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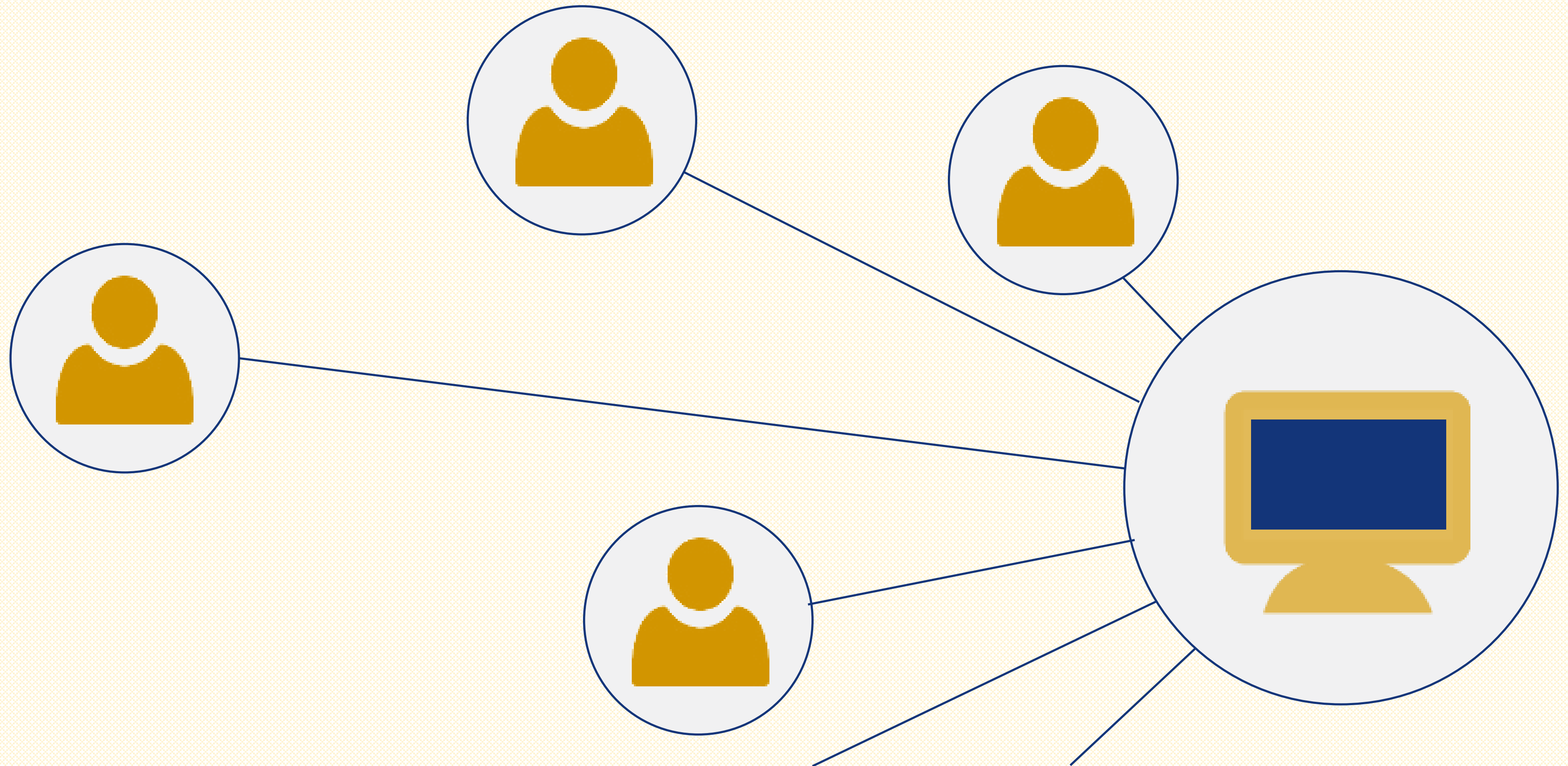
Transportation Infrastructure Resilience to Extreme Weather Events

Tran-SET



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Forecasting Flood Impacts to Transportation Infrastructure

Dr. Jon Miller
Stevens Institute of Technology

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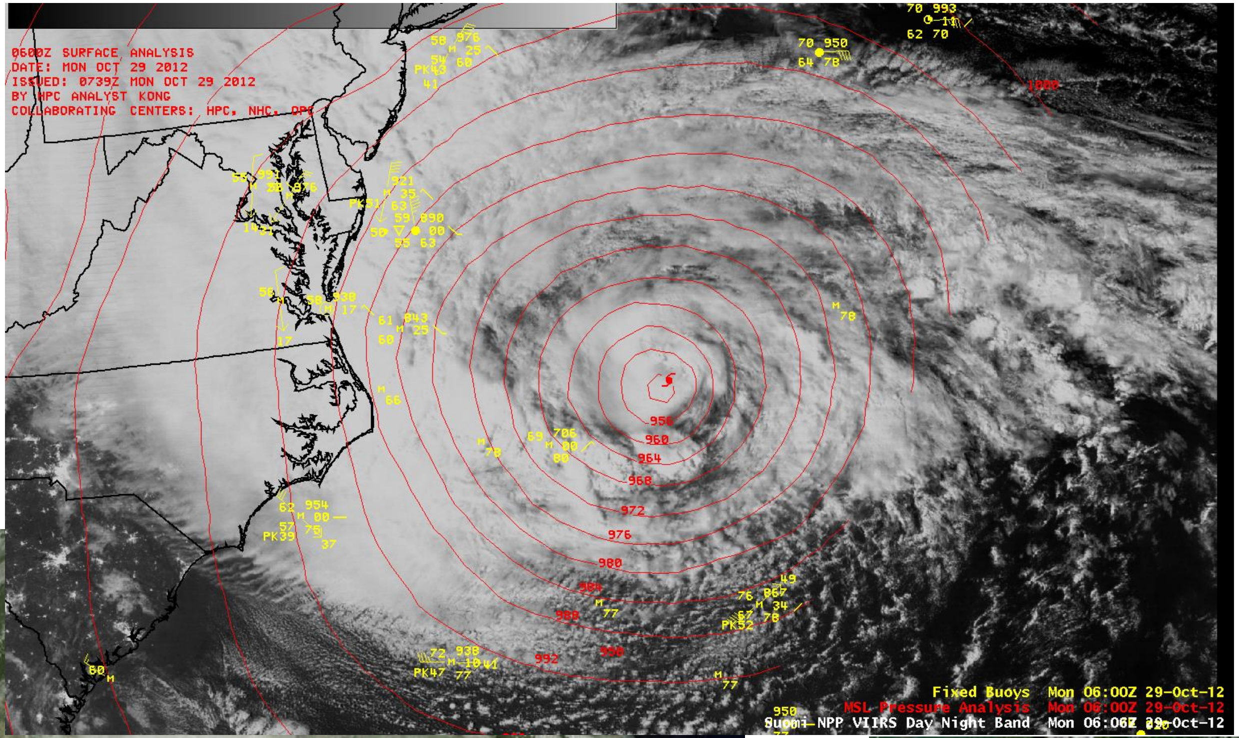
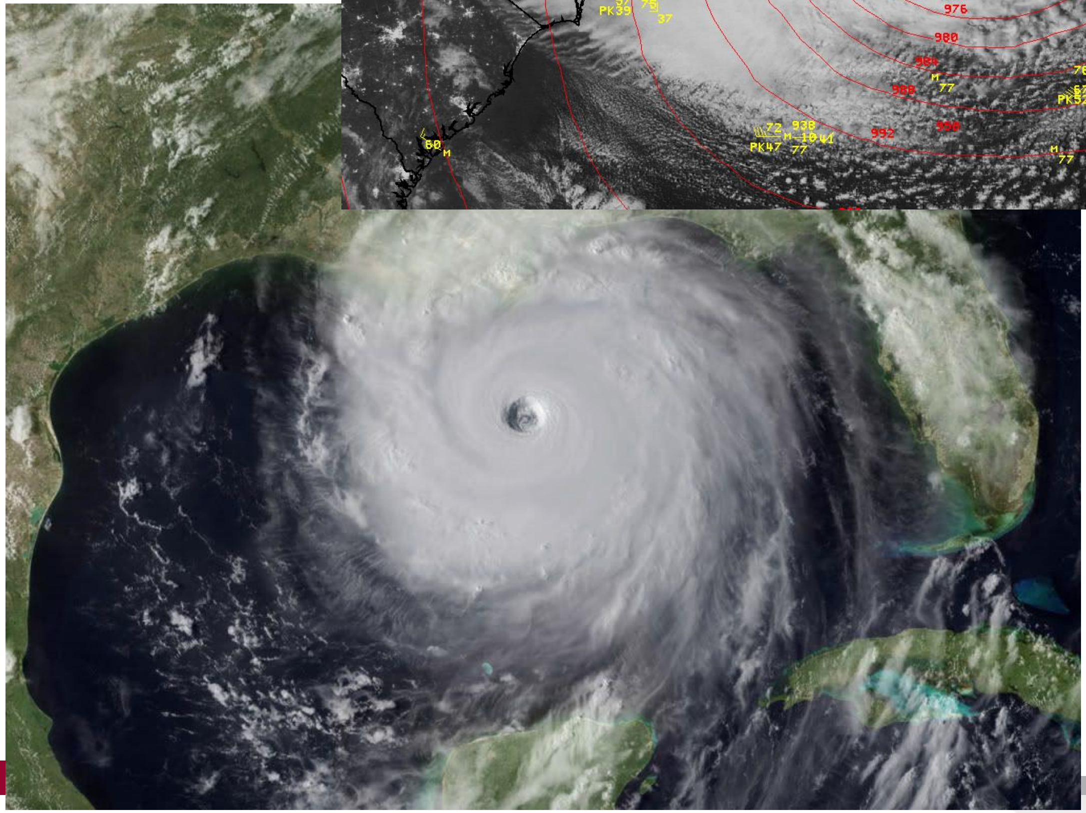
Forecasting Flood Impacts to Transportation Infrastructure

Jon K. Miller
Research Associate Professor
Department of Civil, Environmental, and Coastal Engineering
Stevens Institute of Technology

Why?


0600Z SURFACE ANALYSIS
DATE: MON OCT 29 2012
ISSUED: 0739Z MON OCT 29 2012
BY HPC ANALYST KONG
COLLABORATING CENTERS: HPC, NHC, OPC
Fixed Buoys Mon 06:00Z 29-Oct-12
MSL Pressure Analysis Mon 06:00Z 29-Oct-12
Suomi-NPP VIIRS Day Night Band



Which results in

Observed Transportation System Impacts

Flooding of:

- Major highways
- Freight and passenger rail
- Airports
- Port facilities

Structural Damage to:

- Marine terminals
- Bridges and tunnels
- Roadways

Advanced Warning Critical for Preparation

Knowledge of location, time, and severity of inundation important

Preparations to protect critical infrastructure and move vulnerable populations require 72 to 96 hour lead times

Accurate high-resolution forecasts required to allocate limited resources correctly

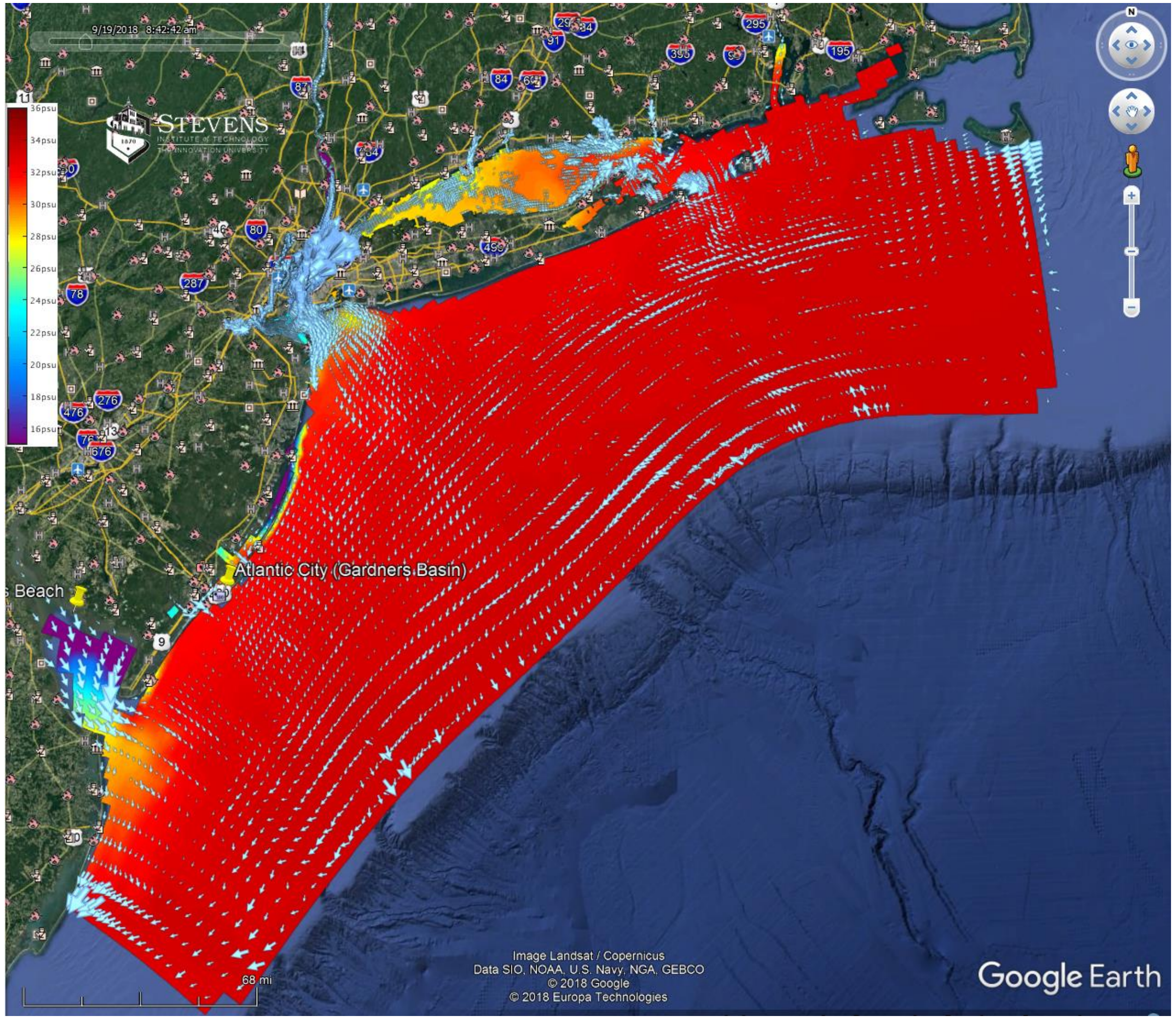
Evacuation capability limited within 24 hours of event

Development of Stevens Dynamic Overland Inundation Modeling System

New York Harbor Observation and Prediction System (NYHOPS)

- Derivative of the Princeton Ocean Model (POM)
- Verified Operational NOAA IOOS Forecast Model
- Recent enhancements include: overland flow, rainfall, ensembling

http://hudson.dl.stevens-tech.edu/maritimeforecast/



Stevens NYHOPS System

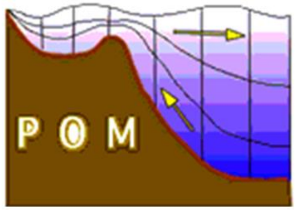
3D Circulation Model (ECOM/POM – derived)

