Probabilistic Assessment of Coastal Bridge Vulnerability to Wave Loading During Hurricanes

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Presentation Contents

The Issue

To build hurricane-resistant coastal highway bridges for climate resilience.

The Research

Establish a reliable approach for probabilistic assessment of the susceptibility of existing coastal bridge inventories to hurricane-induced loading.

The Implications

Results can inform the development of improved design standards for coastal bridges and the selection of appropriate countermeasures to improve bridge stability.

The Issue

The Intergovernmental Panel on Climate Change (IPCC):

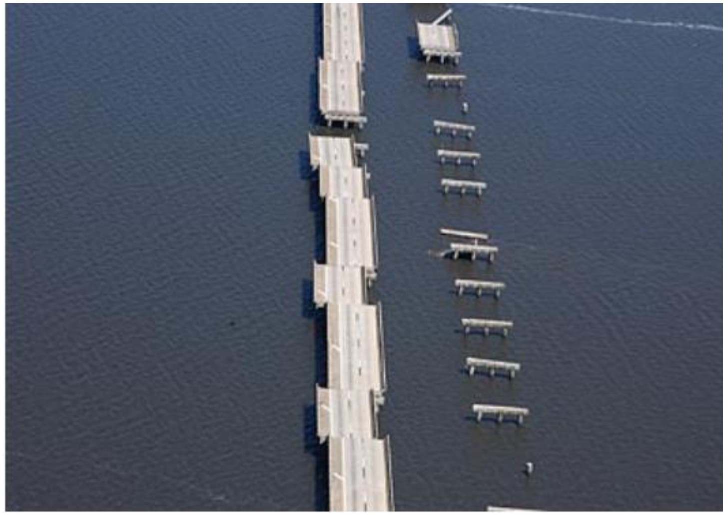
- Continuous increases in global temperature
  - Climate Change & Urbanization

More frequent, severe floods and hurricanes

- Since 1979, the probability of a tropical cyclone becoming a major hurricane (category three or higher) has increased globally by approximately 8% every decade [2].

- In the U.S. alone, 36-billion-dollar flood events occurred between 1980 and 2021, costing a total of approximately $168 billion [1].

Damage of US-90 during Hurricane Katrina, Source: [3]



Collapse of I-10 Escambia bridge during Hurricane Ivan, Source: [4]

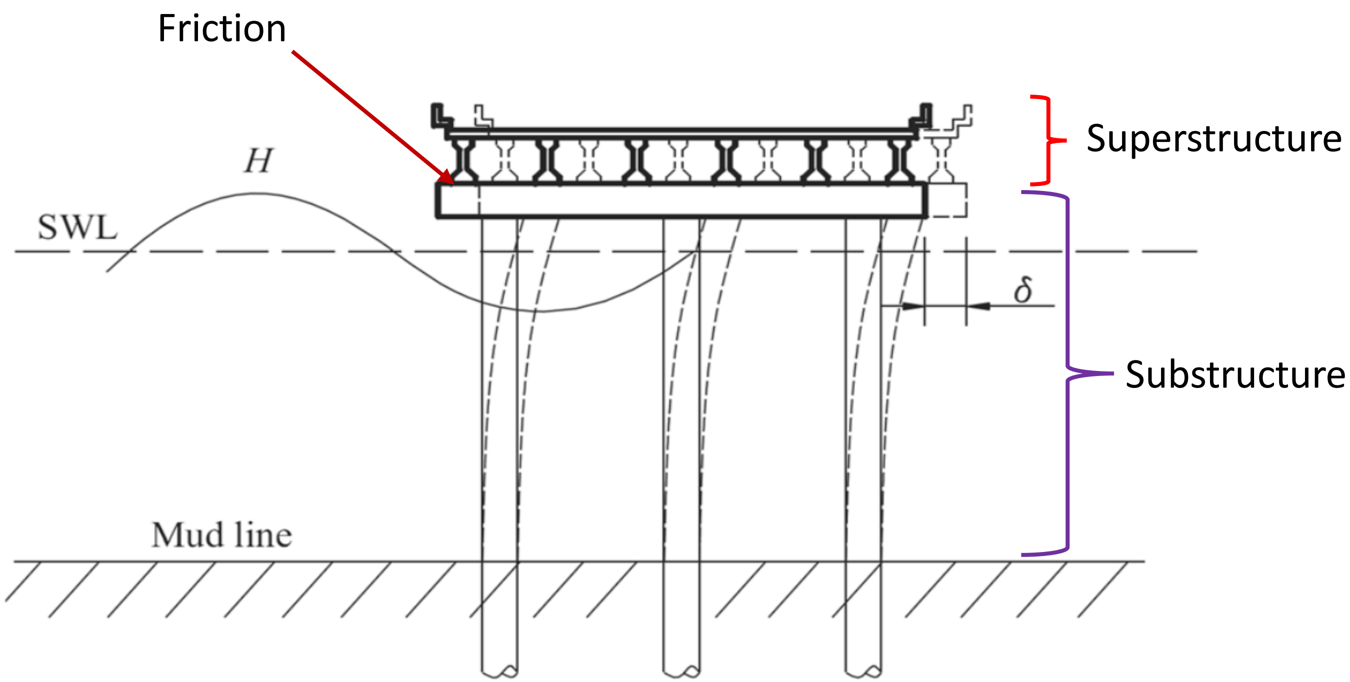
Damage of 7th street bridge at Port Bolivar during Hurricane Ike, Source: [5]

