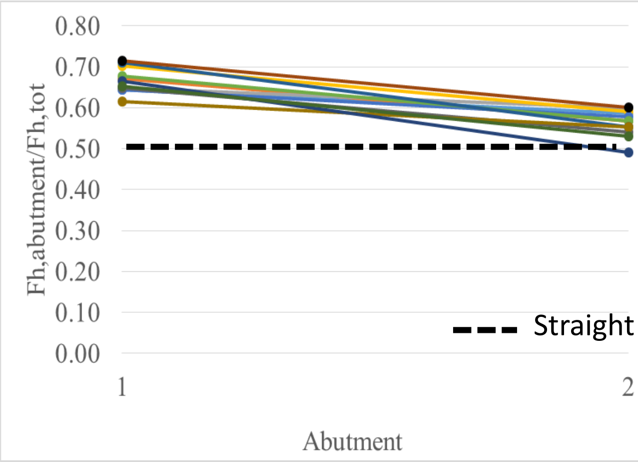
Solitary Waves



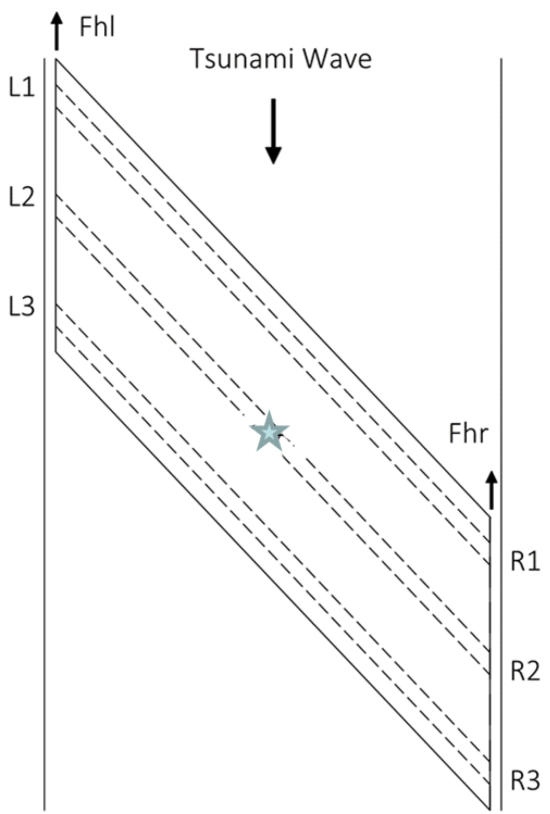


Bores

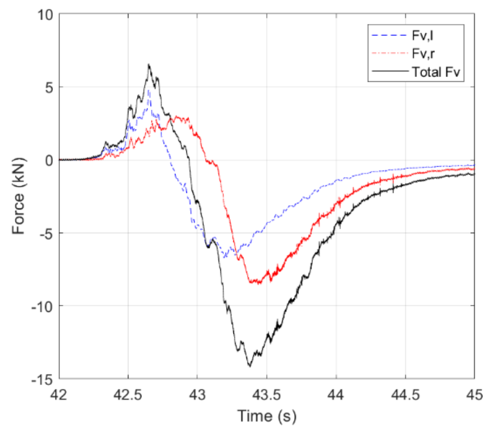


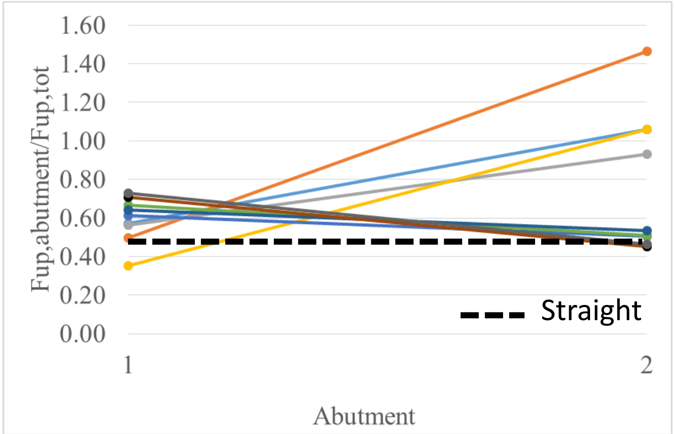


C. Vertical tsunami forces in bridge abutments