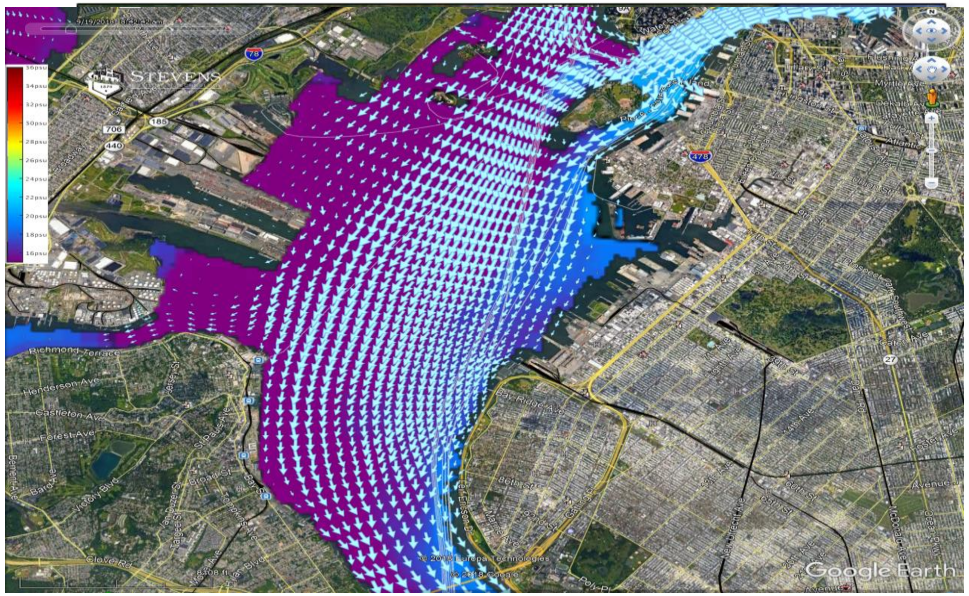
- Boussinesq, hydrostatic, primitive equation, sigma coordinate model
- Smagorinsky lateral diffusion
- Mellor-Yamada 2.5-Kl vertical closure
- Robust, explicit wetting and drying

Dynamically Coupled, Surface Wind Wave Model (GLERL – derived)

- Empirical wave momentum model (JONSWAP Spectrum)
- Wind wave growth and dissipation through bottom friction and depth limited breaking included
- Includes offshore boundary condition (swell input)

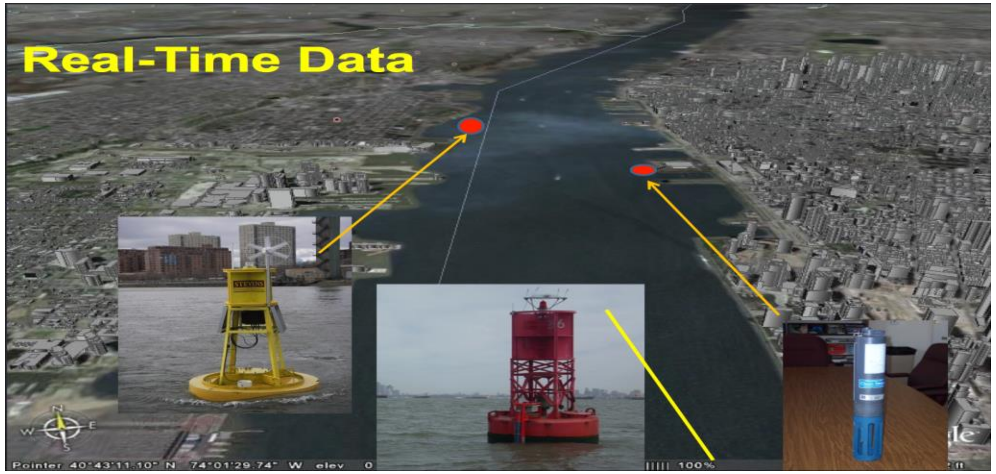
Integrated system of observing sensors and forecast models
TO OBSERVE
TO PREDICT
TO COMMUNICATE
Weather Currents Water Level Salinity Temperature Waves



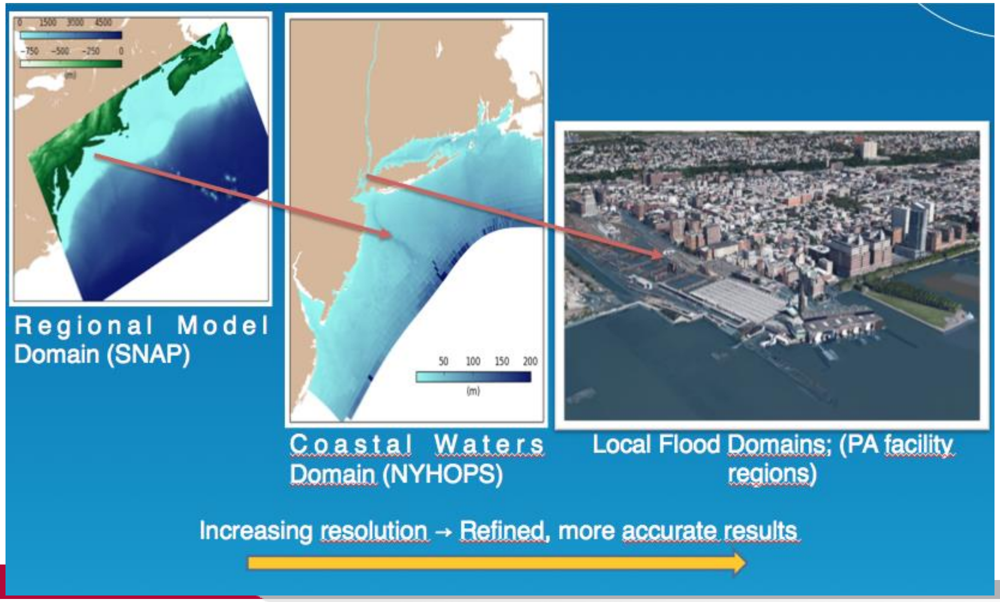


http://hudson.dl.stevens-tech.edu/maritimeforecast/info/

Operational NYHOPS Forecast Model



Input forcing:
- Tides
- Offshore Surge and Steric
- Offshore Waves
- Surface Winds/Pressure
- Heating and Cooling
- 239 Rivers and Streams
- 280 Major Dischargers
- River Ice



Output:
- Hindcasts+96-hr forecasts
- Four times per day
- Total water level
- 3D Currents
- Salinity
- Temperature.
- Significant wave height
- Wave period.

Results every 10 min, since 2006

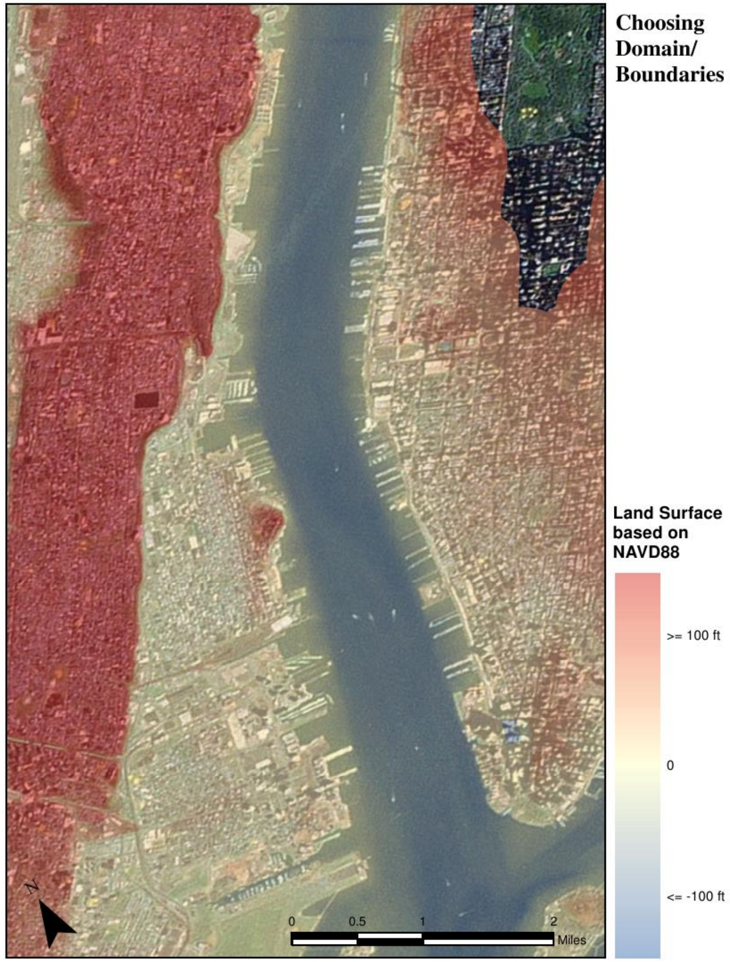
Overland Flow Methodology

Model grid expanded to include overland areas along NY Harbor urban coast

Nested to NYHOPS waterline boundary

High-resolution (3m) LiDAR derived DEMs used to define topography

Inundated model cells employ depth averaged flow equations to predict water levels and overland currents



Depth Integrated Equations of Motion

$$\bar{u} = \frac{1}{D}\int_{-h}^{\eta} u\,dz; \quad \bar{v} = \frac{1}{D}\int_{-h}^{\eta} v\,dz; \quad D = h + \eta$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(\bar{u}D) + \frac{\partial}{\partial y}(\bar{v}D) = 0$$

$$\frac{\partial \bar{u}}{\partial t} + \bar{u}\frac{\partial \bar{u}}{\partial x} + \bar{v}\frac{\partial \bar{u}}{\partial y} - f\,\bar{v} = -g\frac{\partial \eta}{\partial x} + \frac{\tau_{sx} - \tau_{bx}}{\rho_o D}$$

$$\frac{\partial \bar{v}}{\partial t} + \bar{u}\frac{\partial \bar{v}}{\partial x} + \bar{v}\frac{\partial \bar{v}}{\partial y} + f\,\bar{u} = -g\frac{\partial \eta}{\partial y} + \frac{\tau_{sy} - \tau_{by}}{\rho_o D}$$

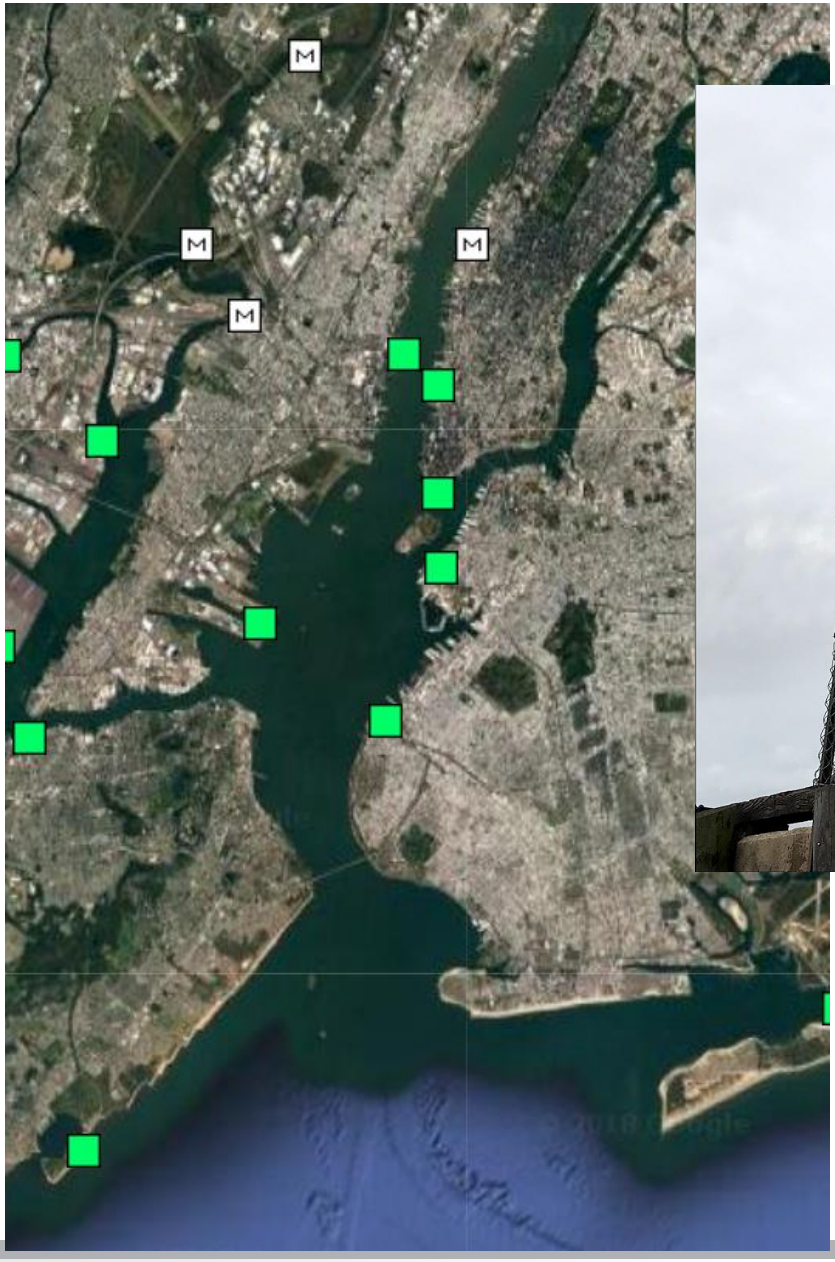
Georgas, N. et al. (2016), The Stevens Flood Advisory System: Operational H3E Flood Forecasts for the Greater New York / New Jersey Metropolitan Region, Int. J. Saf. Secur. Eng., 6(3), 648–662, doi:10.2495/SAFE-V6-N3-648-662

Model Calibration

Model calibrated with Sandy hindcast wind and pressure fields.

Battery tide gauge used as calibration point in Upper Harbor.

Available NOAA and USGS regional water level data used for NY Bight

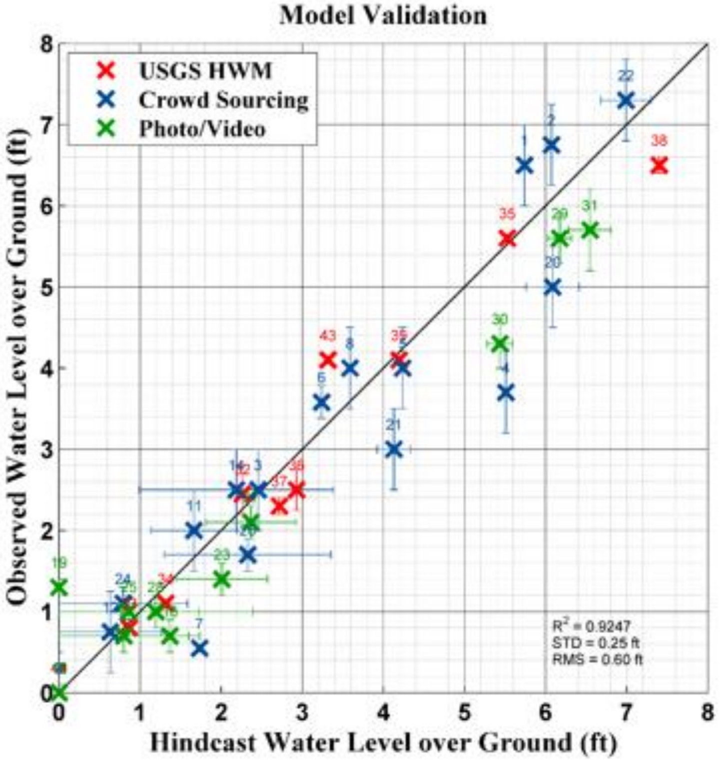


Model Validation

Peak over ground water levels predicted by the model were compared to maximum storm surge extents published by USGS.

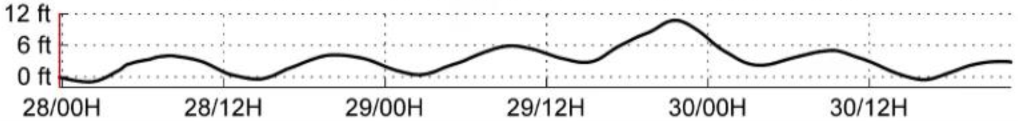
Local water level data recorded by USGS water level sensors used for point verification

Crowed sourcing used to estimate peak water levels.



The correlation coefficient (R^2) between the water mark observations and the model is 0.93.
The standard deviation of the residual error is 0.07 m.
The simulated inundation levels at 78% of the data measurement locations have <20% error.

