



AECOM

 2025 Spring Conference


Hydrodynamic Impact of Flood Debris Accumulation on Bridges Using CFD Modeling

Presenter:
Fahad Pervaiz, PhD, PE, CFM, ENV SP
 Water Resources Engineer
 AECOM, a member of Compass PTS JV
fahad.pervaiz@aecom.com

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Presentation Contents

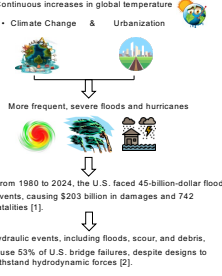

- Overview and Background
- Methodology
- Conclusions
- Future Recommendations




Overview & Background

The Intergovernmental Panel on Climate Change (IPCC):


- Continuous increases in global temperature
 - Climate Change & Urbanization
- More frequent, severe floods and hurricanes
- From 1980 to 2024, the U.S. faced 45-billion-dollar flood events, causing \$203 billion in damages and 742 fatalities [1].
- Hydraulic events, including floods, scour, and debris, cause 53% of U.S. bridge failures, despite designs to withstand hydrodynamic forces [2].

Collapse of Llano River bridge in Texas
Source: [3]



Collapse of Blanco River bridge in Texas
Source: [4]



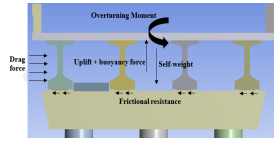
Rising flood water at Shoal Creek in Texas
Source: [5]

3

Overview & Background

Bridge Failure Mechanisms:

- Critical bridge deck failure mechanisms due to hydrodynamic loading includes:
 - i. Sliding due to drag forces
 - ii. Uplifting due to lift and buoyancy forces
 - iii. Overturning due to uneven distribution of the forces on the bridge decks



Hydrodynamic forces acting on the bridge deck Source: [6]
(Created by Bhupendra Raj Acharya)

Hydrodynamic Forces:

$$F_D = \frac{1}{2} \rho_w C_D A_D V^2 \quad (\text{drag force})$$

ρ_w = water density,

$$F_L = \frac{1}{2} \rho_w C_L A_L V^2 \quad (\text{lift force})$$

$C_D, C_L,$ and C_M = drag, lift force, and moment coefficients

$$M_{cg} = \frac{1}{2} \rho_w C_M L W^2 V^2 \quad (\text{overturning moment})$$

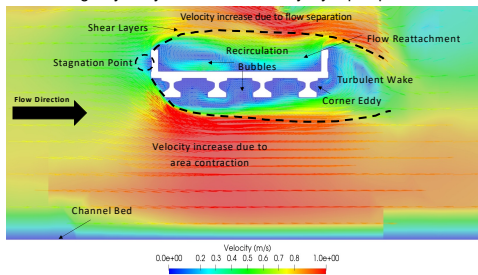
V = Flow velocity

Source: [7]

4

Overview & Background

Bridge Hydrodynamics—A boundary layer perspective



Velocity flow field around bridge deck Tx28 with 8 m deck width for $Fr=0.2, h^*=2.5$

5

Overview & Background

- Debris accumulation during storms could significantly alter hydrodynamic forces on bridges, highlighting a need for further research [3]



Source: USGS



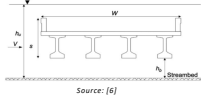
Source: USGS



6

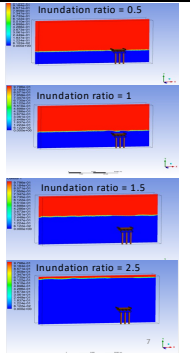
Overview & Background

Hydraulic and Geometric parameters



$$\text{Inundation ratio } h^* = \frac{h_u - h_c}{s}$$

$$\text{Froude number } Fr = \frac{V}{\sqrt{g h_u}}$$



Overview & Background

What is CFD?

- Computational Fluid Dynamics (CFD), is the science of predicting fluid flow, and related phenomena by using numerical methods and computers.
- To predict these phenomena, CFD finds the approximate numerical solution of the governing equations (conservation of mass, momentum and additional transport equations and models) [9].

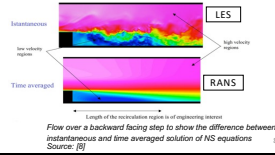
Navier-Stokes (NS) Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (\text{conservation equation for mass})$$

$$\rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} \cdot \nabla) \vec{V} = -\nabla p + \rho \vec{g} + \nabla \cdot \tau_{ij} \quad (\text{conservation equation for momentum})$$

Methods

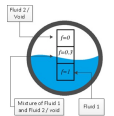
- Reynold Average NS Equations (RANS)
 - Solved time averaged Navier Stokes equations
 - Computationally efficient
- Large Eddy Simulation (LES)
 - Only large eddies resolved
- Direct Numerical Simulation (DNS)
 - Resolve every fluctuating motion in the flow
 - Computationally expensive



Overview & Background

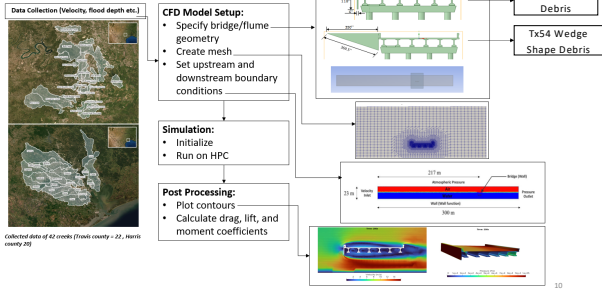
What is OpenFOAM® ?