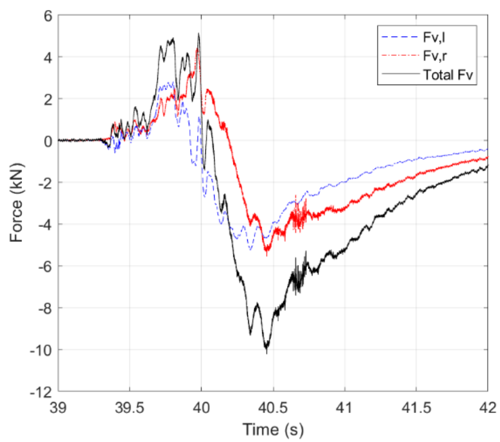


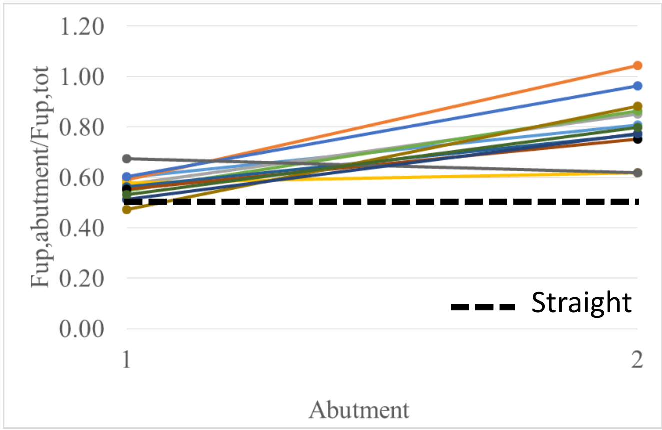
Solitary Waves



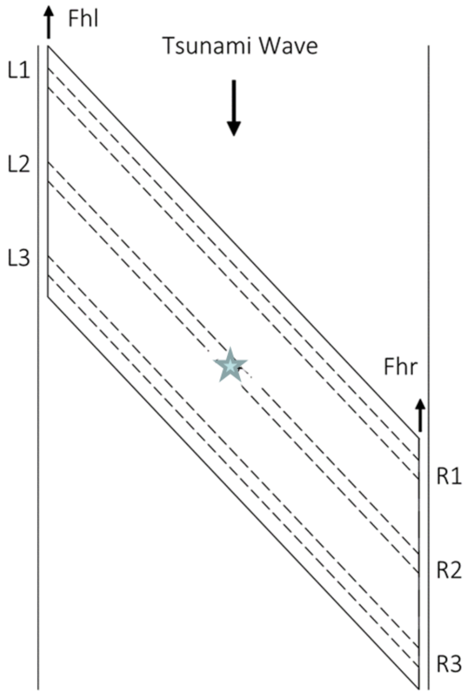


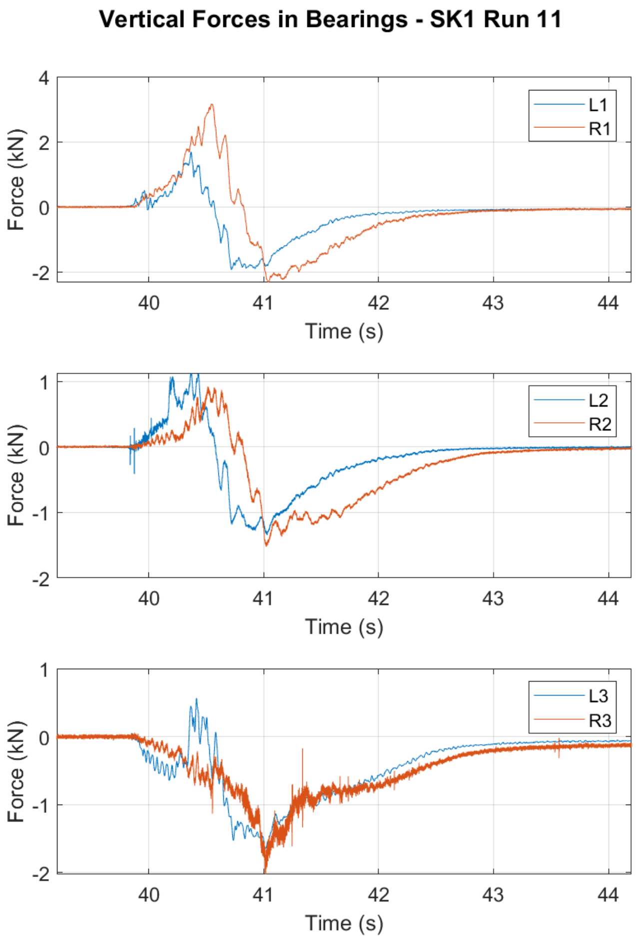
Bores

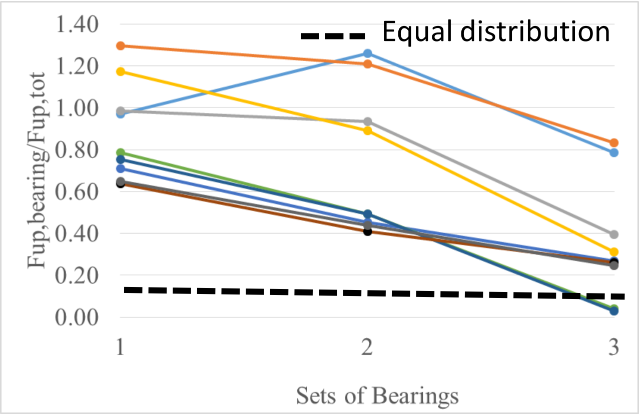