Collapse a bridge near Rosenberg, Texas during Hurricane Harvey, Source: [6]

The Issue: Bridge Failure Mechanisms

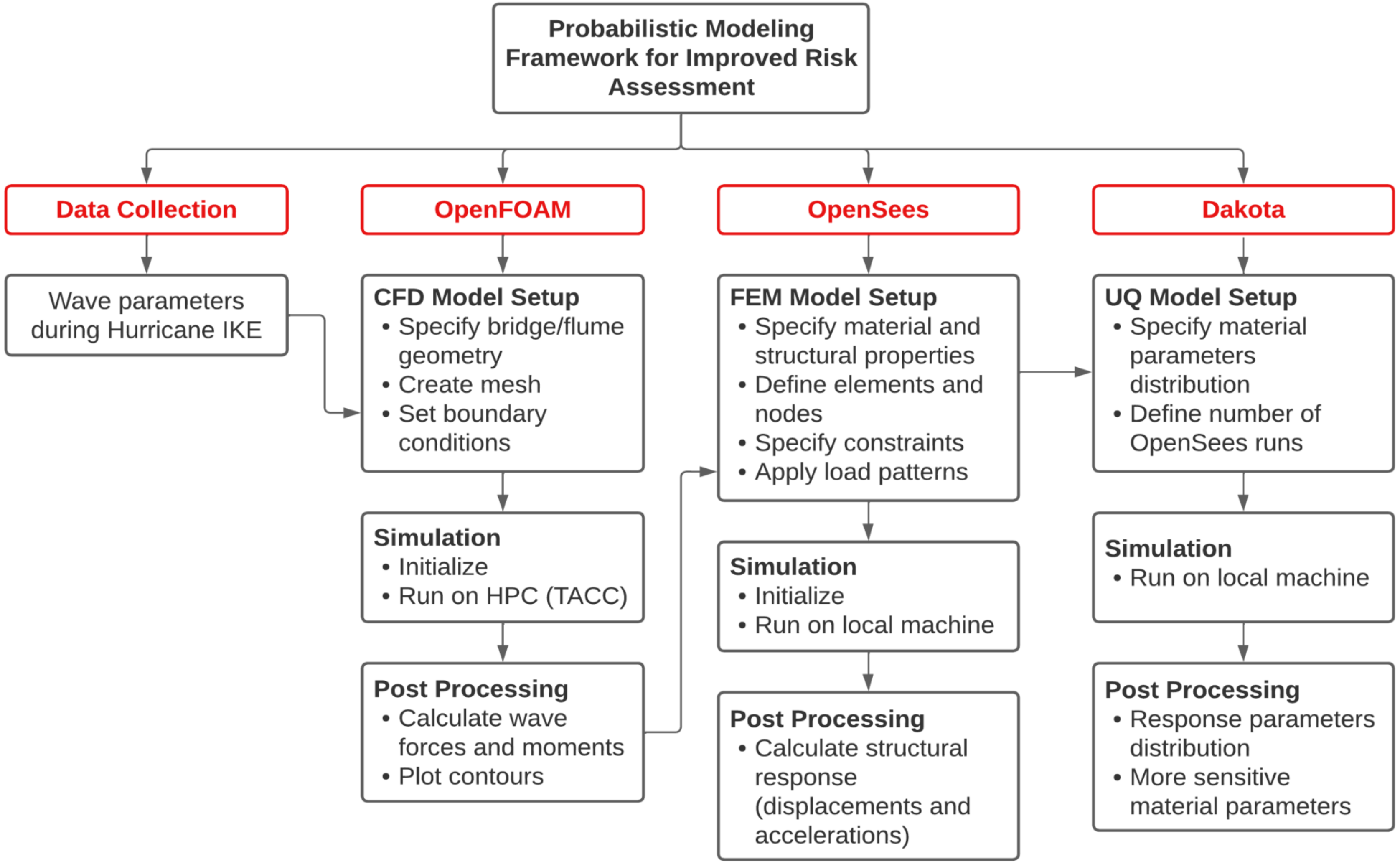
- ❑ The critical bridge deck failure mechanisms due to hurricane loading includes:

i. Sliding due to horizontal forces
ii. Uplifting due to vertical forces
iii. Overturning due to uneven distribution of the forces on the bridge decks