- OpenFOAM® stands for Open-Source Field Operation and Manipulation
- OpenFOAM® is an opensource CFD solver of the Navier-Stokes equations
- Extensive turbulence modeling capabilities (RANS and LES).
- Free surface modeling based on Volume of Fluid method
- Structured rectangular grid meshing
- Full parallelization for high performance computing
- Powerful post-processing using Paraview

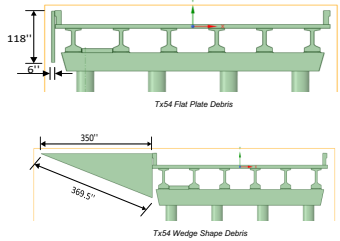


Note: There are other software, i.e., ANSYS, FLOW-3D, STAR CCM+ are available in the market, but they are not open source like OpenFOAM®.

Methodology



Debris Configurations



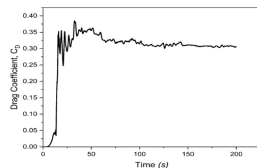
Grid Convergence Study and Model Run

Grid Convergence Study

Elements	Drag (N)	% Diff. (Drag)
3,205,038	1.34	2.46
817,924	1.31	9.17
204,512	1.2	20.85
63,608	0.99	-

Compute Node Specifications

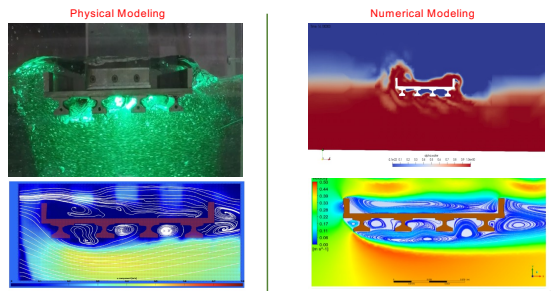
HPC	RAM	Cores	Threads	Processor
UTA	512 GB	22	44	Intel(R) Xeon(R) CPU E5-2699 v4
TACC	96 GB	68	272	Intel Xeon Phi 7250 (Knights Landing)



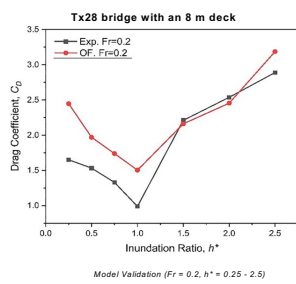
Convergence for (a) drag, (b) lift, and (c) moment coefficients in OpenFOAM for a full-scale box-beam bridge deck with $Fr = 0.8$ and $H^+ = 2.5$

12

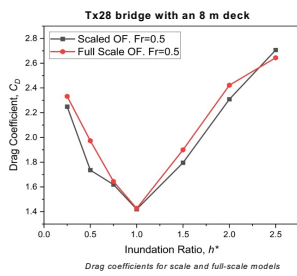
Results: CFD Modeling Animation and Validation



Results: Model Validation



Results: Scaling Effects



Results: Summary of Flow Parameters

Summary of Flow Parameters (FEMA & TxDOT)

County	Annual exceedance probability (AEP) (%)	Maximum subcritical Froude number	Maximum inundation ratio (h*)
Travis	2	0.9	2.5
—	1	0.9	3.6
	0.2	0.9	4.9
Harris	2	0.6	1.5
—	1	0.7	1.6
	0.2	0.7	1.9

16

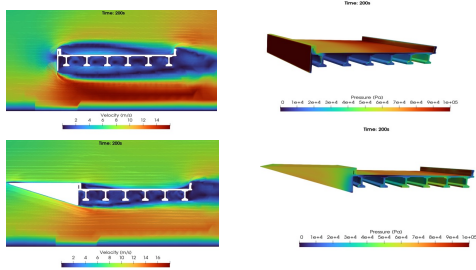
Results: Drag Forces

CFD Modeling Results ($Fr = 0.9$ and $h^* = 2.5$)

Bridge type	Deck width (m)	Span length (m)	Total drag force (kN)	Drag force per unit length (kN/m)
Tx54	14	38	7,162	188
Tx54 (debris flat plate)	14	38	10,409	274
Tx54 (debris wedge-shaped)	14	38	4,515	119

17

Results: Velocity and Pressure Contours



Velocity and pressure distributions for Tx54 flat plate debris; and Tx54 wedge-shaped debris damming configurations.

18

Conclusions & Recommendations

- ❑ OpenFOAM CFD modeling enhances flow simulation flexibility, complementing physical models.
- ❑ Drag forces are influenced by flow blockage area and the upstream edge shape.
- ❑ Flat plate debris causes a 46% increase in drag force compared to no-debris conditions.
- ❑ Streamlined debris (e.g., wedge-shaped) reduces wakes, upstream pressures, and drag forces.
- ❑ Findings guide robust countermeasure designs to mitigate hydraulic failures in bridges.
- ❑ CFD is attractive to industry since it is more cost-effective than physical testing. However, one must note that complex flow simulations are challenging and error-prone and it takes a lot of engineering expertise to obtain validated solutions.
- ❑ Further studies needed for multi-span bridges and 3D terrain-based CFD for real bridge sites.

19

Thank you!

For more info, contact:
fahad.pervaiz@aecom.com

Acknowledgments:

UT Arlington: Dr. Michelle Hummel, Dr. Habib Ahmari and Dr. Simon Chao's
Research Group

Texas Department of Transportation (TxDOT) Project 0-7068

20

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21