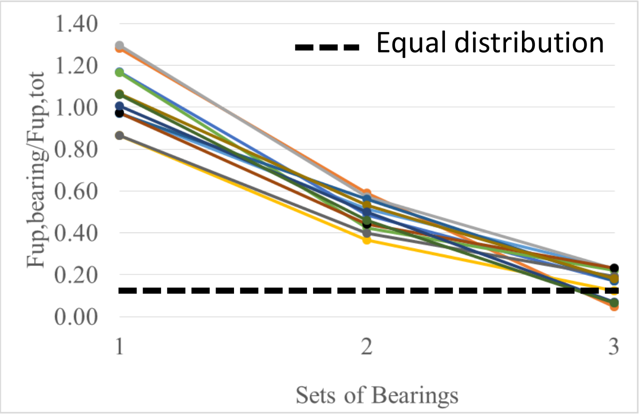


D. Tsunami-induced uplift forces in bearings

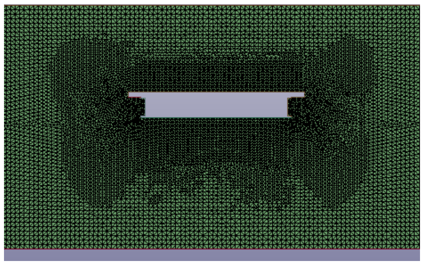


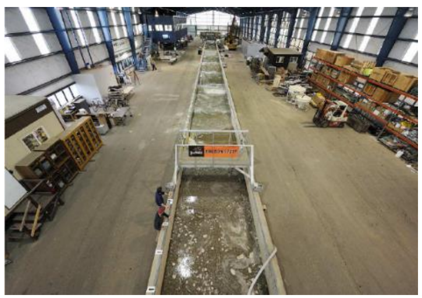






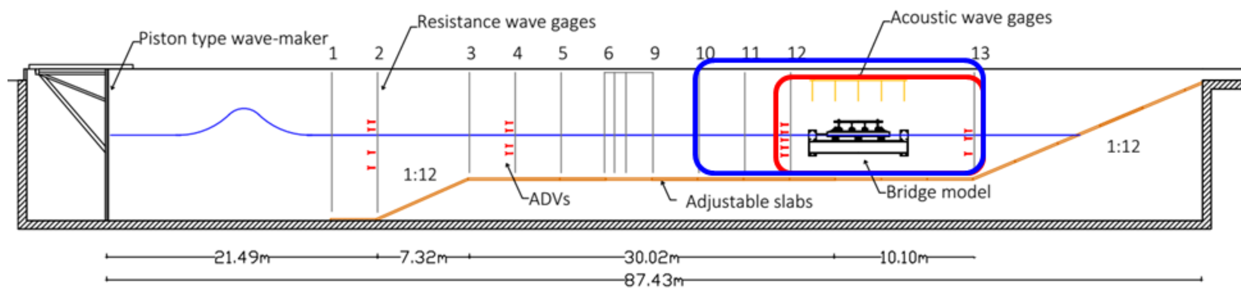
Numerical models to complement experiments