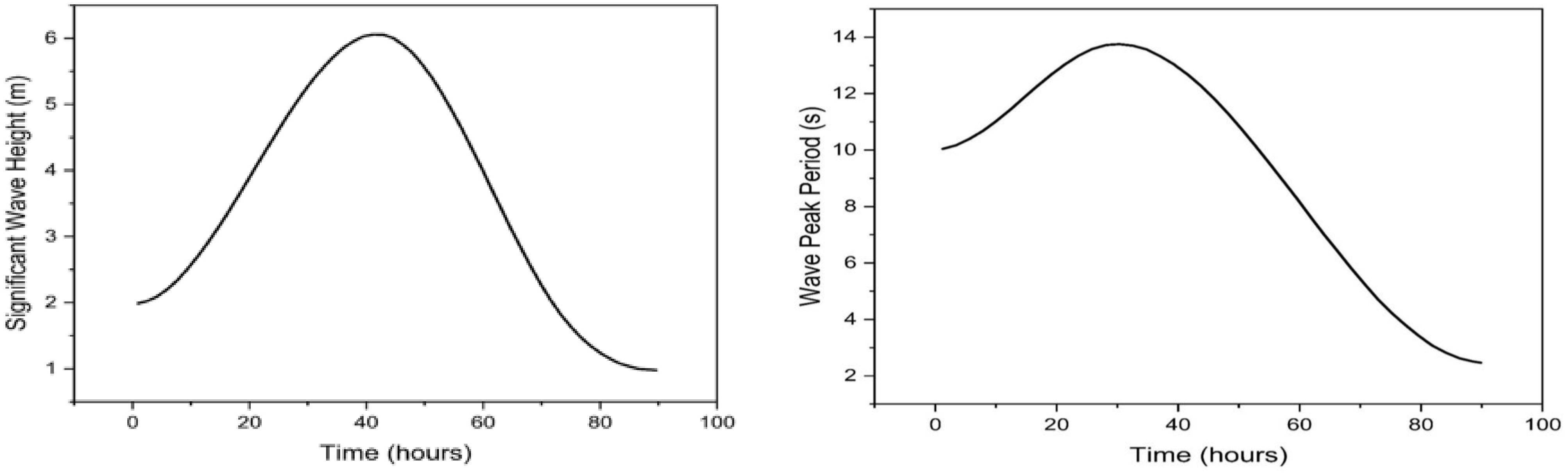
Schematic diagram for the bridge deck-wave interaction under extreme waves. H is the wave height; δ is the motion displacement of the bridge deck; SWL refers to the still water level
Source: [7]

The Research: Methods



Probabilistic framework for improved risk assessment

The Research: Data Collection

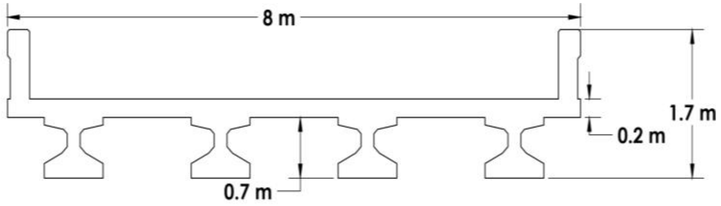


Time series of significant wave height and peak period during Hurricane Ike by rapidly deployed buoys in around 10m water depth along the Upper Texas Coast Source: [8,9]

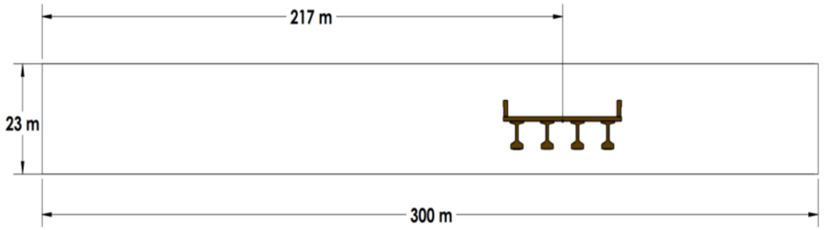
The Research: CFD Model Setup

Bridge geometry

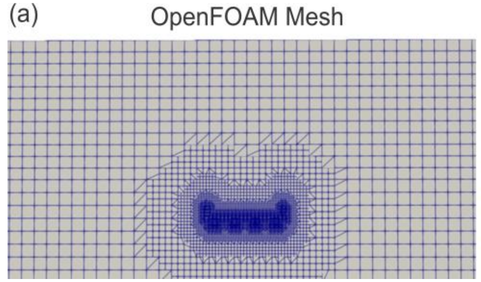
(Tx28)



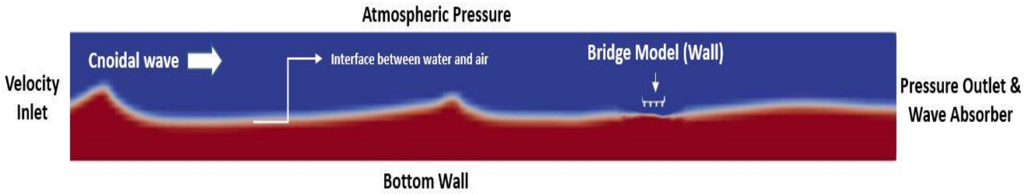
Flume dimensions



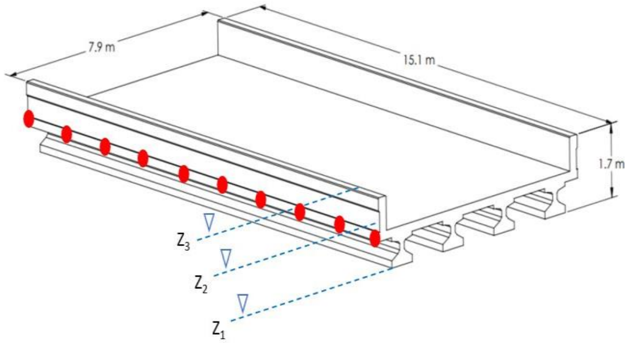
Meshing



Boundary conditions



Force capturing points (red circles) and Stillwater level scenarios (blue dash line)