Hudson River Water Elevation above Mean Sea Level



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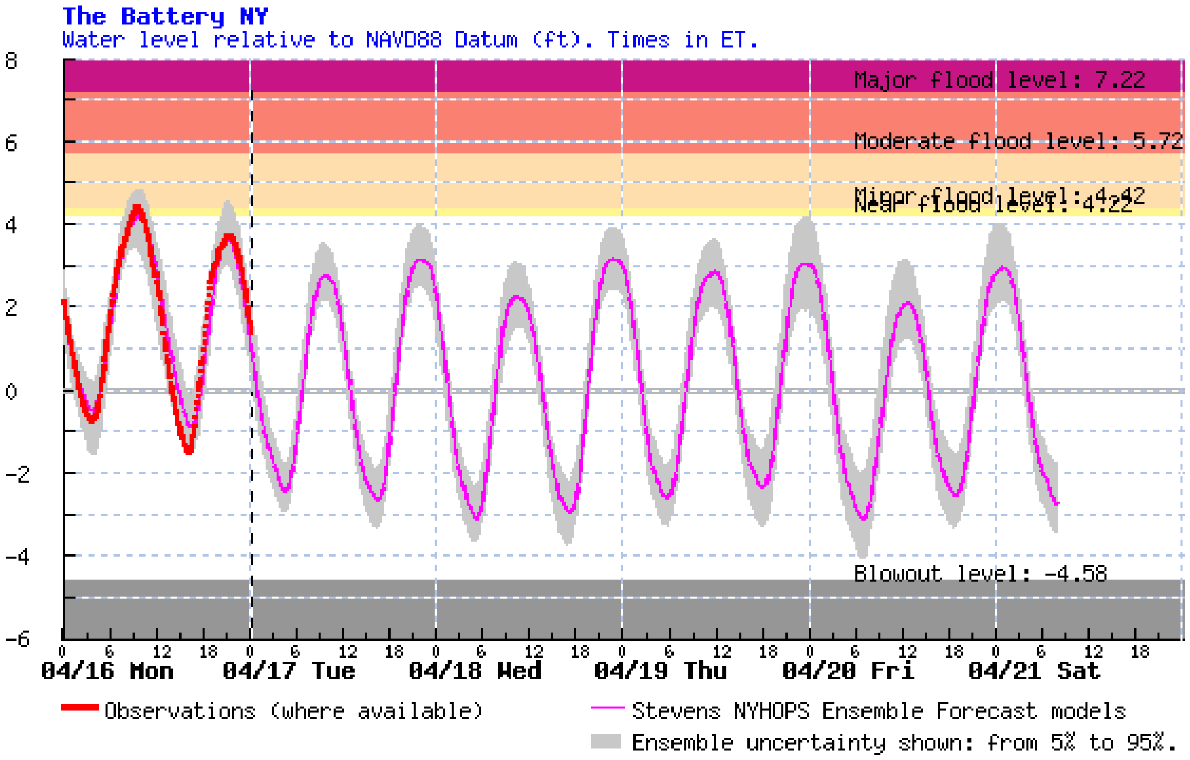
2012-10-27 23:45 EDT

NOLOGY

Implementing Ensembles to Improve Forecast Confidence

Ensemble water level forecast

- Forced by 125 weather model ensemble members plus deterministic models
- 375 hydrodynamic simulations generated every 6 hours
- Produces probabilistic ensemble water level forecasts with a 96 hour forecast horizon
- 95% confidence bands provide a measure of fore

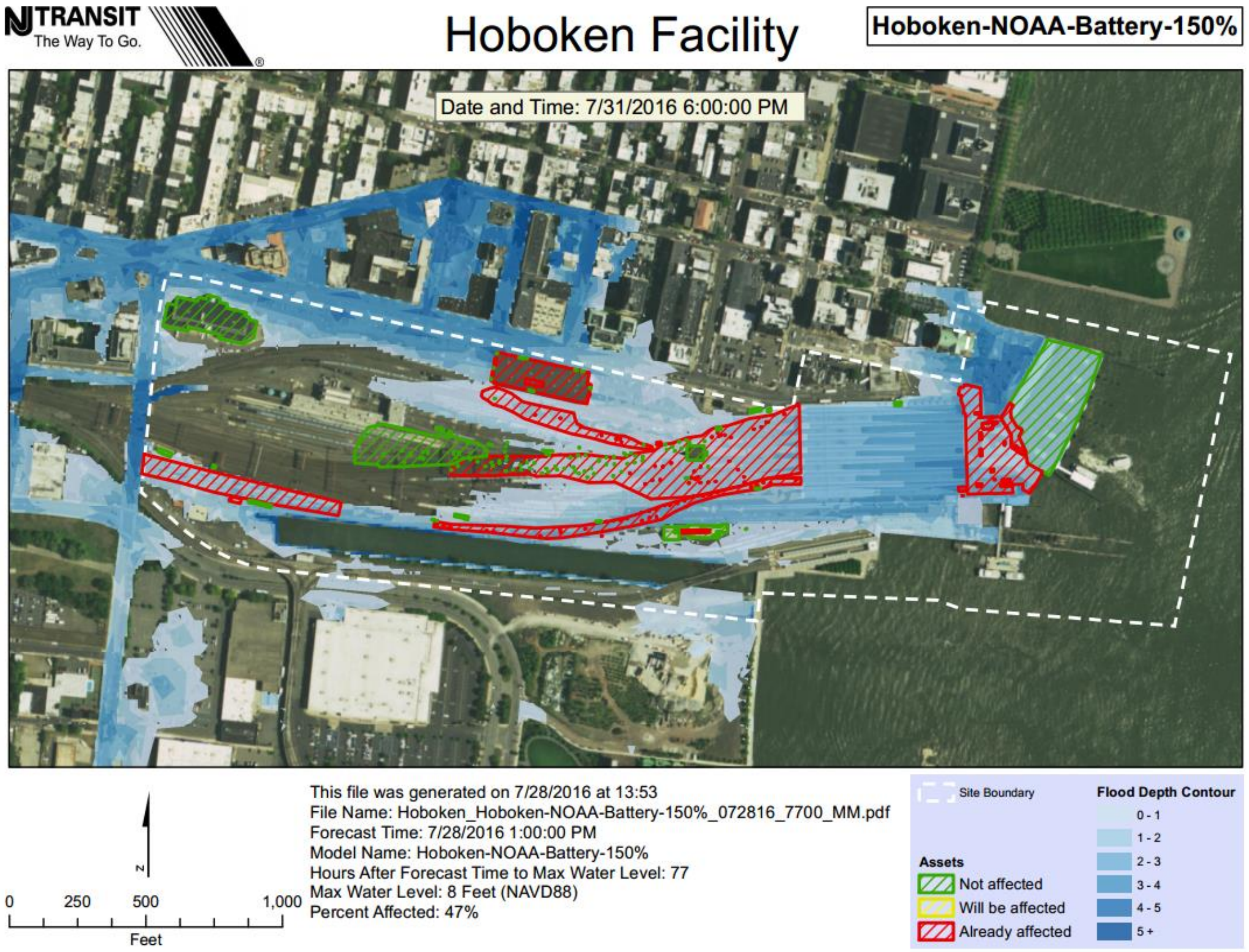


Transit Application

Integrating ground-truthed DEM's with accurate ensemble modeling and local data collection identification of critical facility impacts is possible

Timing can also be predicted

Information available 96 hours in advance of an event



(image courtesy BEM Environmental Systems)

Application to Planning/Design

Scenario Building

- NOAA sea level rise ignores land subsidence
- FEMA Inefficiencies
  - Two-dimensional (2D) water flow modeling
  - Does not typically combine surge and rainfall/ tributary flooding
  - FEMA cannot include SLR effects in the flood insurance program

In present collaborative NPCC work (Orton, Line, Colle) we are looking to probabilistically incorporate:

- Changes to future storms
- Sea level rise
- Uncertainty at all stages of analysis

AGU PUBLICATIONS JGR

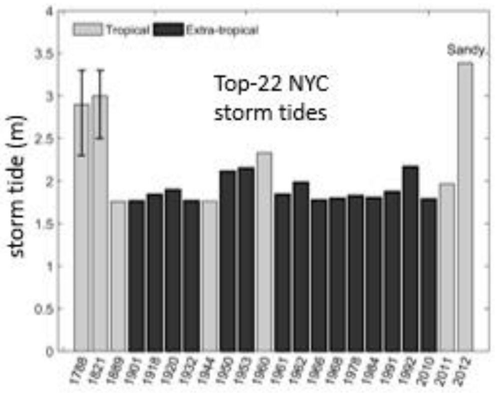
Journal of Geophysical Research: Oceans

RESEARCH ARTICLE
10.1002/2016JC011679

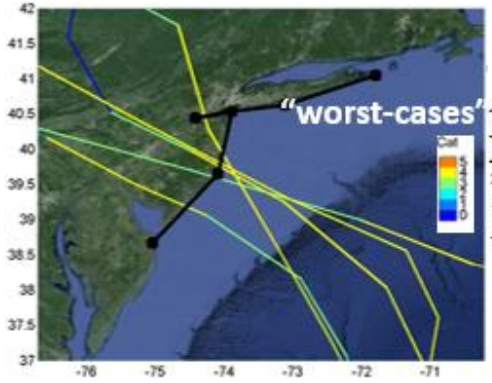
A validated tropical-extratropical flood hazard assessment for New York Harbor

(2016) Authors: Orton, Hall, Talke, Georgas, Blumberg, Vinogradov

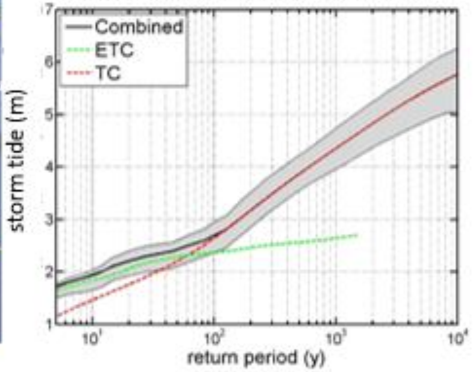
Historical data give many examples of extratropical cyclones; few hurricanes



We use a 600+ storm climatology representing 1.1 million years of synthetic hurricane events



Extratropicals – important for shorter return periods
Tropicals – 100-year and longer
Sandy was a 260-year flood (170-420 at 95% uncertainty)



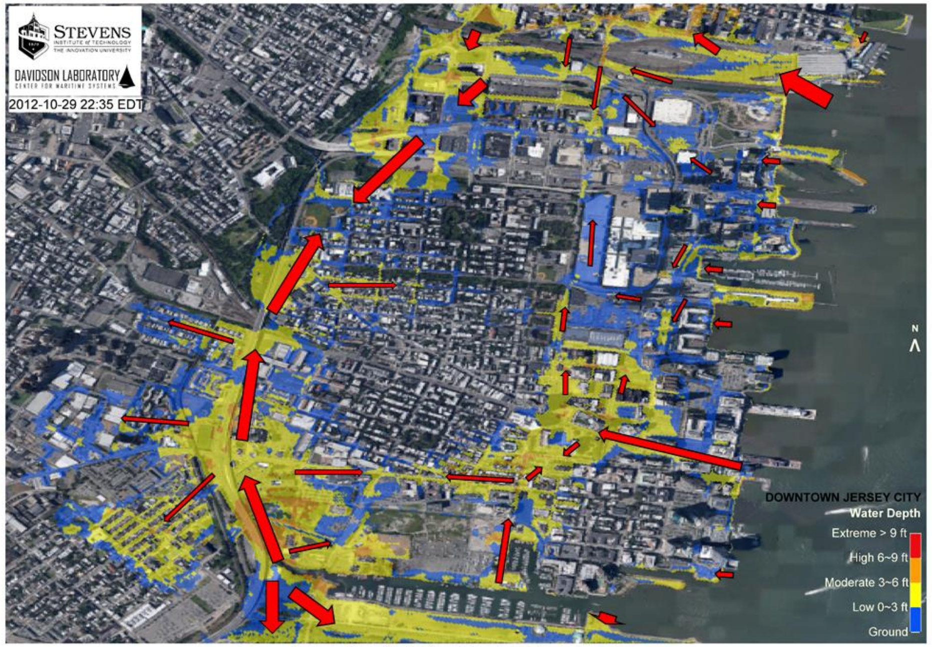
Conclusions

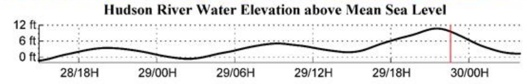
Advanced high resolution hydrodynamic models are available and have significant applications in the transportation domain

- High-resolution flood forecasts up to 96 hours in advance of a flood event are possible
- 95% confidence intervals on predicted water elevations provide a useful measure of forecast uncertainty
- High-resolution overland flood forecast can accurately predict timing, depth and velocity of flood waters using existing momentum based hydrodynamic models

Models are currently being used, but in many cases we are only scratching the surface

Examples presented here mostly focused on inundation; however there is significant potential to move beyond this to look at currents/waves (forces)





Acknowledgements

The development of the NYHOPS model and the Stevens Flood Advisory System was supported by numerous organizations since its creation. The support of all of them is acknowledged, in particular the Governor's Office of Recovery and Rebuilding, the NJDEP Bureau of Coastal Engineering, the National Science Foundation (under grant 1318169), NJ Transit, and the Port Authority of New York and New Jersey, who funded many of the most recent improvements.

Special thanks to the US Geological Survey for providing verified Sandy storm tide data available for the verification of the model, as well as Mr. John P. Carey who provided much of the crowed source data. The authors dutifully acknowledge their current and former colleagues including Dr. Alan Blumberg, Dr. Nickitas Georgas, Dr. Thomas Herrington, Dr. Michael Bruno, and Dr. Philip Orton for their efforts in advancing NYHOPS.