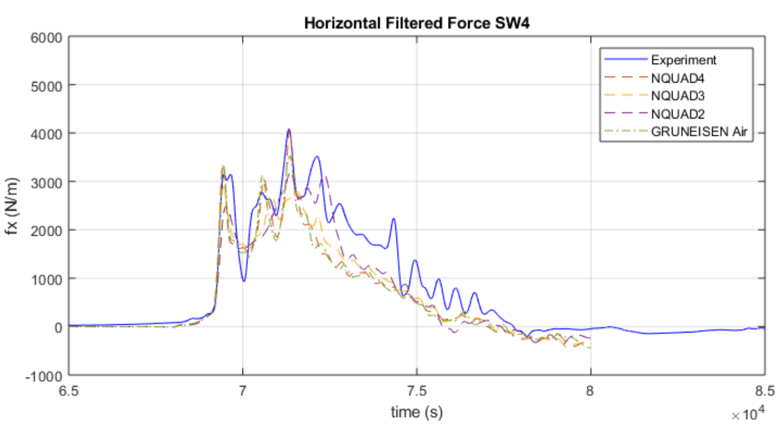


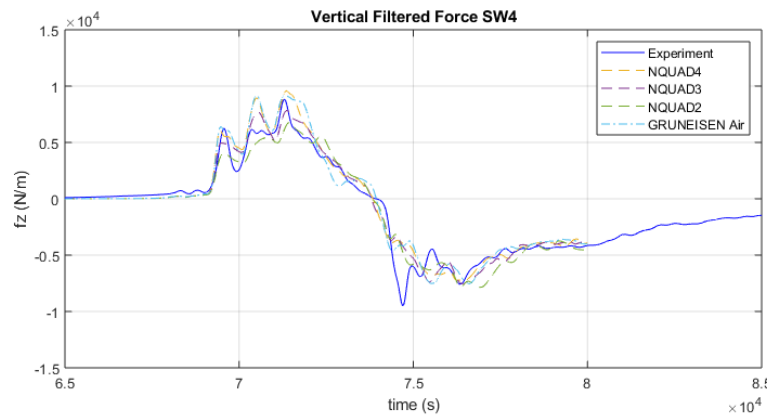


In order to speed-up numerical calculations:

- see if a truncated domain can provide reasonable results
- determined how large the computational domain should be







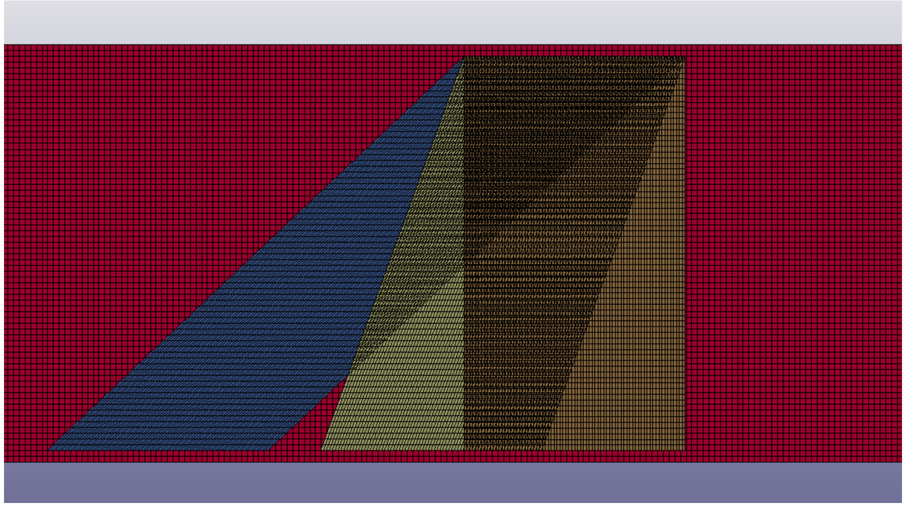
Numerical vs Experimental Results (Source: Istrati and Xiang (2020))