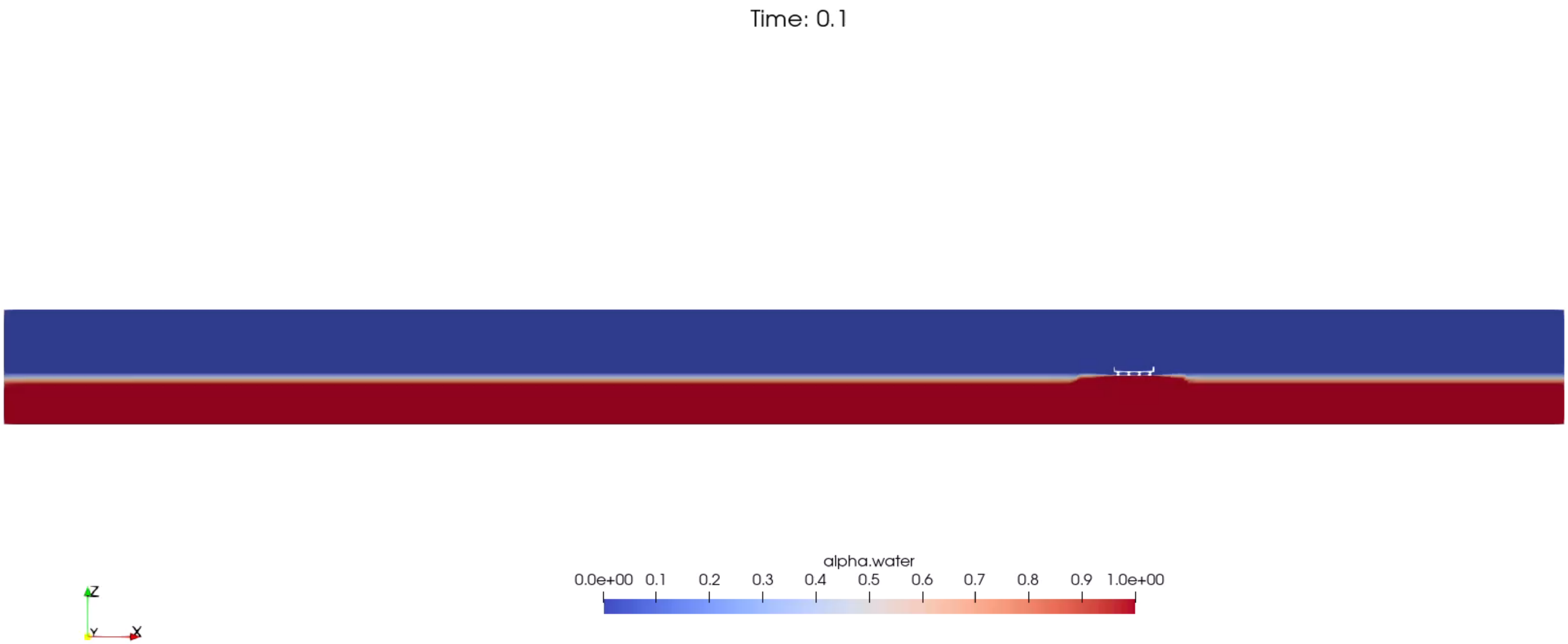
Run on TACC

- Normal Queue
- KNL cache-quadrant
- 5 nodes per simulation
- 340 mpi tasks
- 48 hours

Detail of numerical setup and HPC run

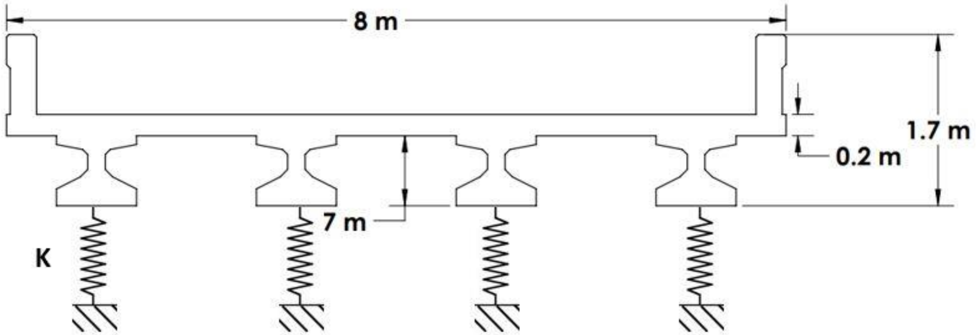
The Research: CFD Wave Modeling Animation

40th hour of the storm during Hurricane IKE (H_s = 6.04 m and T_p = 12.80 s), SWL is at Z_1