State of New Jersey
Department of Environmental Protection
Coastal Engineering

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National Science Foundation
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State of New Jersey
Governor's Office of Recovery and Rebuilding

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Coastal Bridges under Hurricane Stresses along the Texas and Louisiana Coast

Dr. Adolfo Matamoros

University of Texas at San Antonio

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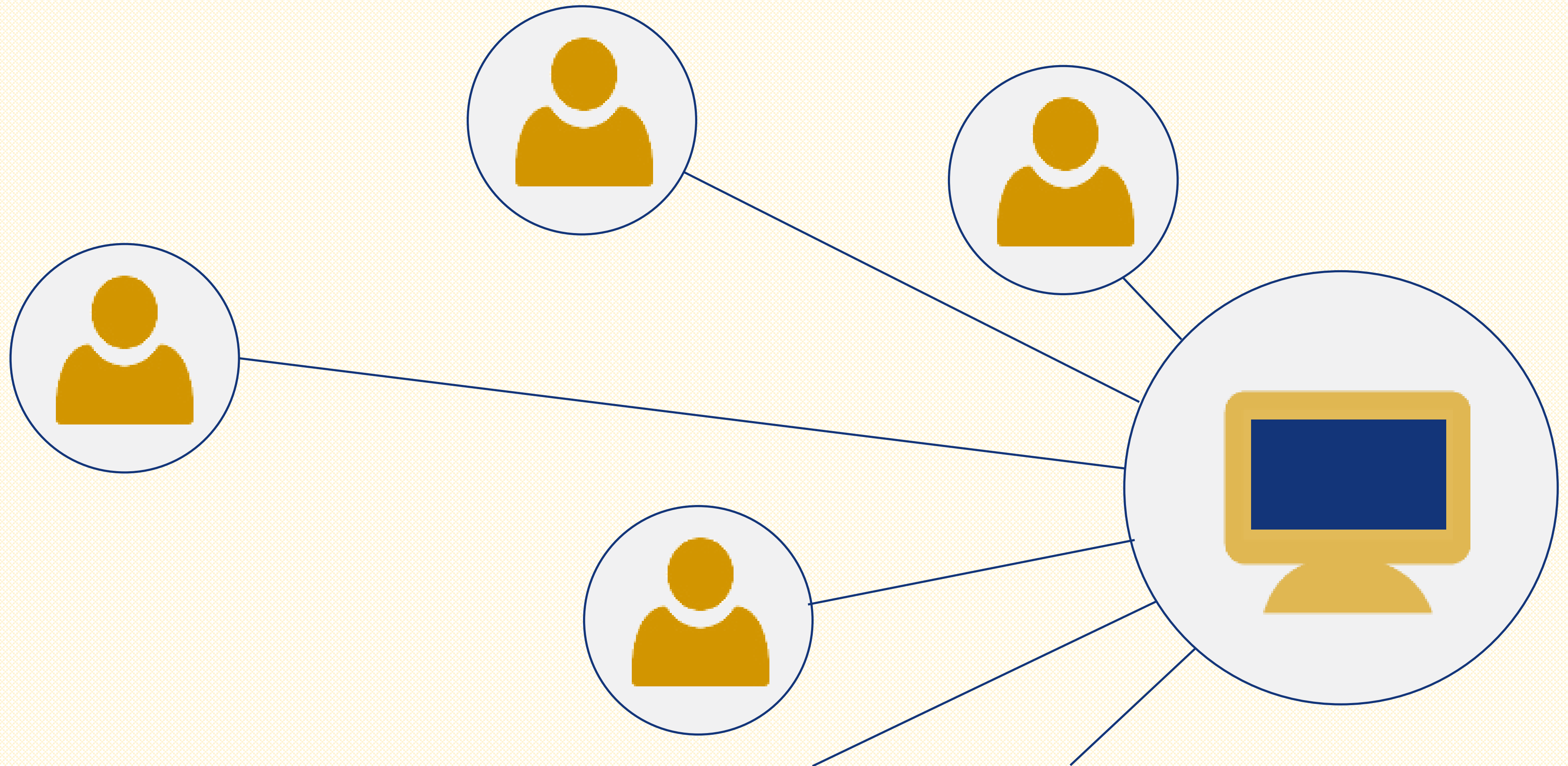
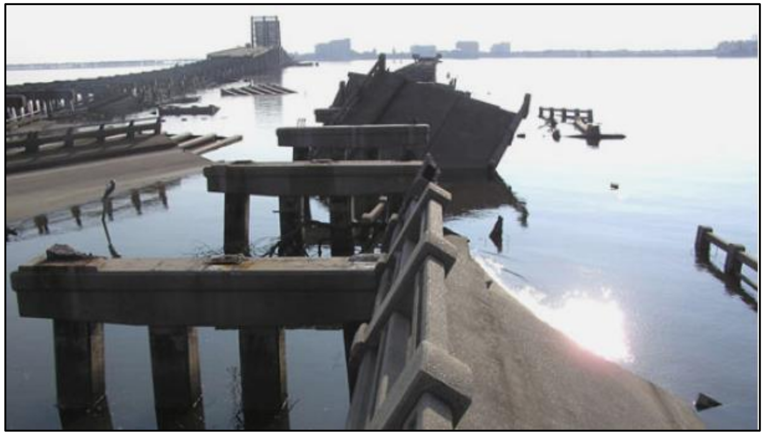


Coastal Bridges under Hurricane Stresses along the Texas and Louisiana Coast

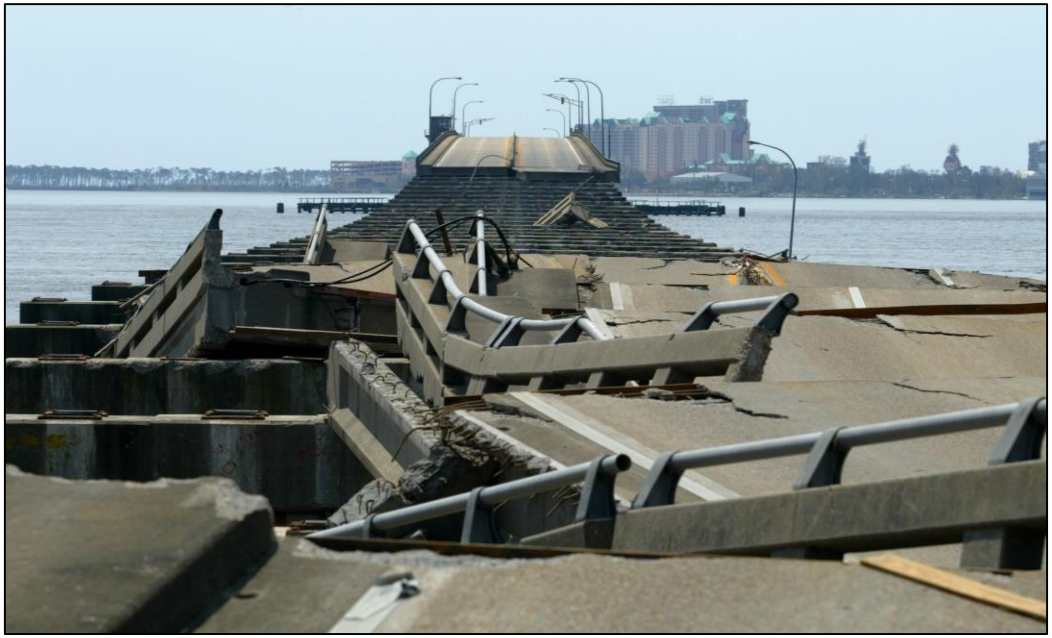
R. Nasouri, A. Matamoros, F. Testik, A. Montoya
University of Texas at San Antonio

Hurricane Bridge Damage

Cost of repair and replacement of bridges after Hurricane Katrina was estimated to be 1 billion dollars



www.trec.pdx.edu



Damage to the U.S. 90 Biloxi Bay Bridge caused by Hurricane Katrina

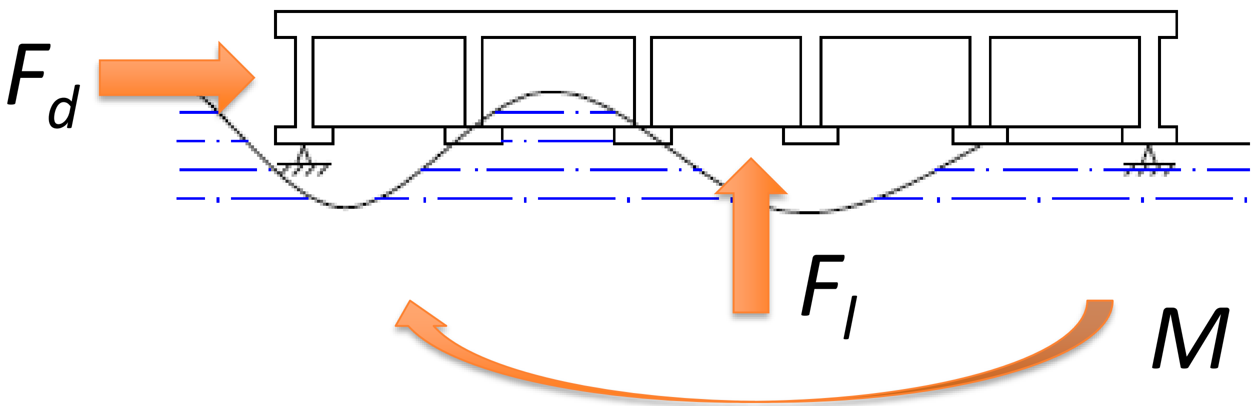
Hurricane Actions

- Horizontal hydrodynamic load

$$F_d = [1 + c_r(N - 1)]c_{h-va}\,\gamma\,(\Delta z_h)A_h$$

- Vertical hydrodynamic uplift load

$$F_l = c_{v-va}\,\gamma\,(\Delta z_v)A_v$$



Hurricane Bridge Damage

Project Objective

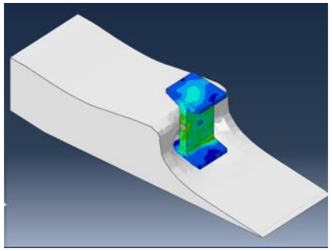
Develop a high-resolution model to estimating damage to bridge structures due to hydrodynamic loads caused by hurricanes

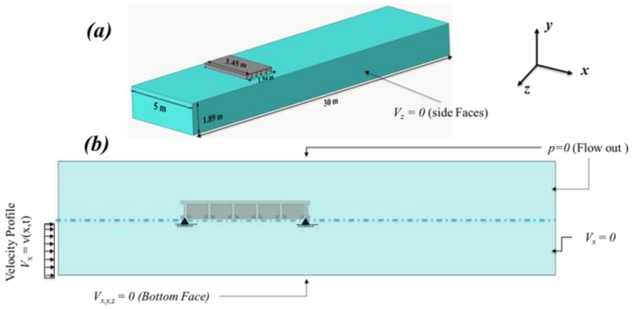
Research Methodology

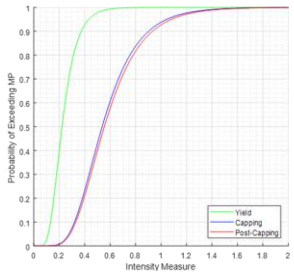
Simple Multiphysics models to simulate fluid-structure interaction

Simulation of large-scale experiments

Development of fragility relationships for bridge structure

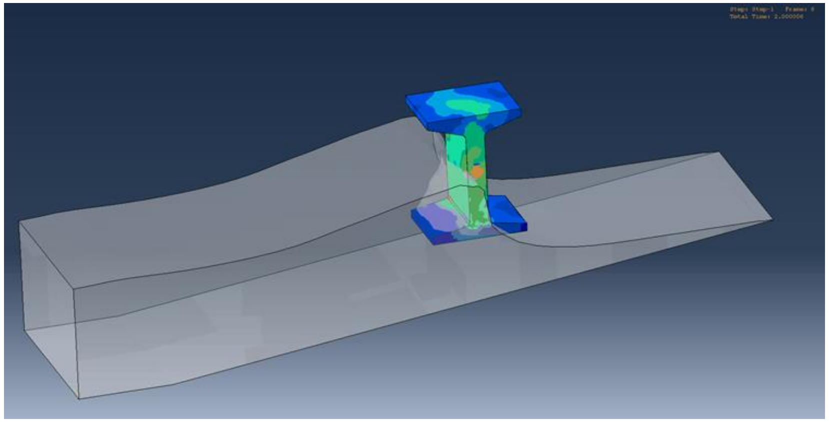




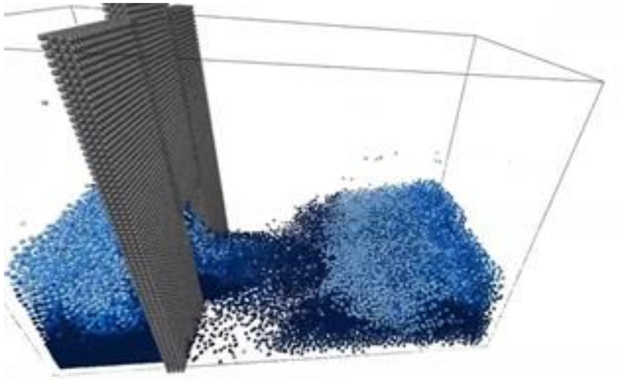


Modeling Approach

- Implement new modeling techniques in computational fluid dynamics to study wave impact problem



Coupled Eulerian Lagrangian



Smooth Particle Hydrodynamics

Modeling Approach

Lagrangian	Eulerian
Solid	Fluid
Equilibrium Equations	Equations of State
Three-dimensional brick elements	U_s U_p Fluid (shock wave velocity- particle velocity) Mie-Grüneisen EOS, linear Hugoniot form.

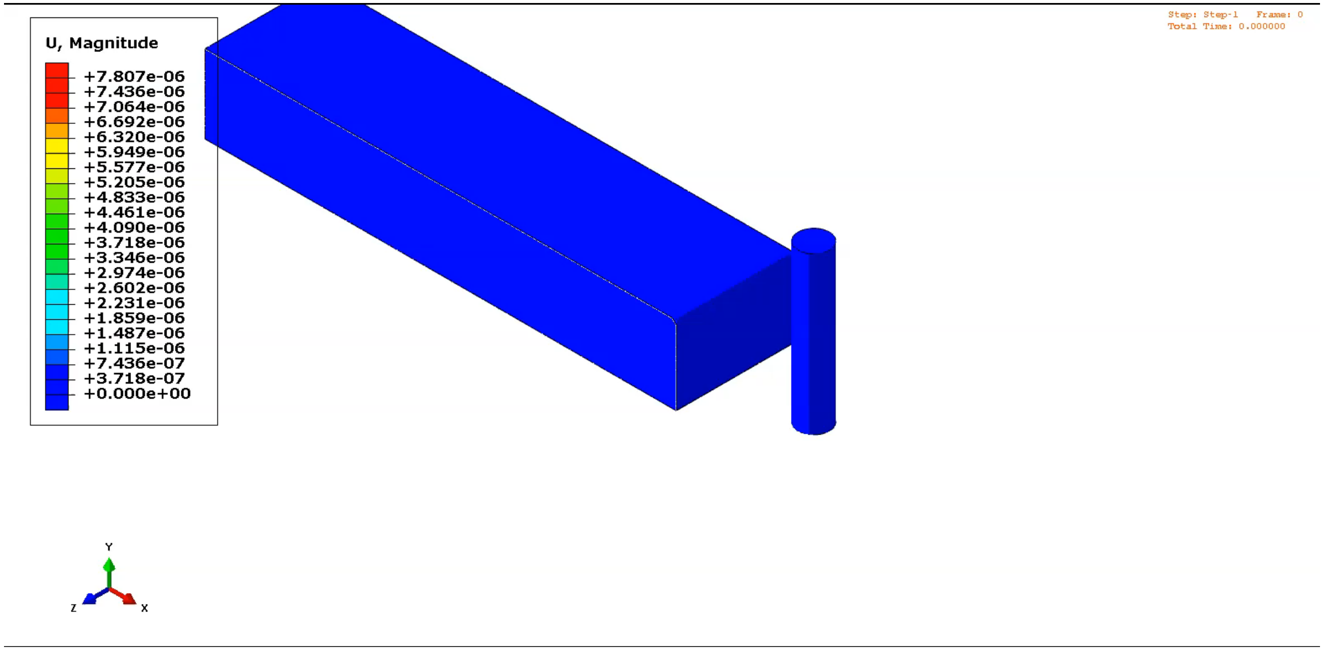
Early Stage Models

- Wave impact on a bridge girder
- Accurate representation of boundary conditions
  - Wave shape
  - Wave velocity
  - Fluid inlet and outlet
- Accurate representation of fluid-structure interactions
- Eulerian (fluid) mesh optimization

Coupled Eulerian-Lagrangian (CEL)

Coupled Eulerian-Lagrangian (CEL) Approach:

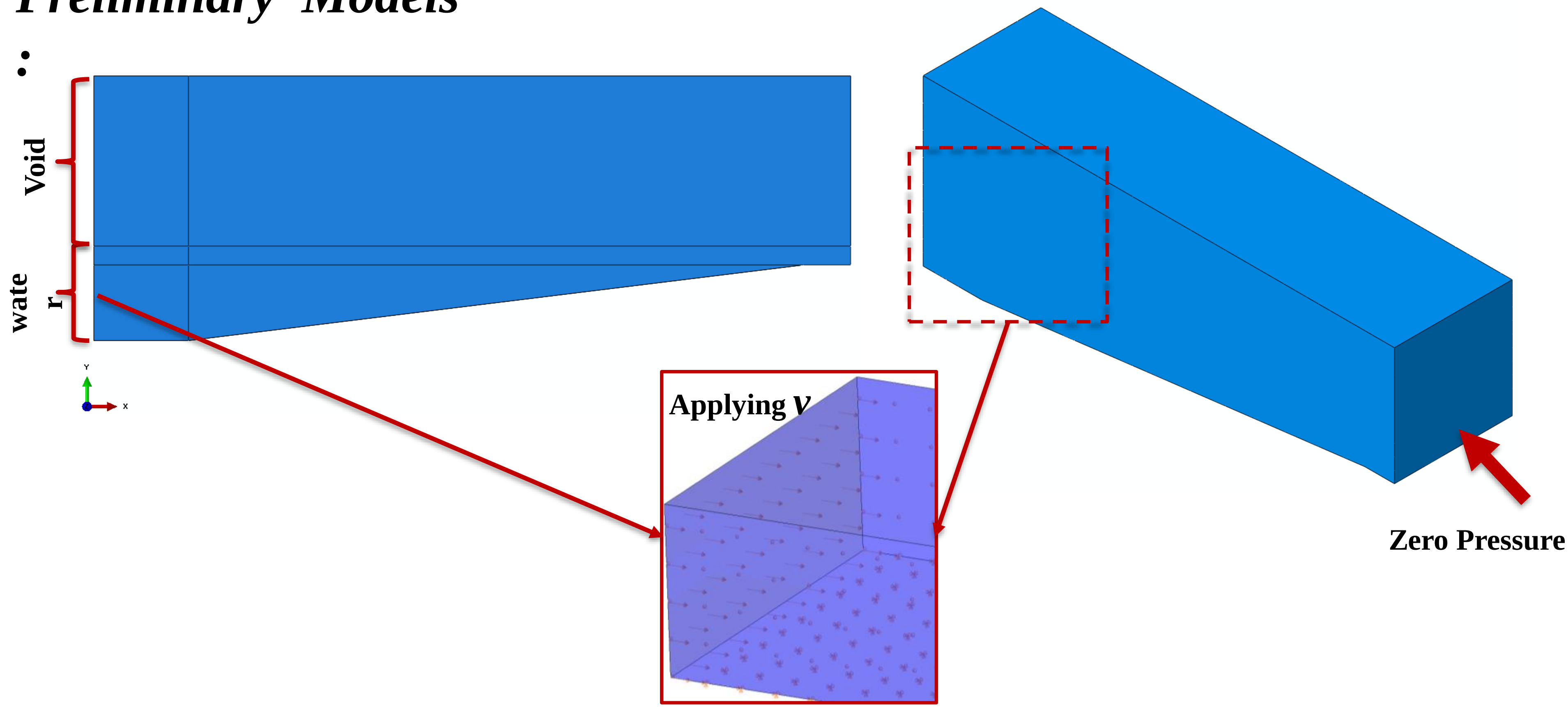
The Interaction between Structures and Fluids is Solved Simultaneously



Coupled Eulerian Lagrangian Analysis

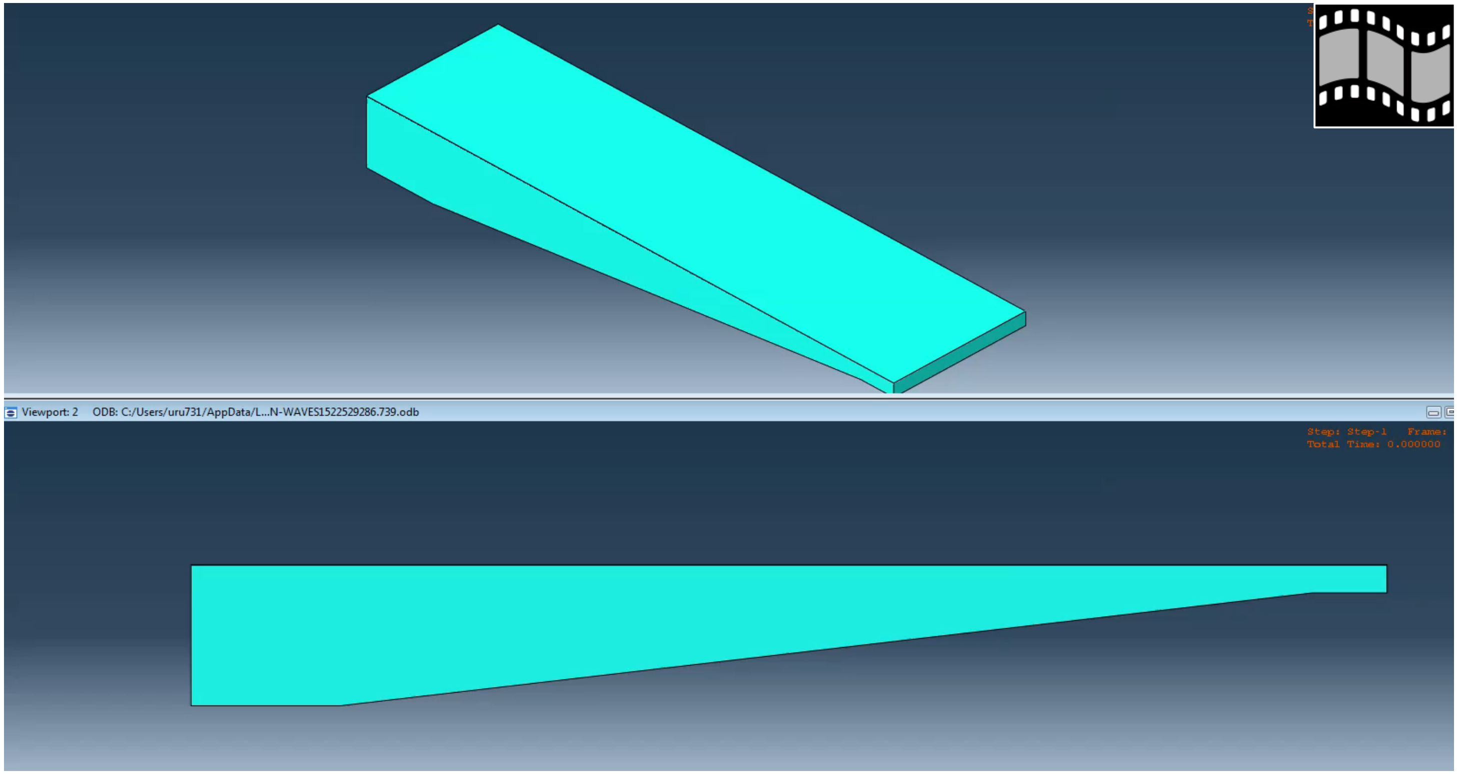
Preliminary Models

•

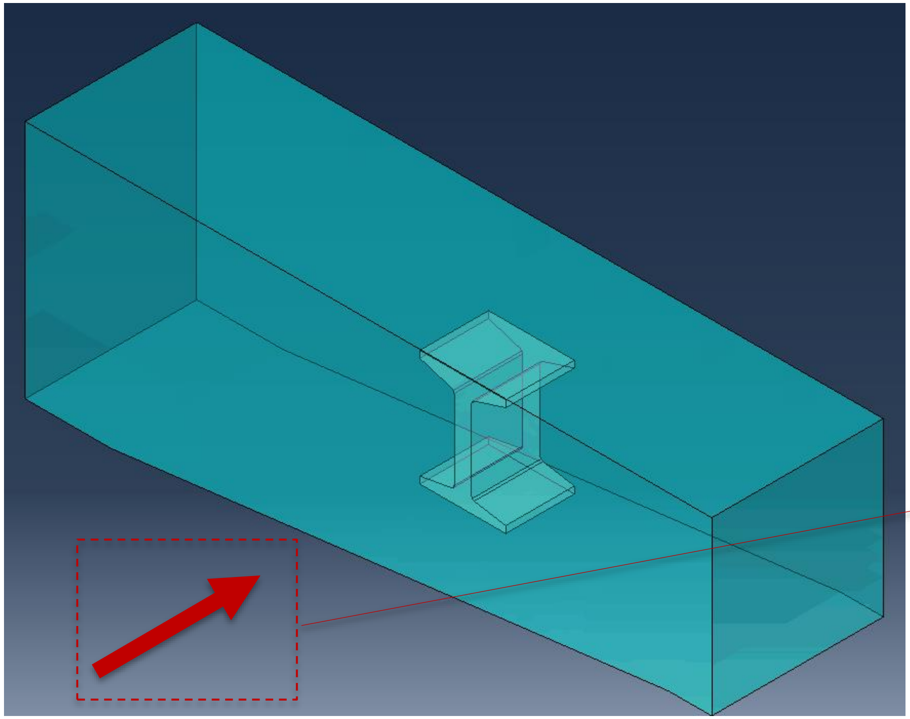


Wave simulation

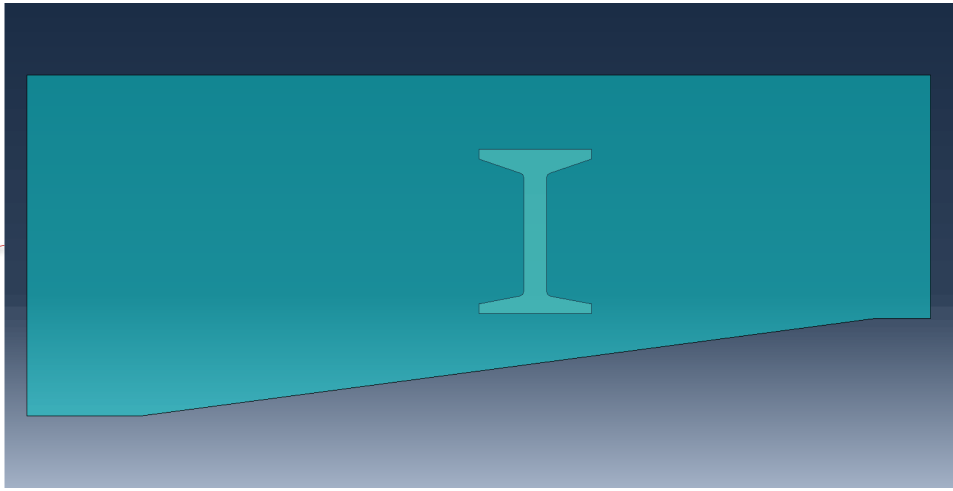
Sine Waves



Integration of Eulerian and Lagrangian Domains

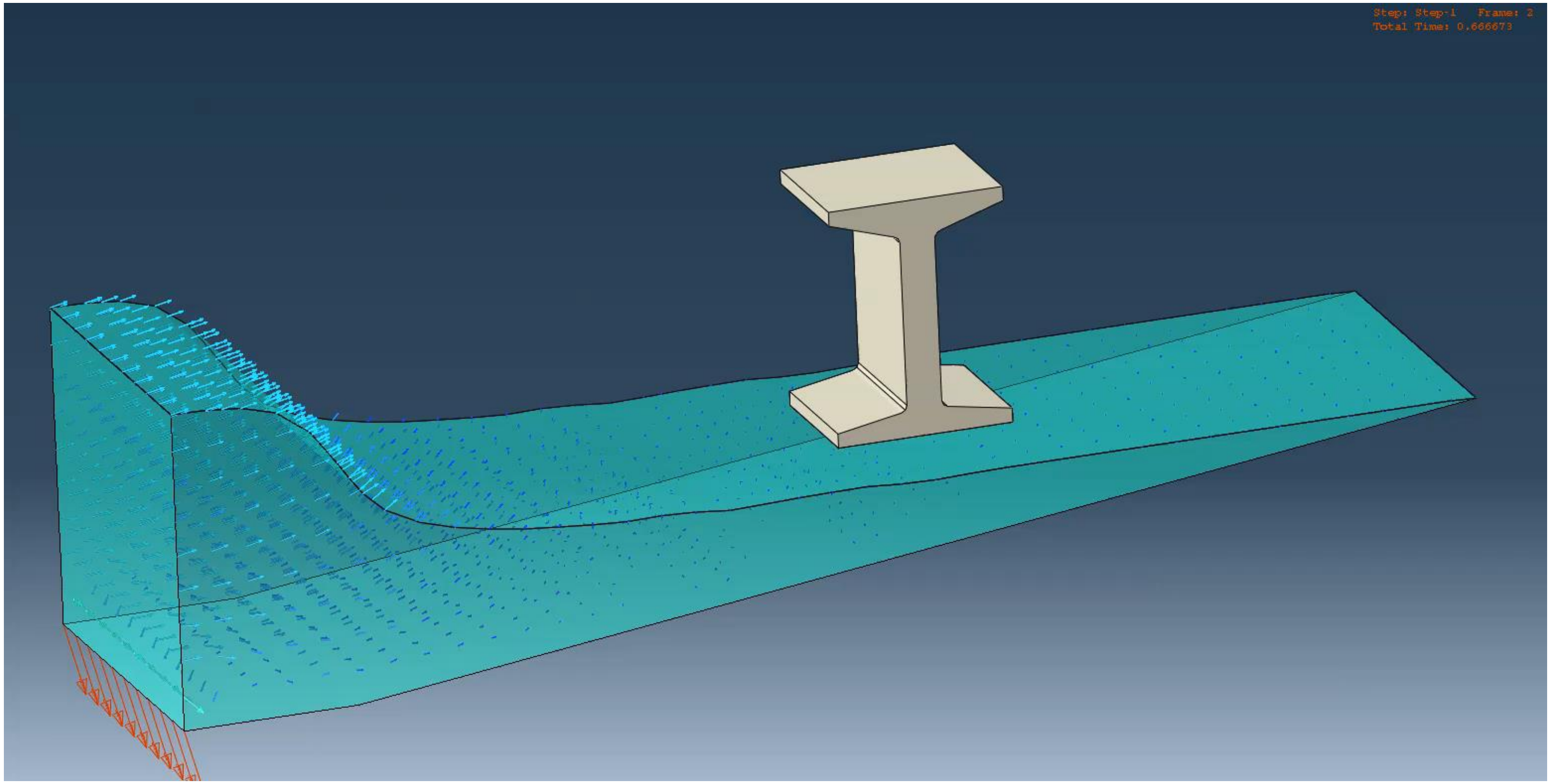


Side View



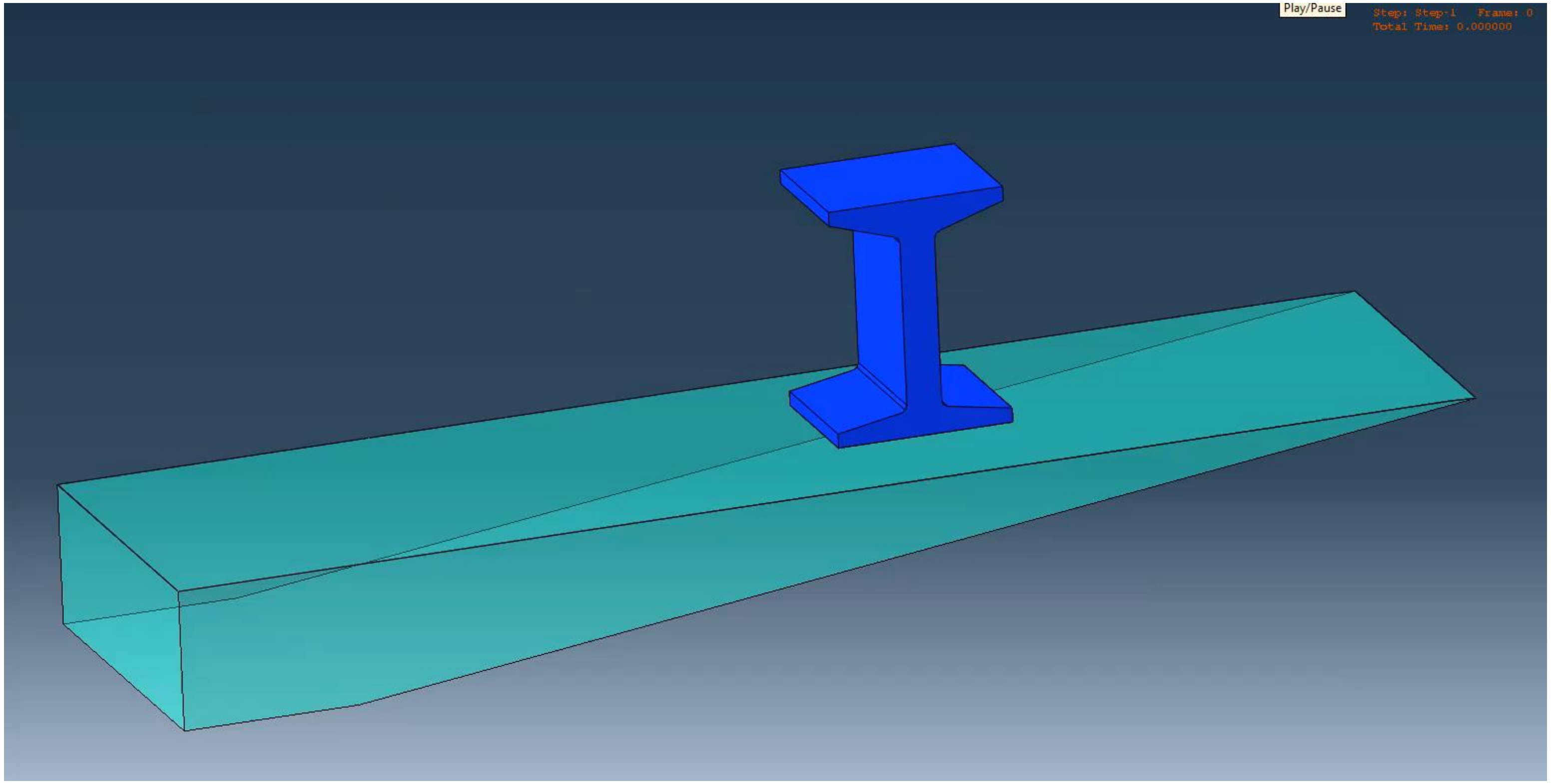
Definition of Lagrangian Domain:

Bridge Girder Model



Fluid Directional Velocity

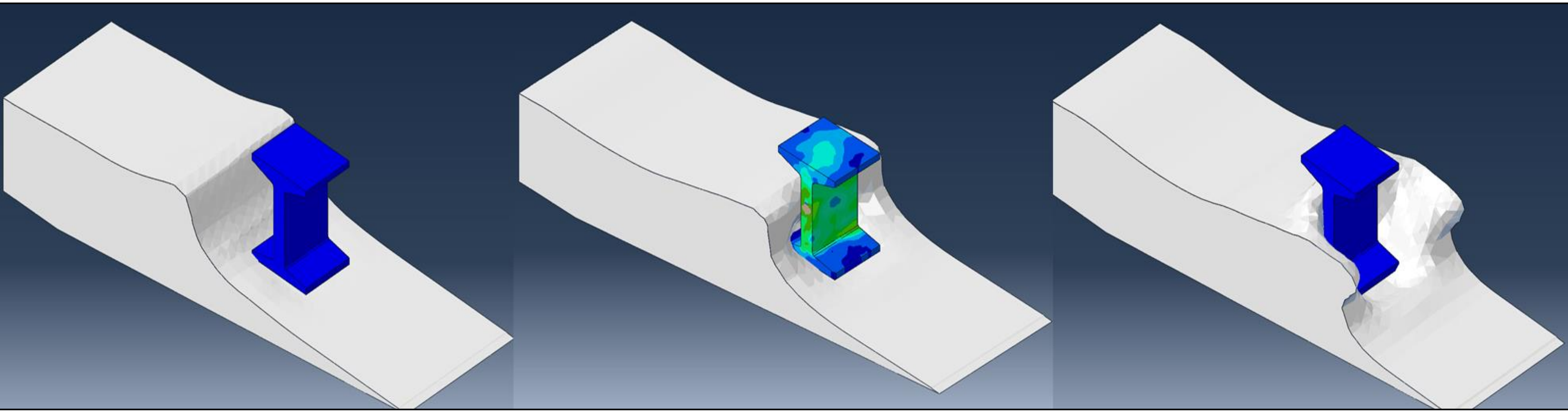
Bridge Girder Model



Girder Stress

Model Results

Stress Contour Generated by the Wave

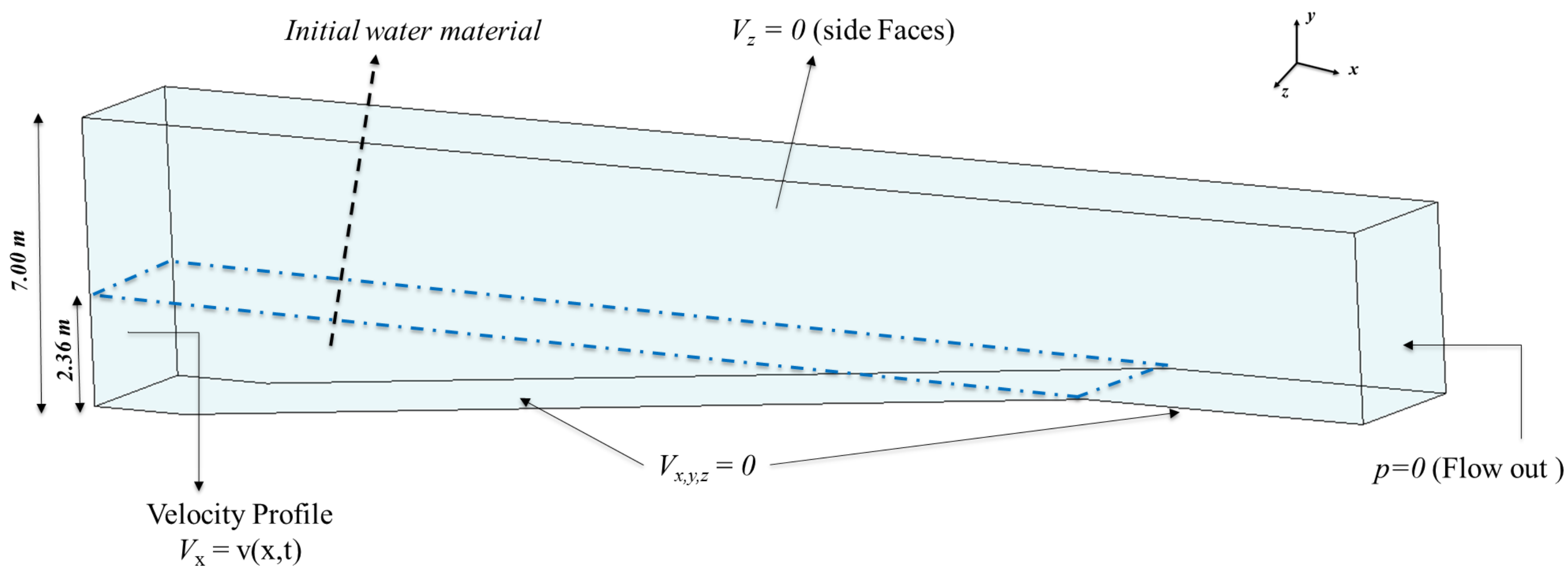


Model Calibration

Calibration was performed using data sets from physical experiments at Oregon State University Large Wave Flume

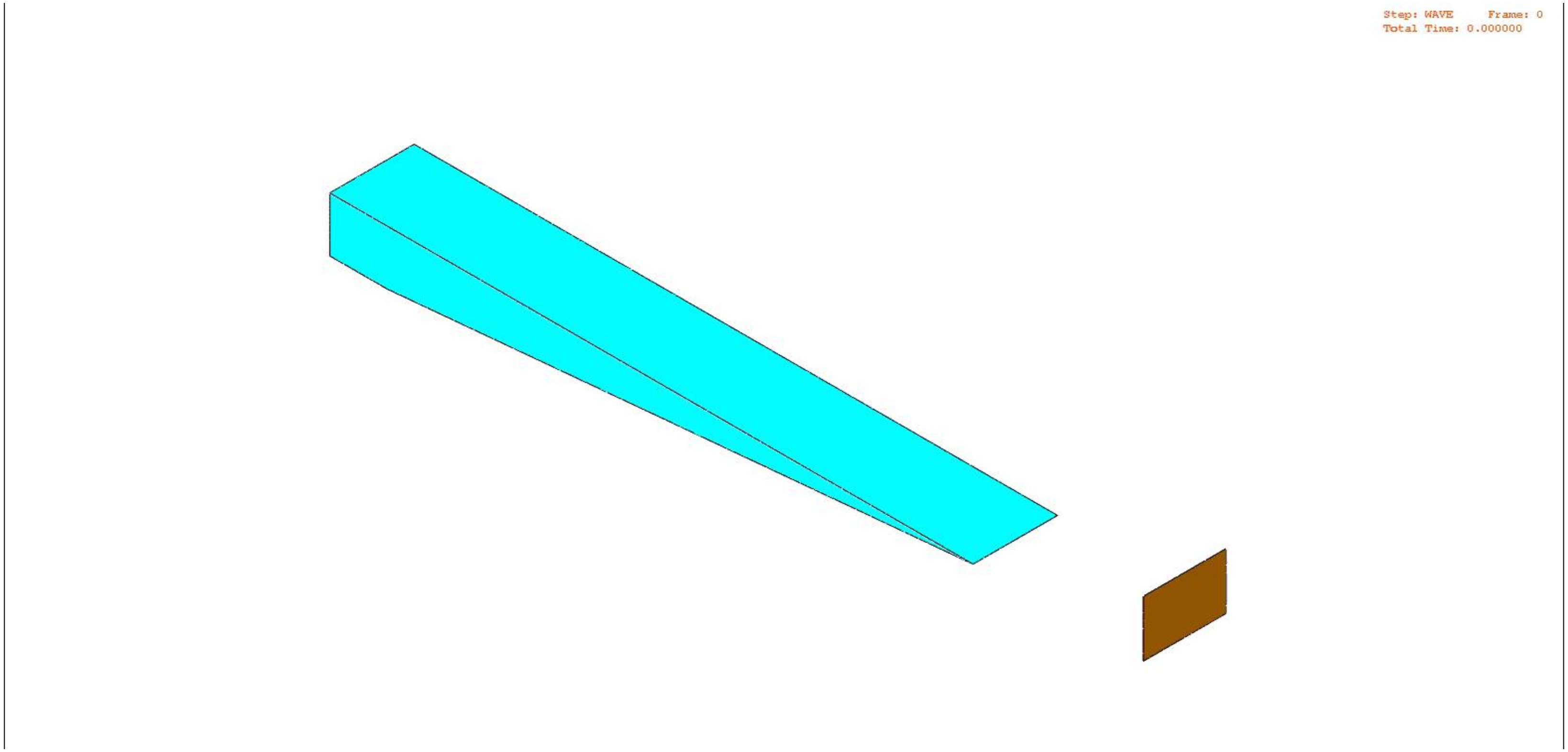
- Tsunami wave impact on timber wall
- wave impact on I-10 bridge over Escambia Bay, FL

Timber Wall Model Boundaries

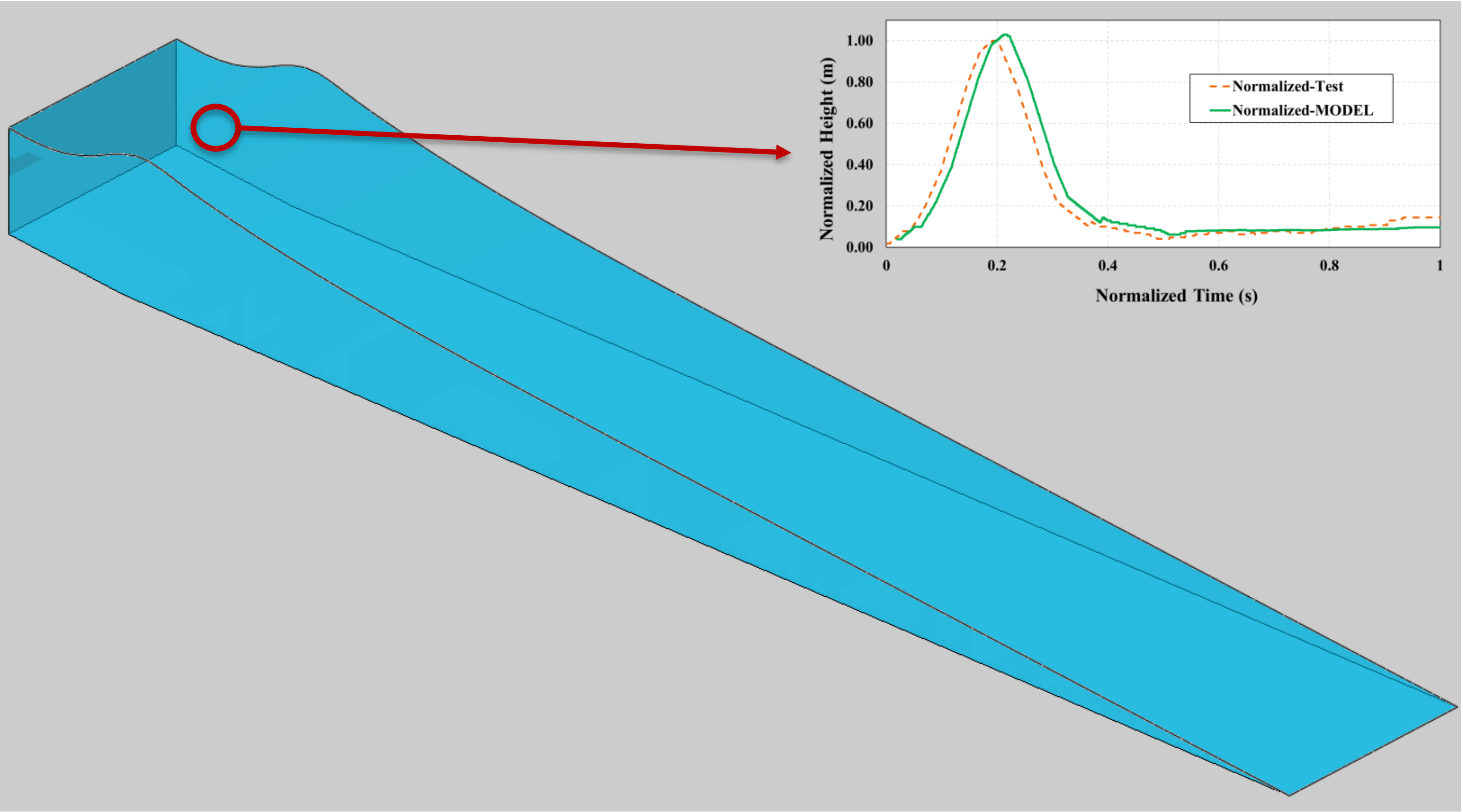


UTSA The University of Texas at San Antonio

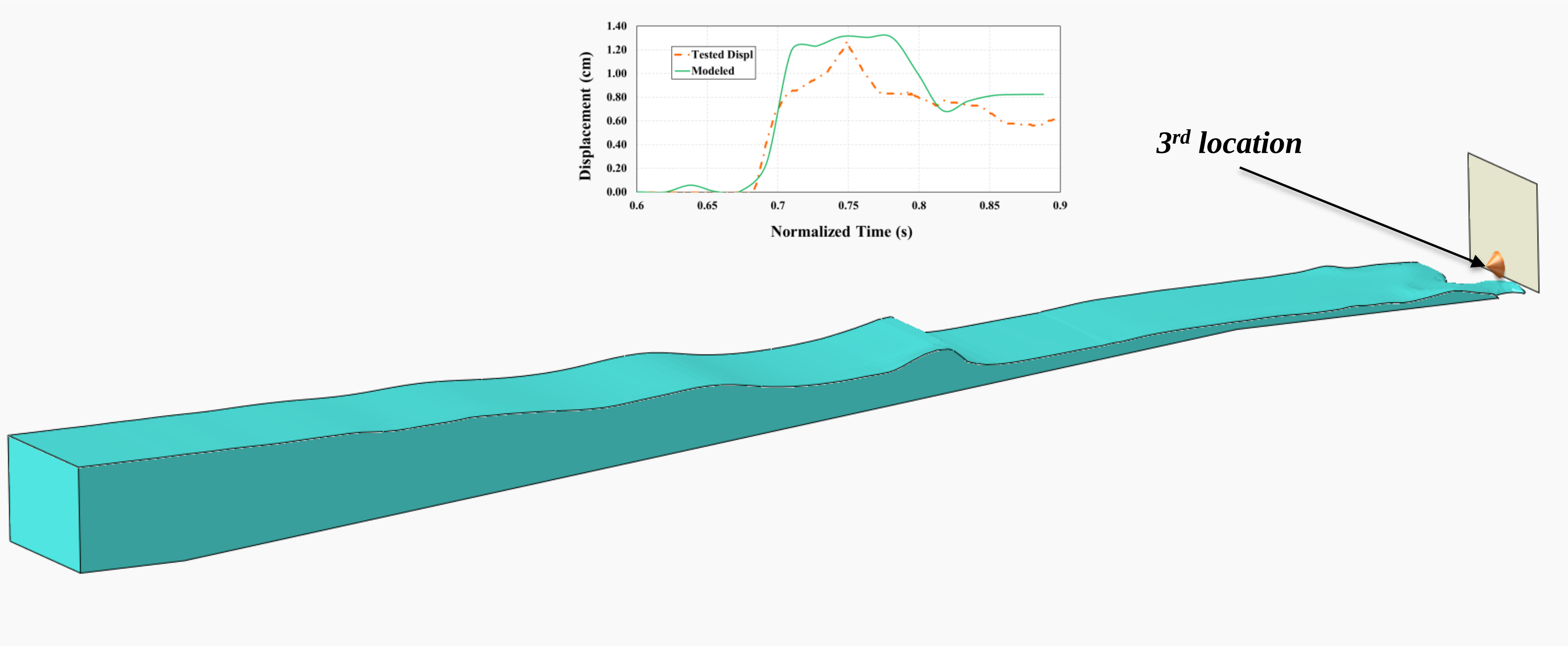
Timber Wall Simulation for Initial Vel 2.2 m/s