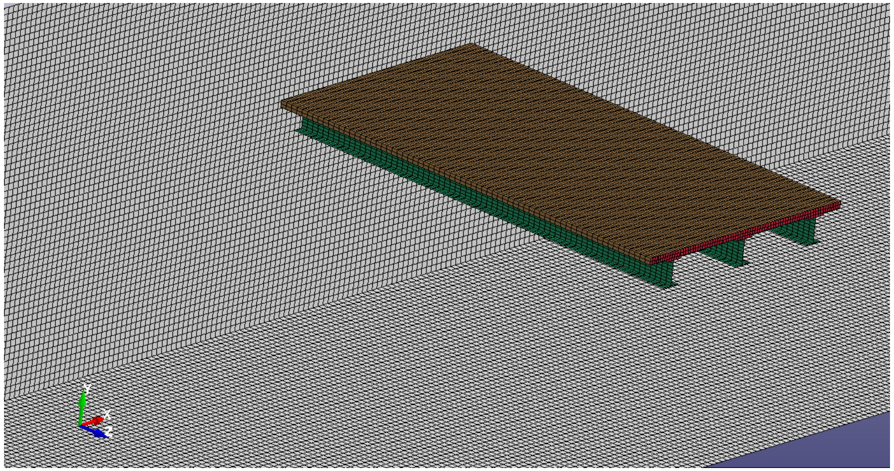
Parametric investigation of skew angle

- 3D models of skew bridges with a skew angle equal to **0, 5, 20, 15, 20, 30** and **45 degrees** have been developed and analyzed for several solitary waves, short-duration bores and long-duration bores

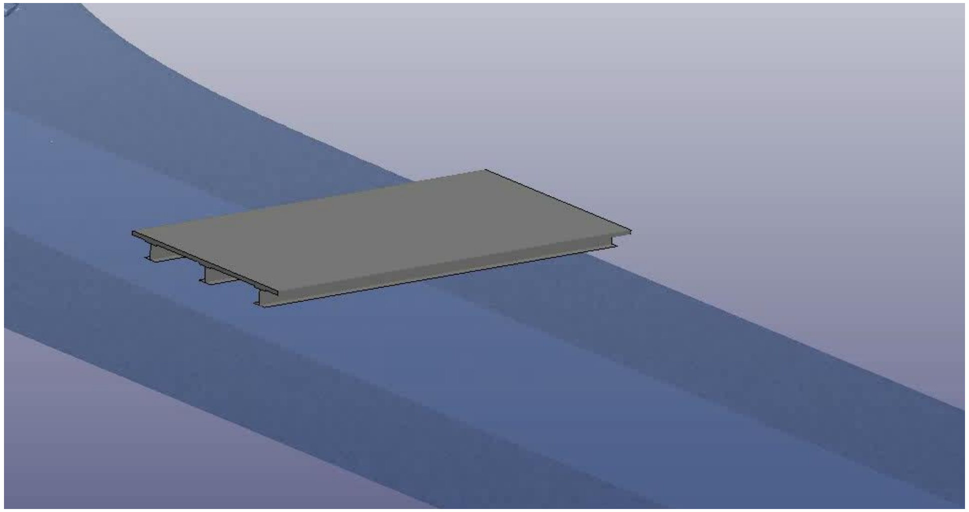
- Different types of bridges have been investigated including open-girder bridges with 3 and 5-girders and box-girder ones

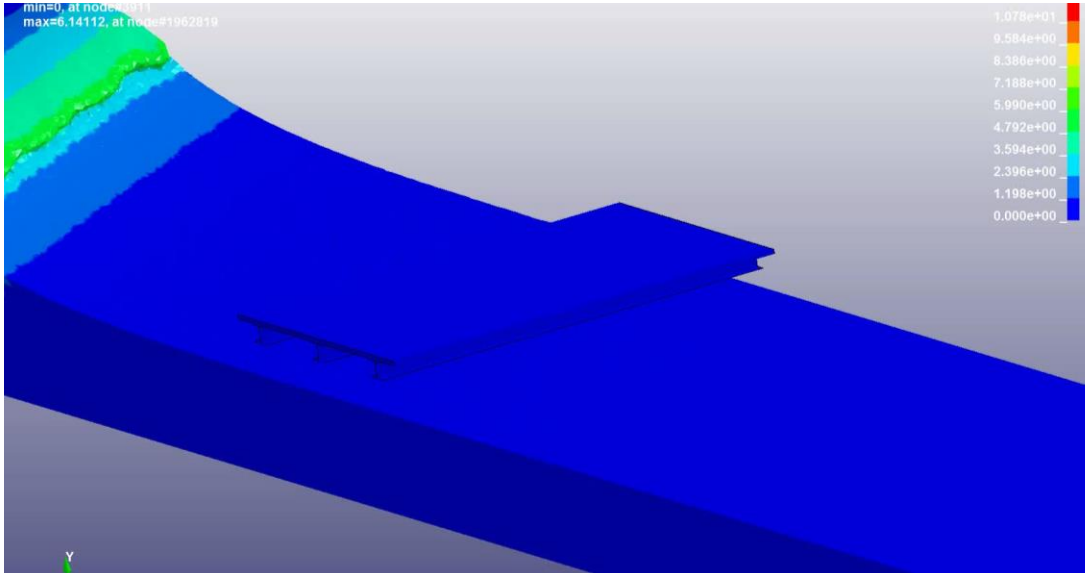
- Orientation of axes:
  X-axis = transverse
  Z-axis = longitudinal
  Y-axis = vertical