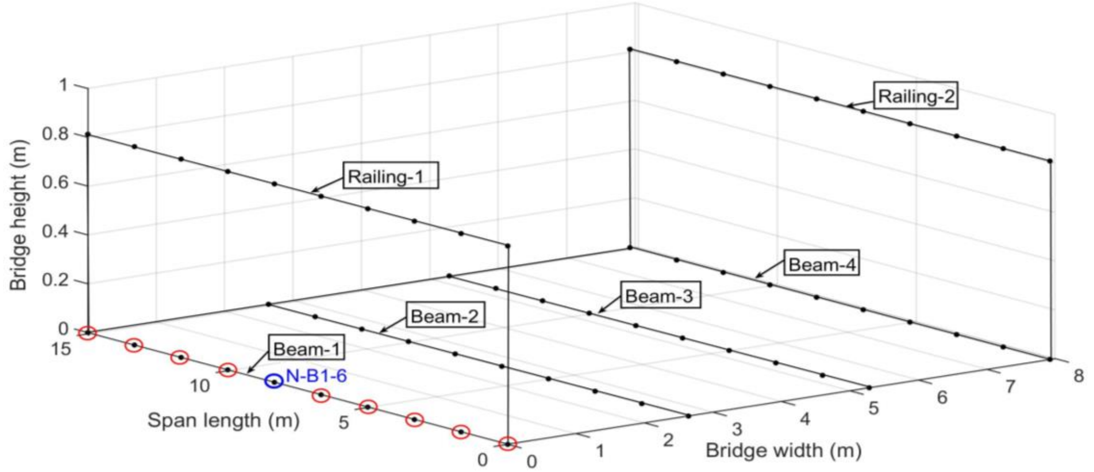


The Research: FE and UQ Model Setup

FEM

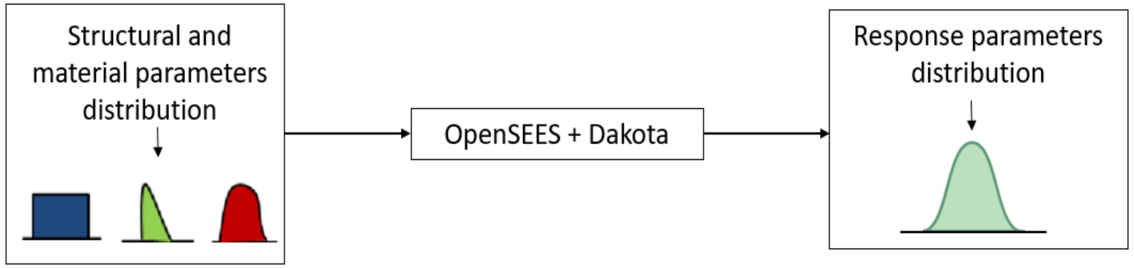


Bridge model with bearing constraints



Node configuration of the finite element model (FEM)