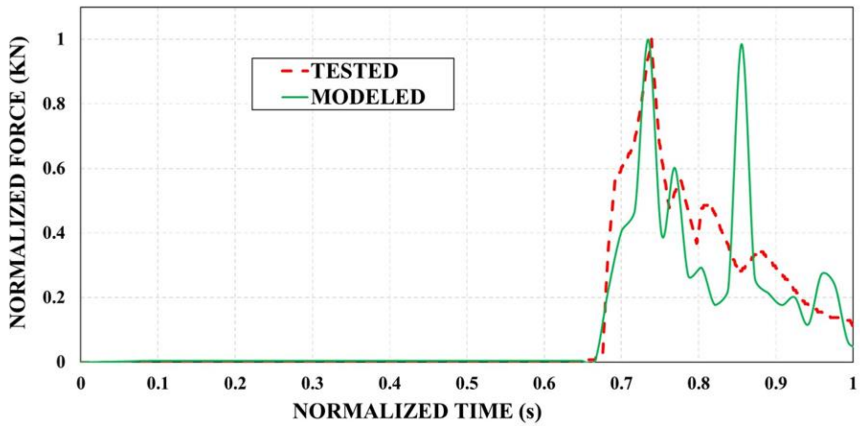
Wave Height Measurement Location

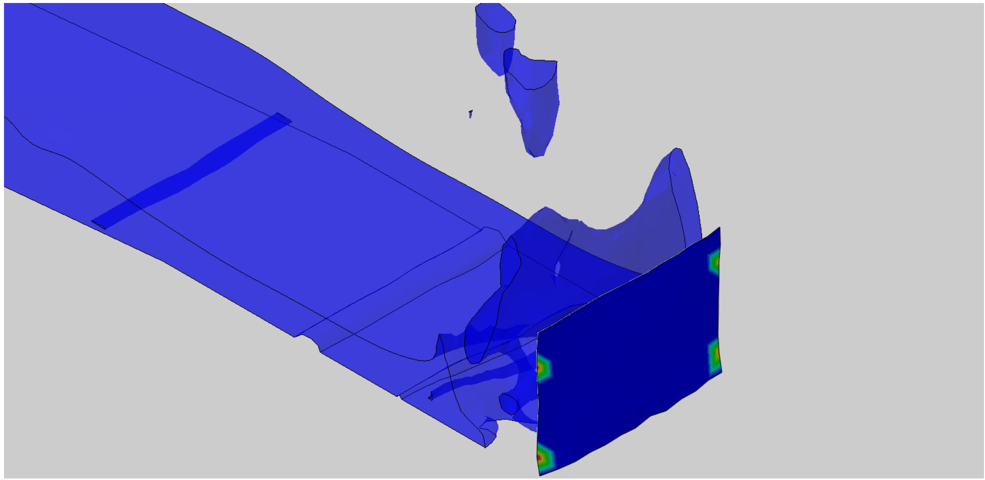


Displacement Measurement Location

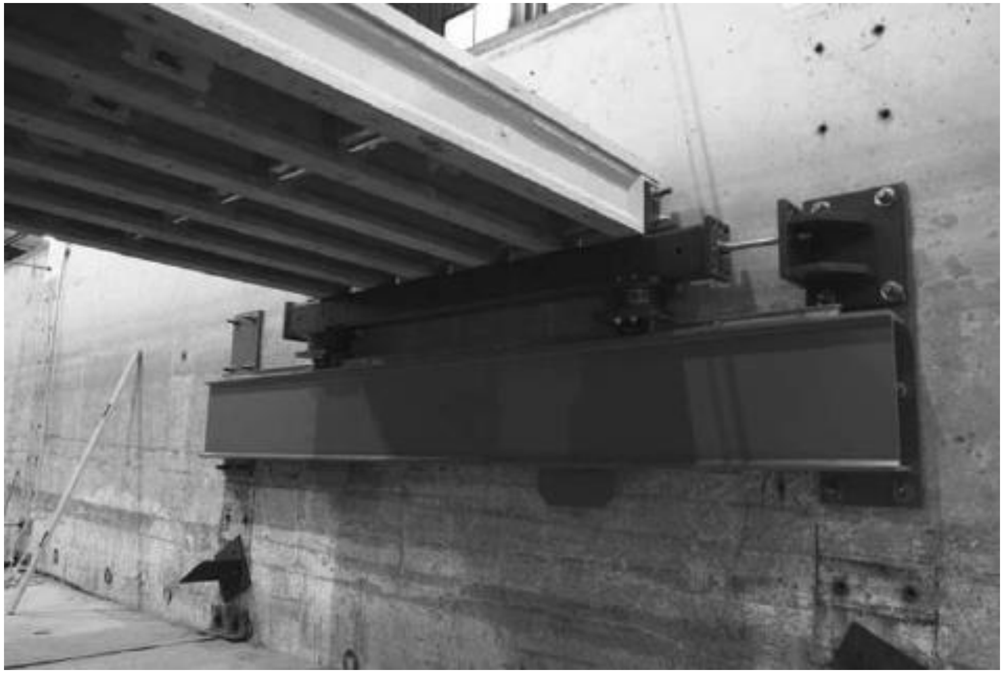


Timber Wall-Reaction Force for High Speed Wave

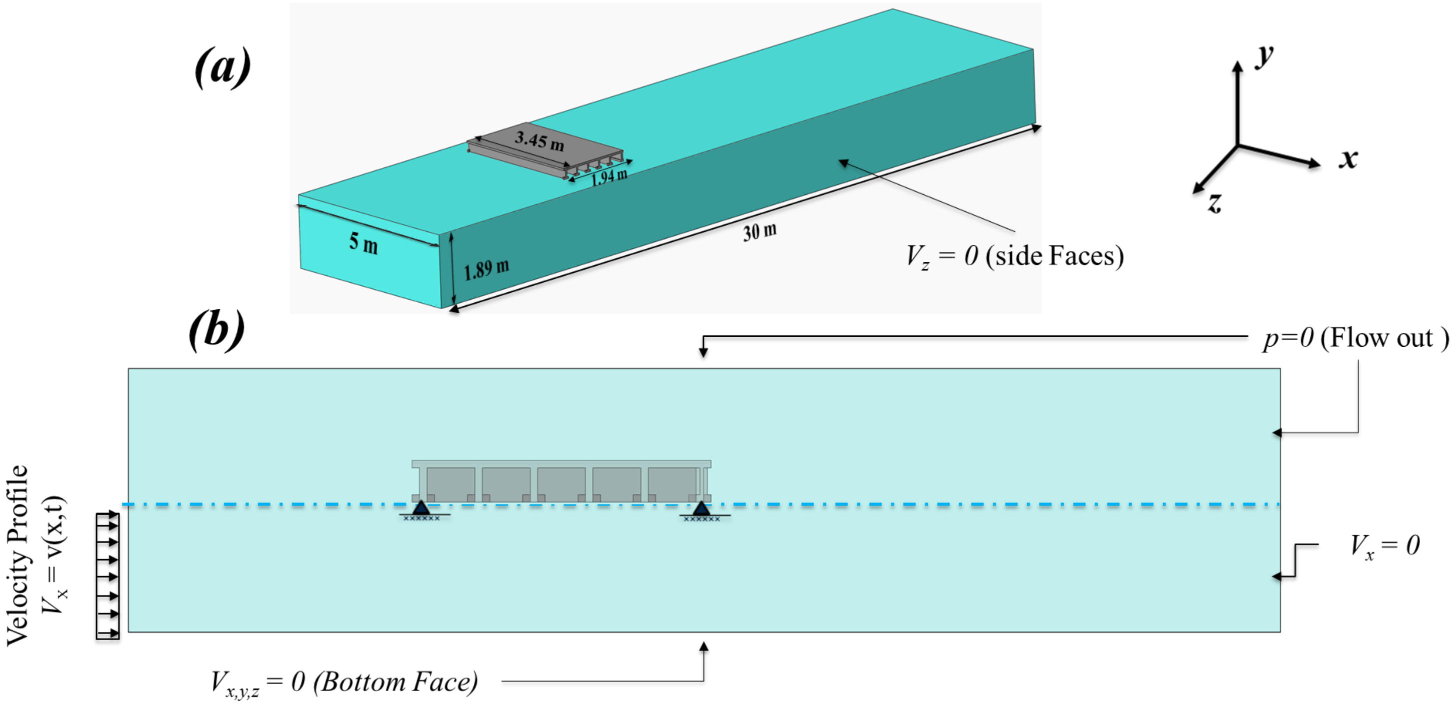




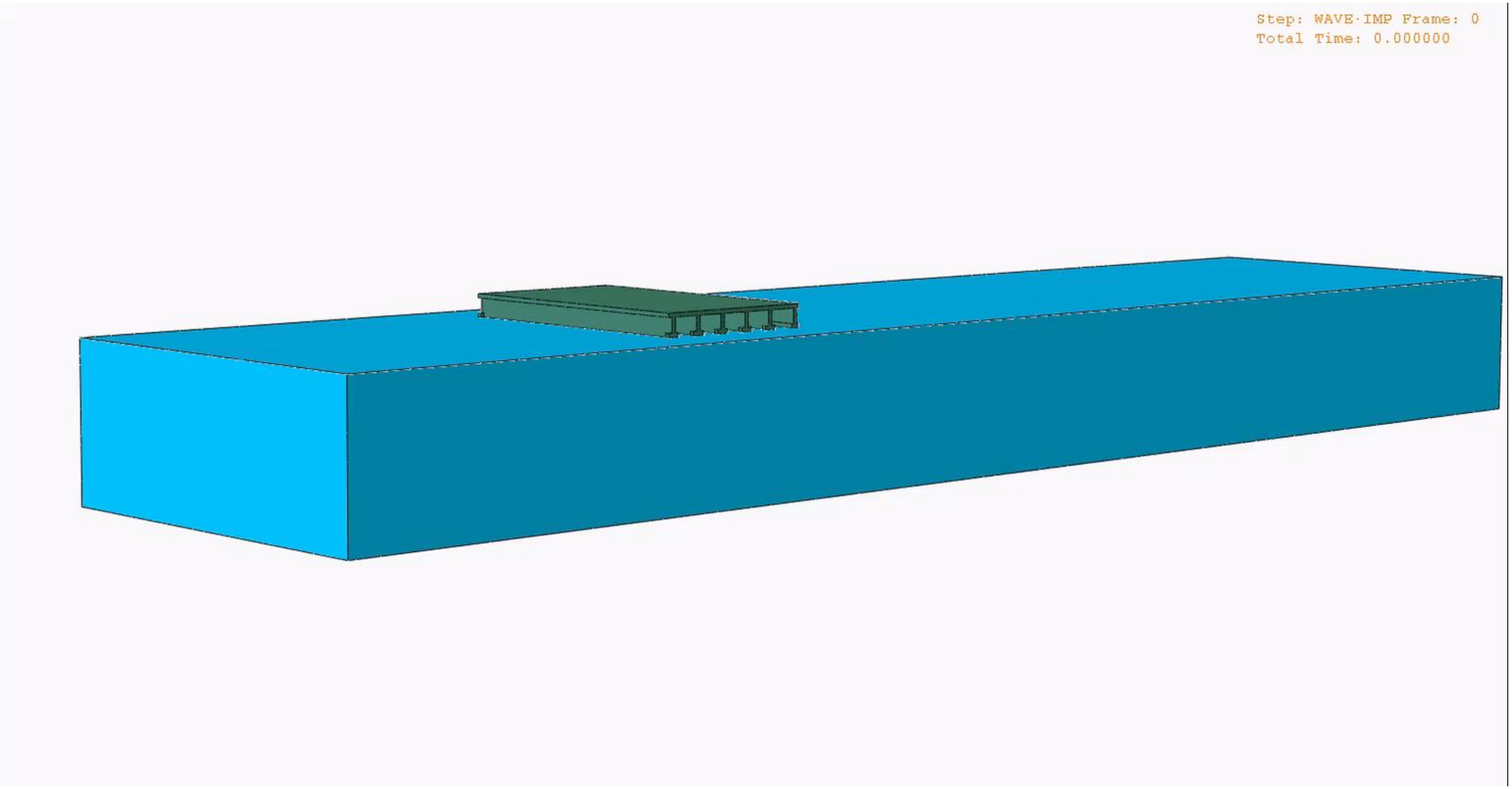
Escambia Bay Bridge Model Configuration



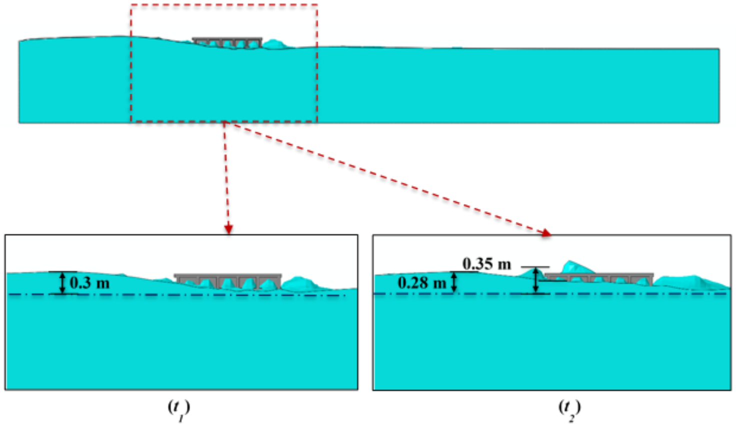
Escambia Bay Bridge Model Configuration

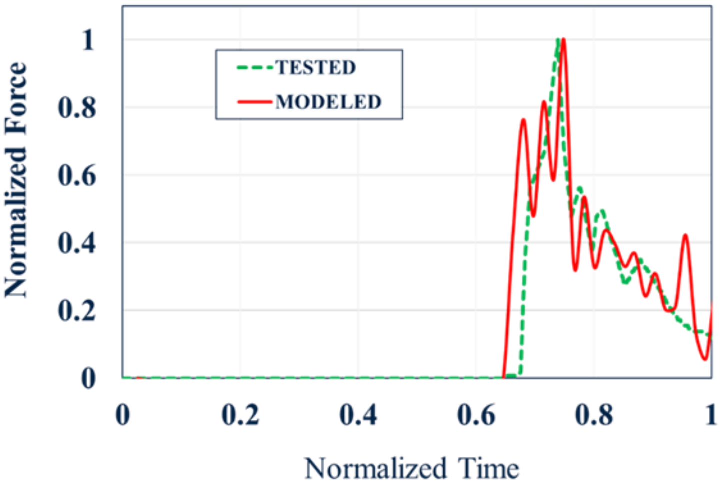


Escambia Bay Bridge Simulation

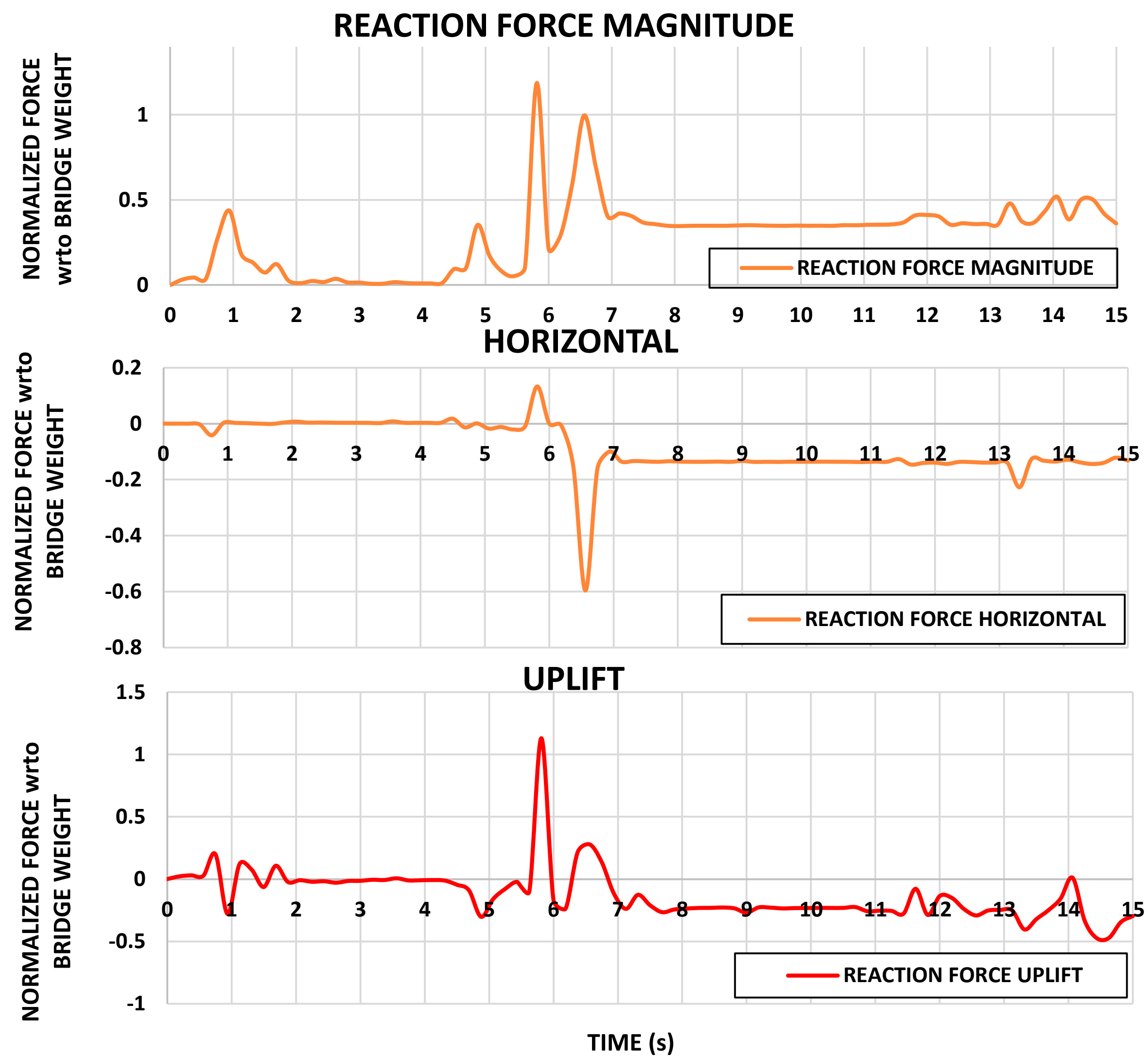


Escambia Bay Bridge Simulation



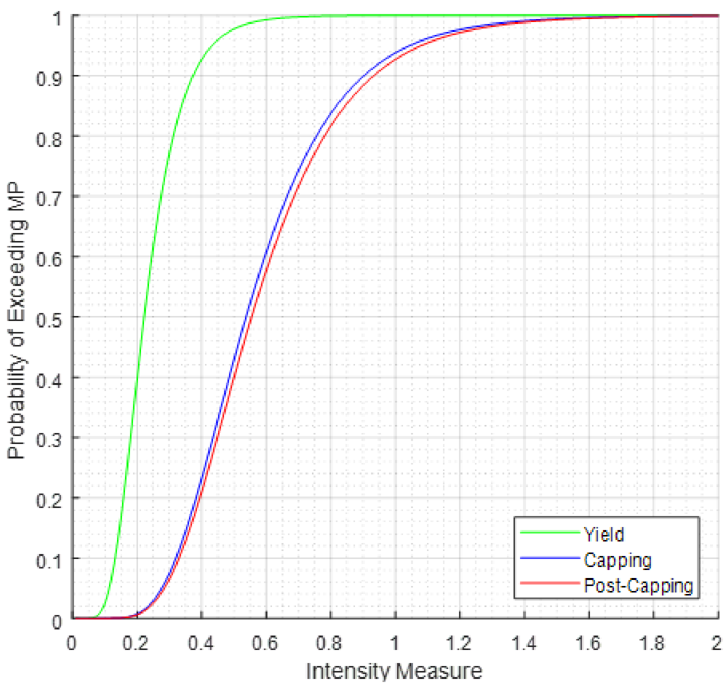


Escambia Bay Bridge Simulation



Future work

Development of fragility relationships (damage vrs hydrodynamic force intensity).



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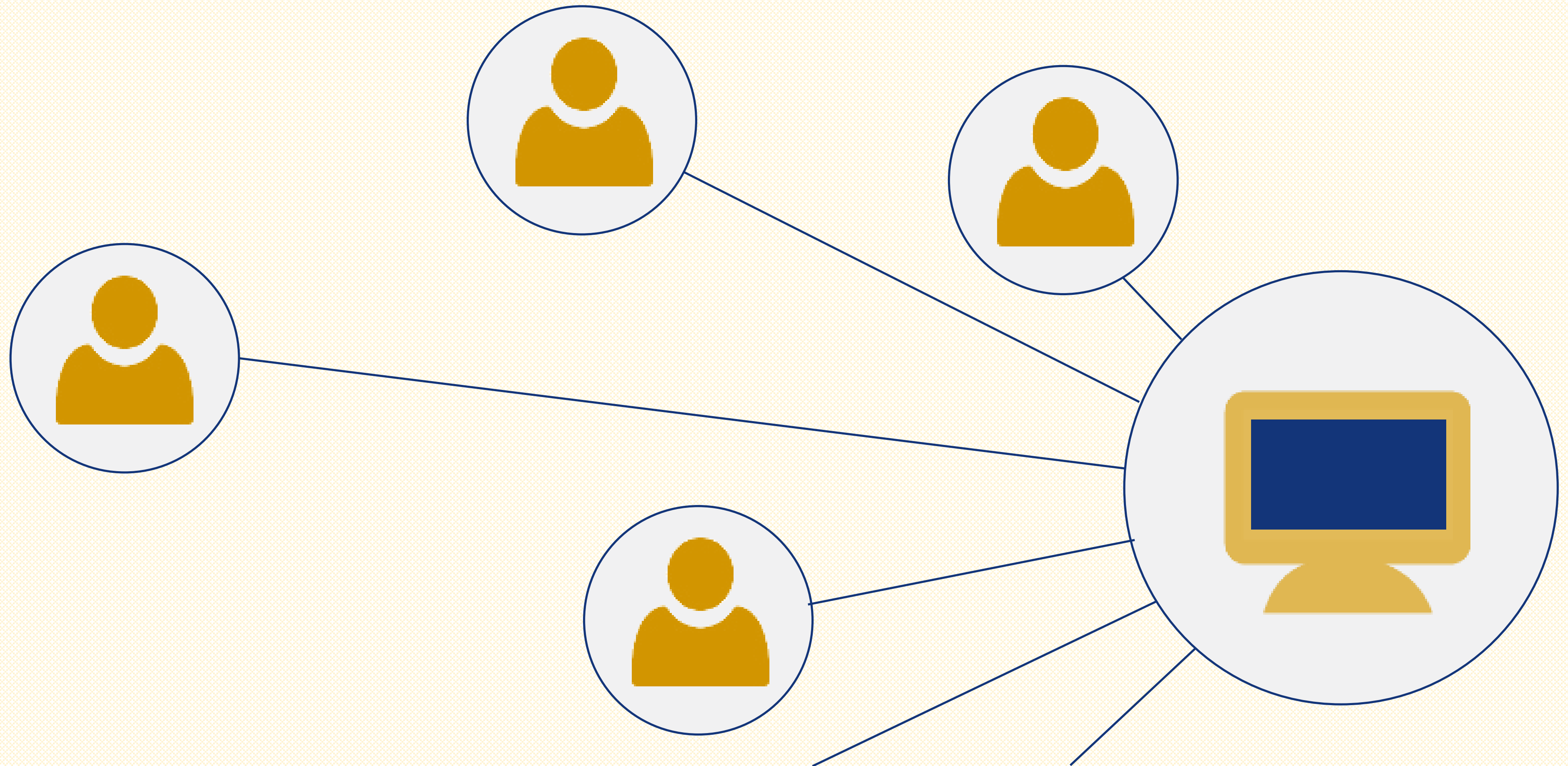
I-70 Risk and Resiliency Pilot – Planning Ahead for a Stronger System

Dr. Oana Ford
Colorado DOT

Ms. Lizzie Kemp Herrera
Colorado DOT

CO CDOT ™



CDOT Planning Ahead for a Strong Transportation System – I-70 Pilot and Next Steps

Lizzie Kemp Herrera

Oana Ford

COLORADO Department of Transportation

Opportunity to Learn from Past

- 1976 and 2013 floods destroyed many of the same facilities.

US 34 1976

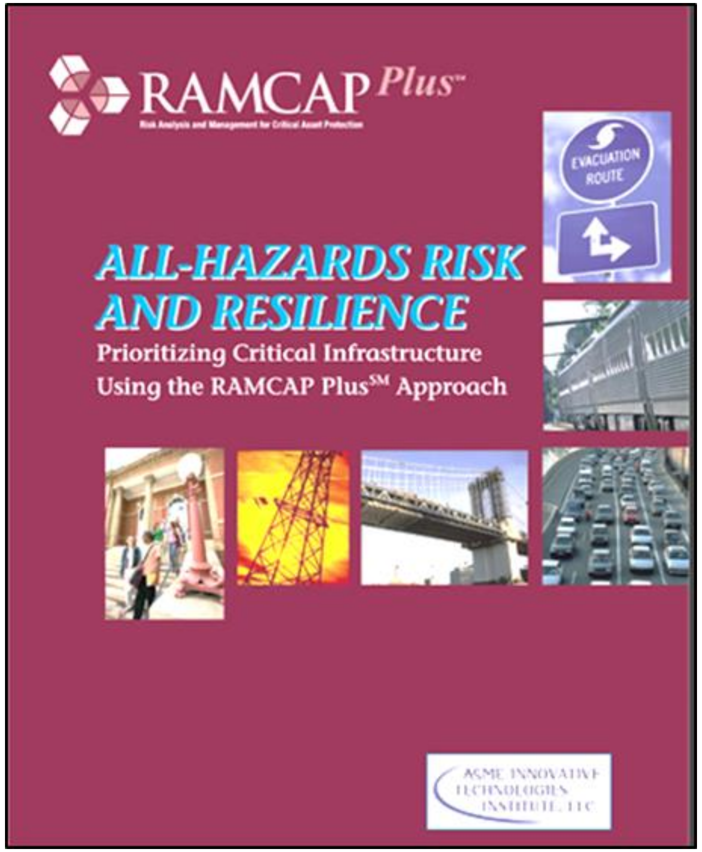
US 34 2013

What can we do now ….

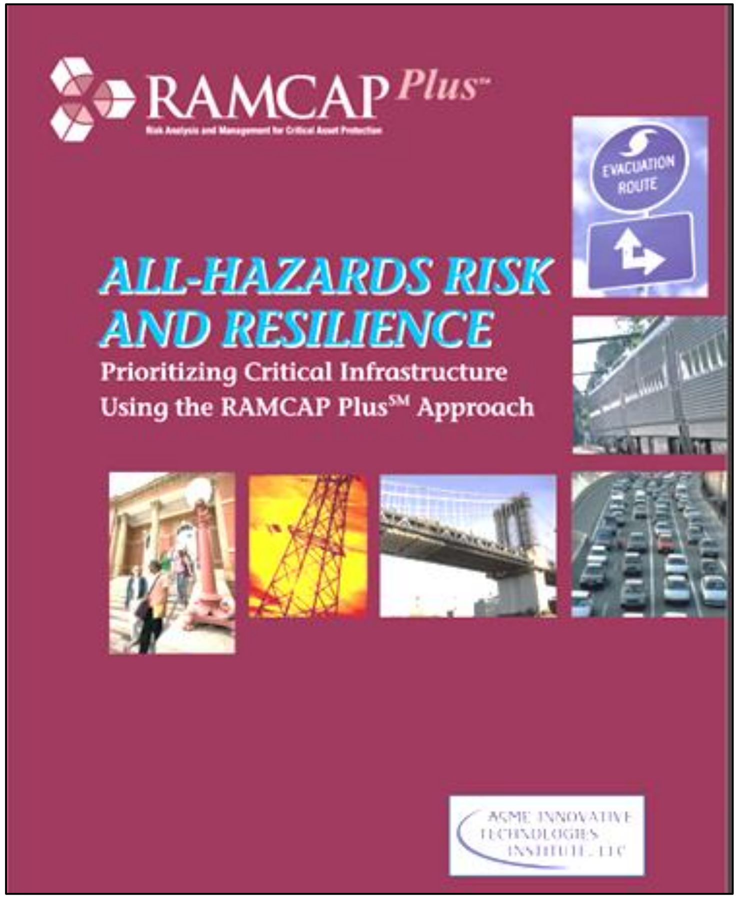
… To avoid this in the future?

I-70 Corridor Risk & Resiliency Pilot Scope

- Analysis of risk potential and system resilience of I-70 from Kansas to Utah
- Proactive look at optimal investments we can make now, in advance of future events, to improve system resilience
- Builds on the 7-step RAMCAP process utilized in flood recovery effort



RAMCAP Plus ➡ R&R for Highways