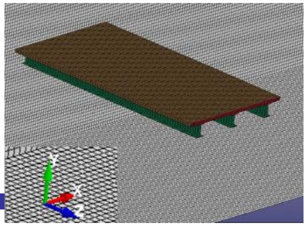


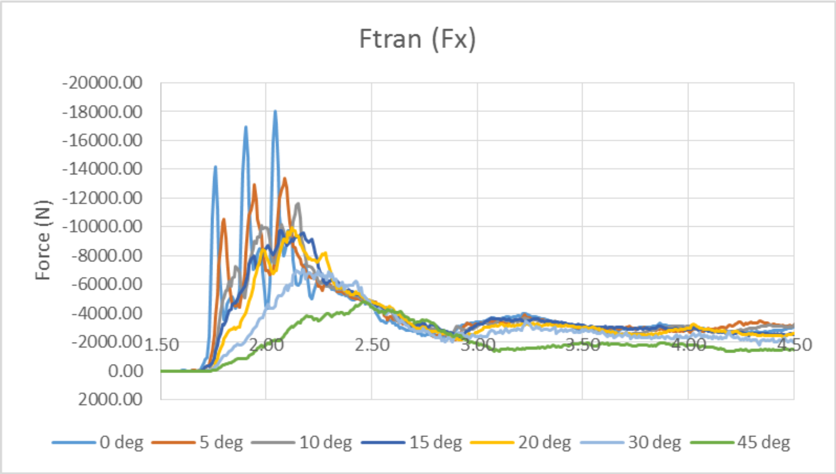
Parametric investigation of skew angle effect