UQ

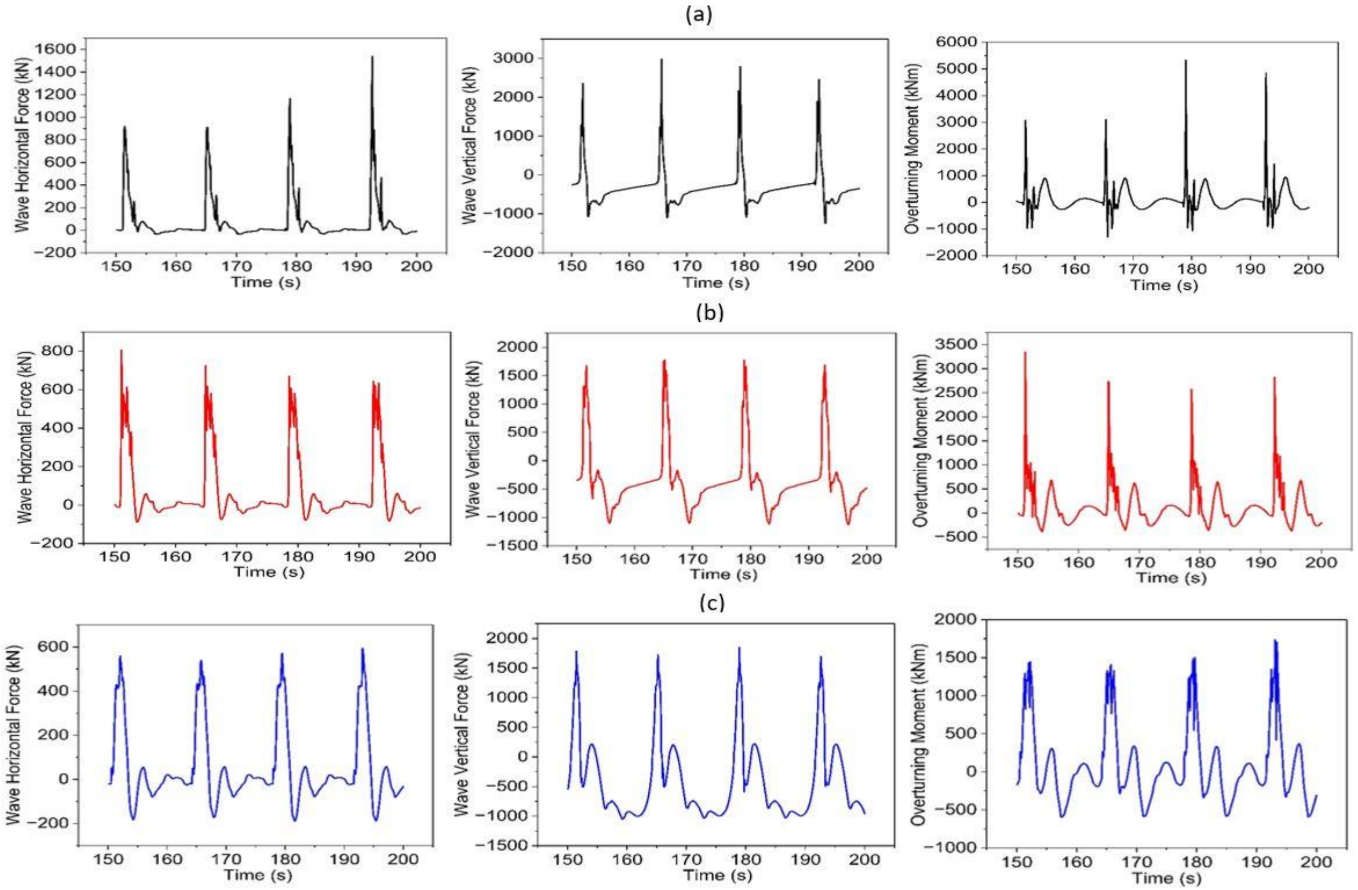


Uncertainty analysis of structural response

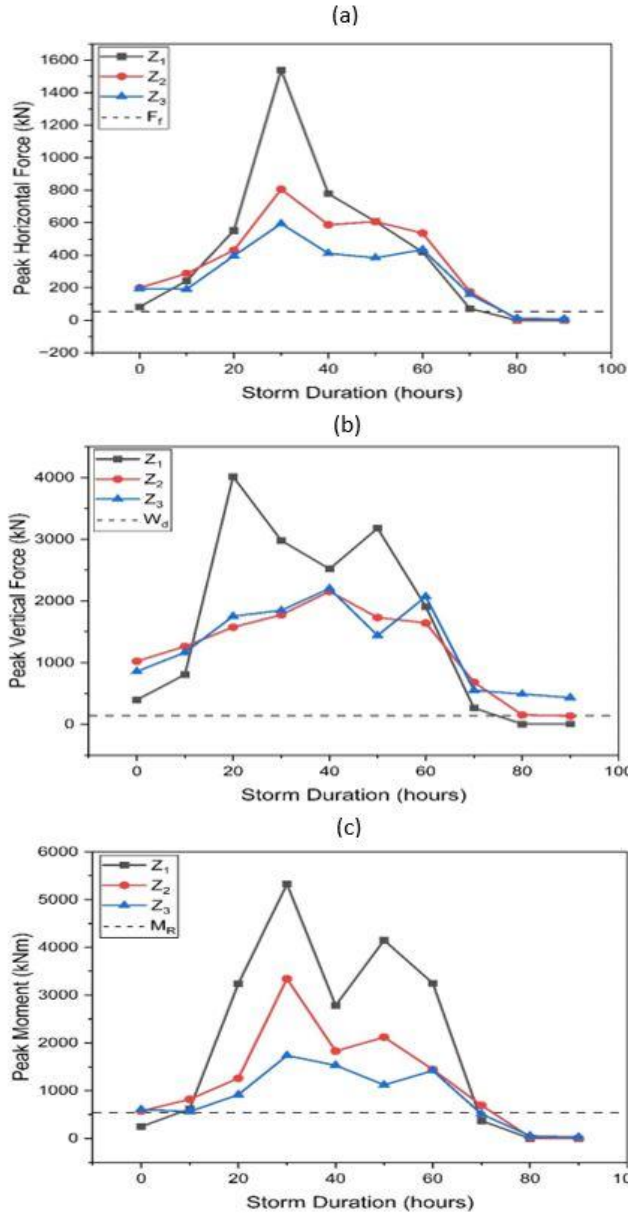
Parameters	Distribution	Values	Units
Modulus of elasticity (E)	Normal	N(5000,500)	ksi
Concrete density (γ)	Normal	N($8.68e^{-5}$,$3.47e^{-6}$)	k/in^3
Lateral stiffness of bearings (K_L)	LogNormal	LN(0.4,0.048)	k/in

Variables for uncertainty analysis with probability distributions and values