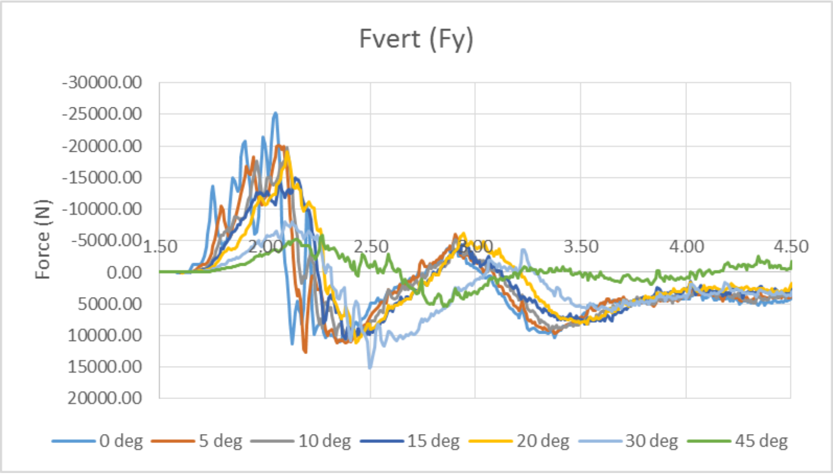


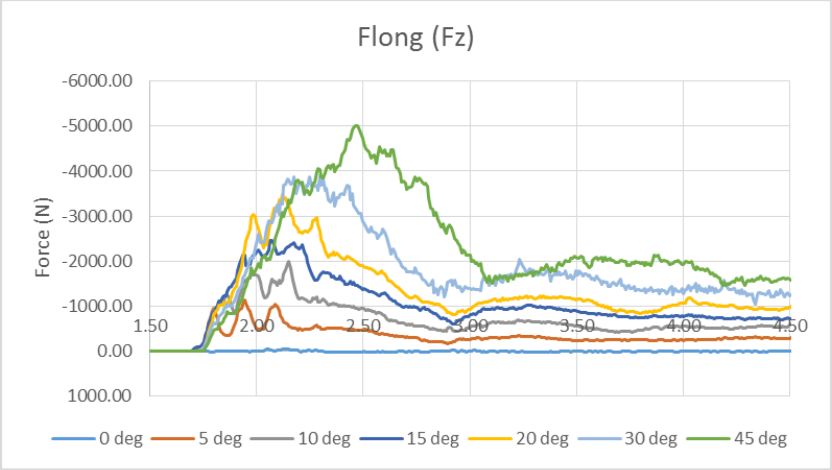


Skew Bridges: Forces



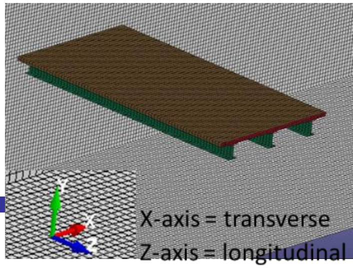


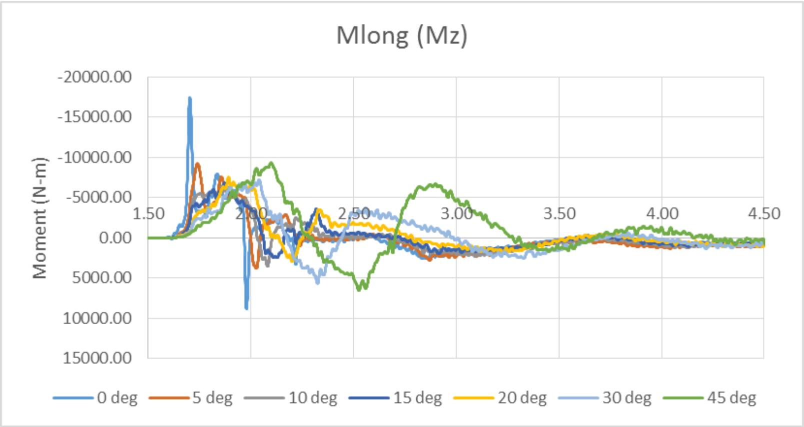




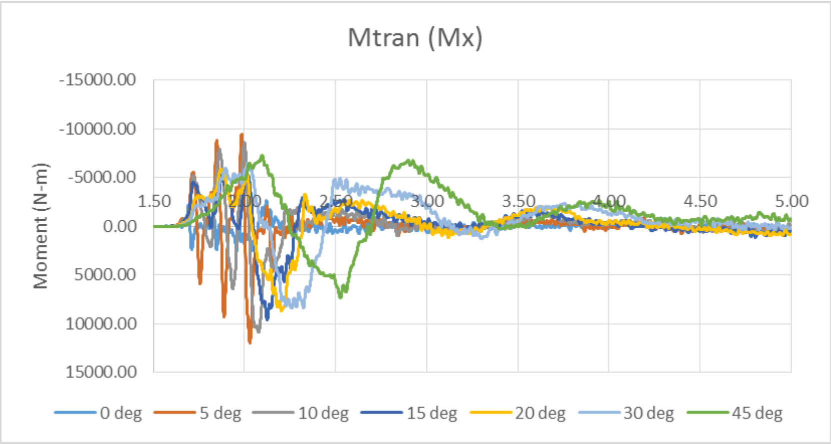
- The impulsive components of the transverse and vertical loading are decreasing with the skew angle. However, the increase of the skew angle generates a longitudinal force, which is normal to the direction of the flow and does not exist in straight bridges.
- Currently, no suggestion available in the literature about the longitudinal force. Depending on the skew angle this force can be quite significant!
- For example, for a 30 degrees skew angle $F_{longitudinal}$ is 58% of $F_{transverse}$.

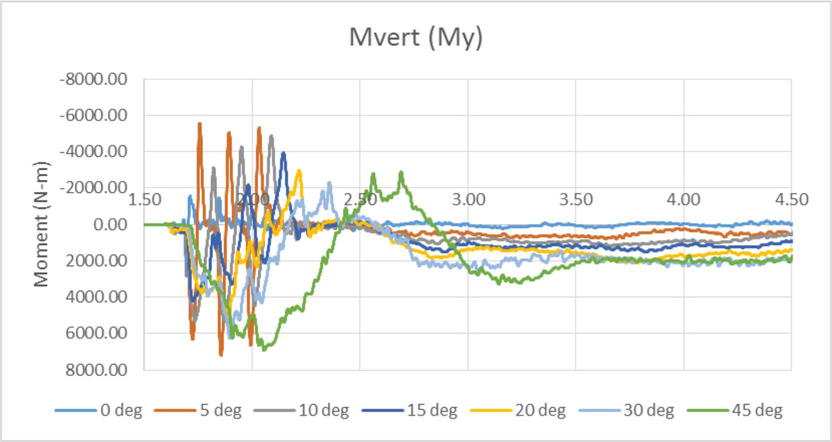
Skew bridges: Moments



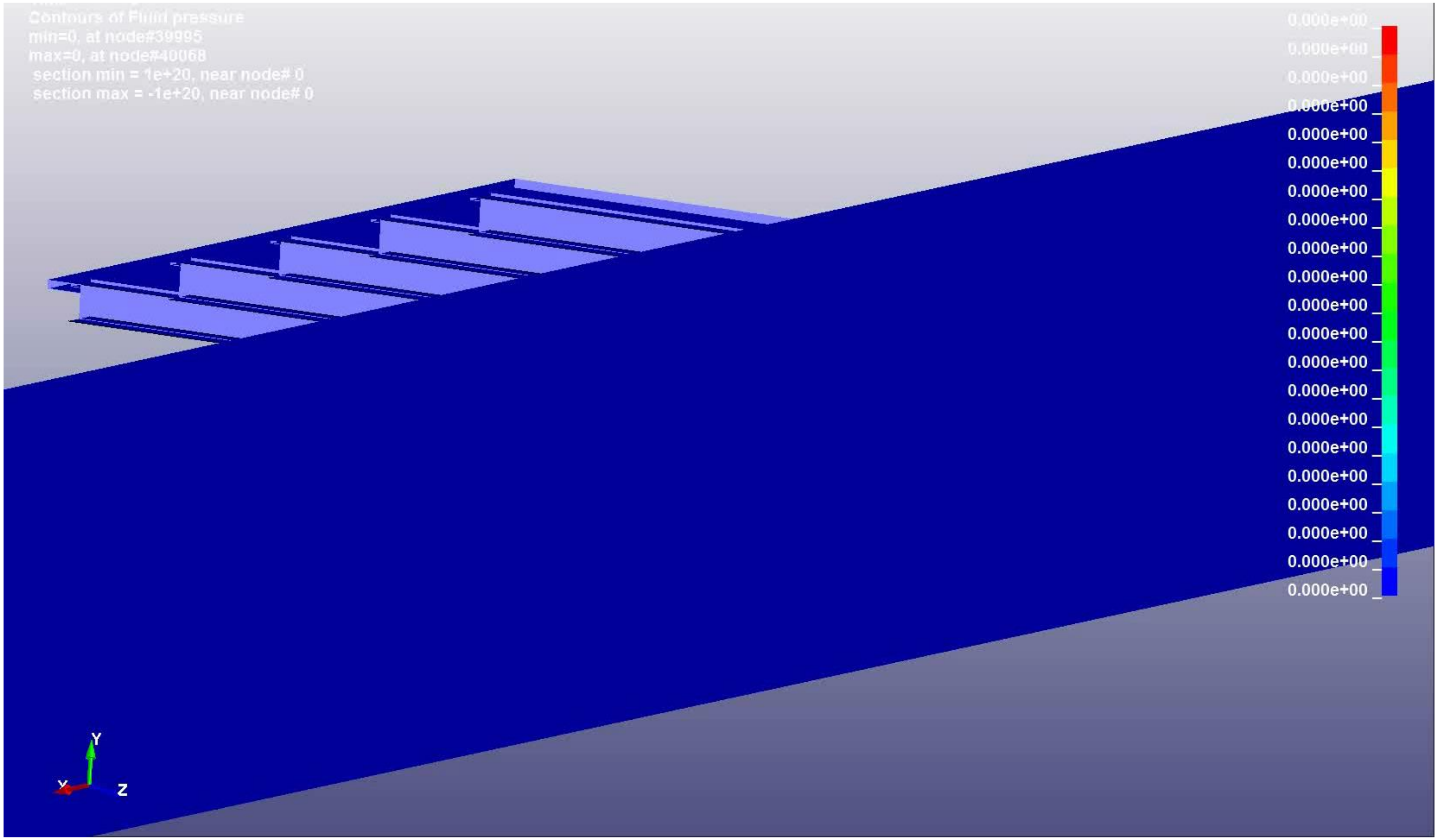


- The impulsive part of the overturning moment tends to reduce with the skew angle.
- However, due to the complex interaction of the bridge geometry with the hydrodynamic flow, additional significant moments are generated about the two axes, which result in the **non-uniform distribution of the tsunami forces to bearings, abutments and columns**.





Why?


Contours of Fluid pressure
min=0, at node#39995
max=0, at node#40068
section min = 1e+20, near node# 0
section max = -1e+20, near node# 0
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
Y
X
Z


Thank you!