Source: [10,11]

Results: Wave Forces and Bridge Deck Failure Mechanisms



Set of plots showing time history of wave loading at the 30th hour of the storm when Stillwater level is at a) Z_1 b) Z_2 and c) Z_3



a) Peak Horizontal Forces

b) Peak Vertical Forces

c) Peak Moments

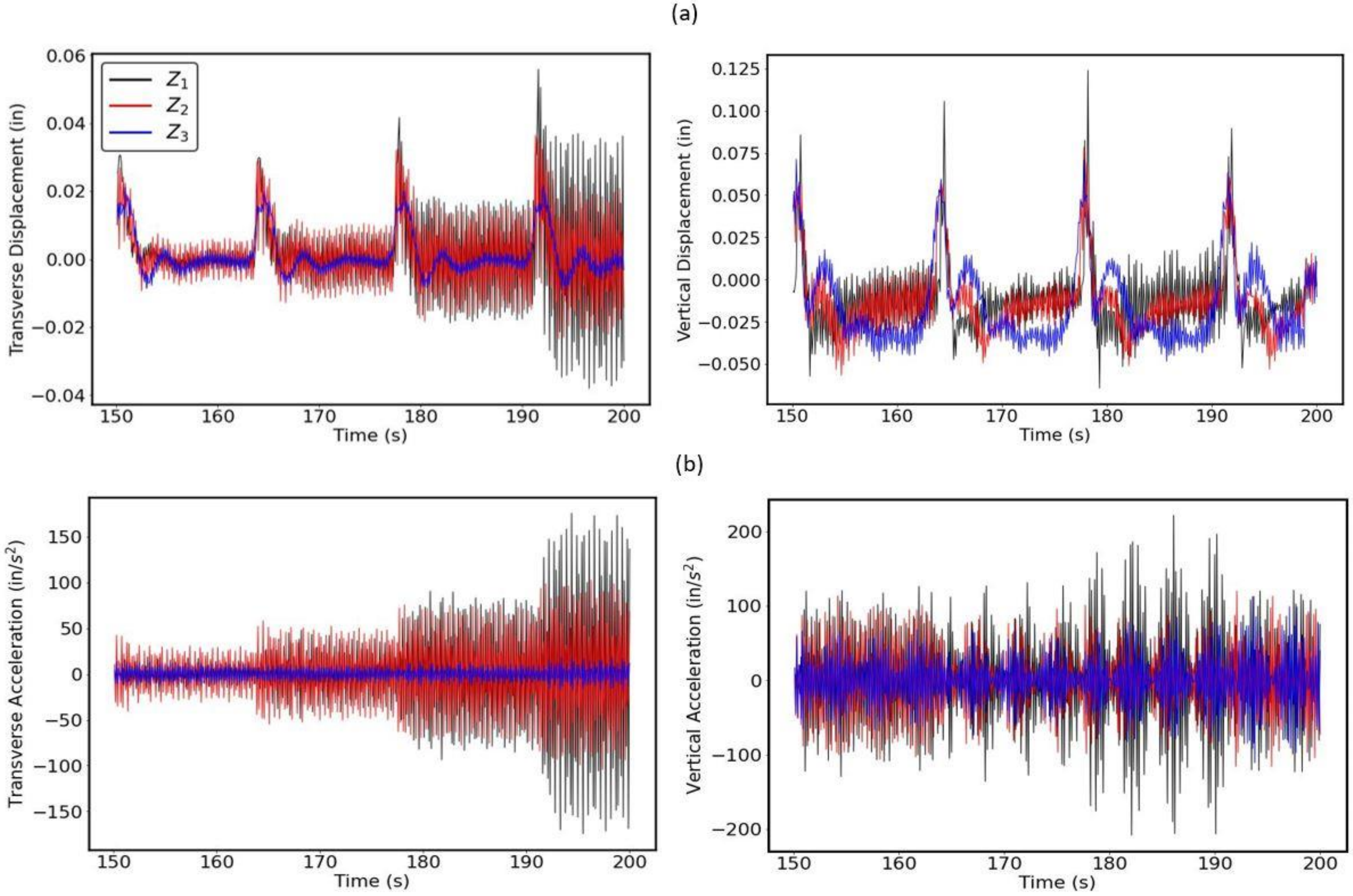
Peak wave forces and overturning moments under different storm hours and SWL scenarios

Results: Structural response of bridge under different loading conditions

Peak Transverse Acceleration = 157 in/s^2

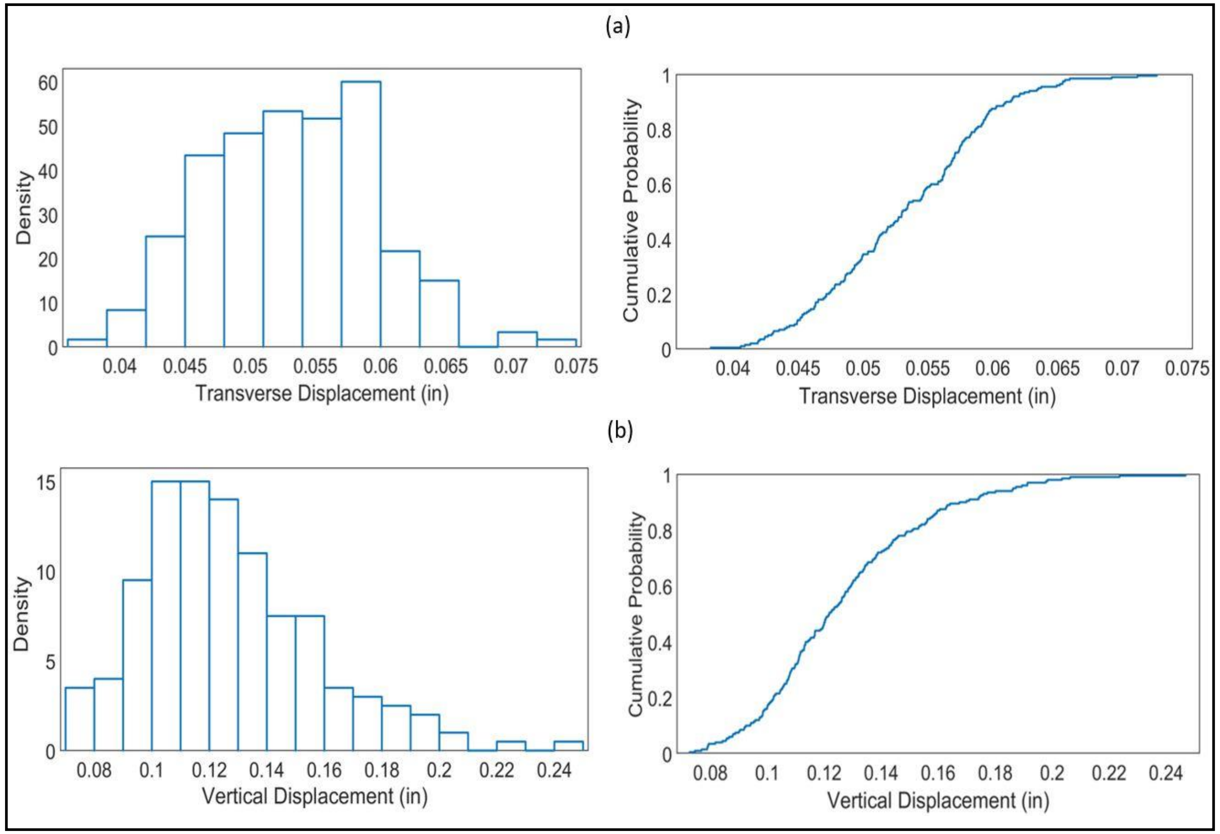
Peak Vertical Acceleration = 210 in/s^2

FHWA LRFD limit = 100 in/s^2

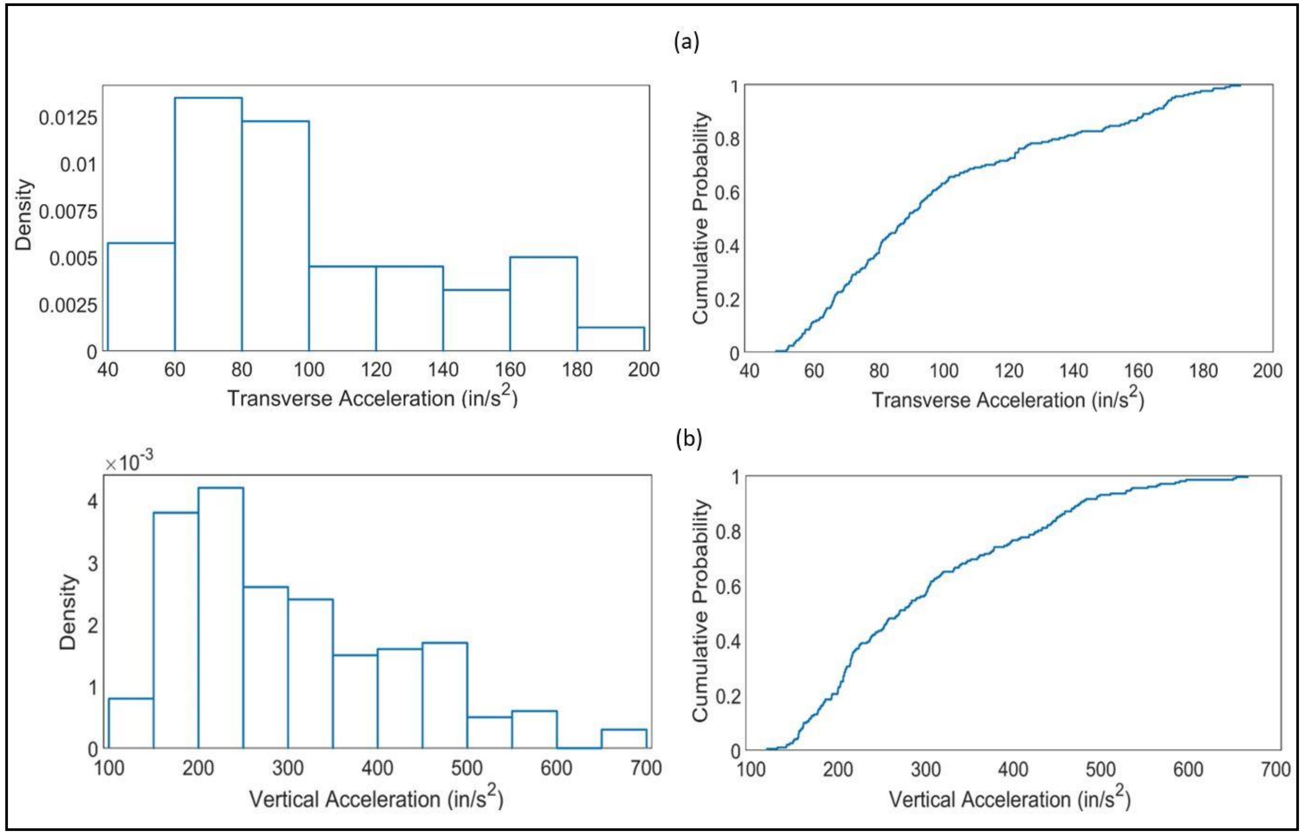


Set of plots showing time history of a) transverse and vertical displacements, b) transverse and vertical accelerations, at node N-B1-6

Results: Uncertainty in Structural Response



Density and CDF of a) transverse displacement, b) vertical displacement



Density and CDF of a) transverse acceleration, b) vertical acceleration

- FEM computes a deterministic structural response due to wave loading while accounting for uncertainties in the most sensitive material parameters, indicating the spectrum of bridge response parameters, which can aid in risk analysis and decision-making.

Results: Most Sensitive Material Parameters

Random Variable	SSI (δ_t)	SSI (δ_v)	SSI (A_t)	SSI (A_v)
Modulus of elasticity (E)	0.172	0.13	0.189	0.015
Concrete density (γ)	0.262	0.632	0.306	0.675
Lateral stiffness of bearings (K_L)	0.567	0.238	0.505	0.311

Sobol sensitivity indices of material parameters

SSI = Sobol sensitivity index
δ_t = Transverse displacement
δ_v = Vertical displacement
A_t = Transverse acceleration
A_v = Vertical acceleration

- Concrete density is the most sensitive parameter in case of vertical stability while lateral stiffness of bearings is the most sensitive parameter in case of horizontal stability.

- Sensitivity analysis aids in categorizing bridge inventory in coastal areas regarding storm susceptibility, determining the locations with the most significant surge and wave influence, and identifying more sensitive bridges based on age and bridge material attributes. These findings also highlight modeling variables that bridge reliability analysis should carefully consider.

The Implications

- Long-wavelength waves have a substantial impact on bridge stability
- Concrete density is a critical structural parameter affecting vertical stability and Lateral stiffness of bearing is a key factor influencing horizontal stability of the bridge
- Informs more robust bridge vulnerability model
- Enhance understanding of bridge behavior in extreme coastal conditions
- Improved quantification of failure probability for coastal bridges
- Enhance prioritization of maintenance and retrofitting in coastal regions
- Advances past research by accounting for time-varying wave histories, simulating dynamic structural response, and including uncertainties in material properties
- Probabilistic framework developed for coastal bridge, the approach can also be used for riverine bridge risk assessment

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Thank you!

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Picture credit: Mark Wilson [12]