1. Asset Characterization	• What assets exist, which are critical, and what should be considered?
2. Threat Characterization	• What threats and hazards should be considered?
3. Consequence Analysis	• What happens to assets if a threat or hazard occurs? What are the expected asset losses, economic impacts, injuries, and lives lost?
4. Vulnerability Analysis	• What are the asset vulnerabilities that would allow a threat or hazard to result in expected consequences? How vulnerable is the asset to the identified threat?
5. Threat Assessment	• What is the likelihood of the identified threat?
6. Risk/Resilience Assessment	• What is the anticipated asset total risk and resilience? • **Risk= Consequences x Vulnerability x Threat** • **Resilience= Service Outage x Vulnerability x Threat**
7. Risk/Resilience Management	• What options are there to reduce risk and increase resilience? What is the risk reduction? What is the economic analysis of mitigation alternatives?

I-70 Corridor R&R Pilot

- "Pilot" the data, assumptions, and methodology needed to quantify:
  - What are CDOT's ***assets***?
    - Location, value, condition, criticality
  - What are relevant ***physical threats***?
    - Likelihood and location
  - What ***impact*** would they have on our system?
    - Consequences and vulnerability
  - What are the ***optimal investments*** we can make now to improve resiliency in advance of future events?

Key Concepts – Risk Definition

Risk (R) → C x V x T

Risk *(R) ($)* → *Potential cost of asset losses in a threat-filled environment*
Consequence (C) ($) → *Result of asset failure*
Vulnerability (V) (%) → *Susceptibility to the threat*
Threat Likelihood (T) (%) → *Potential of threat occurrence*

Risk – potential cost of losses to CDOT assets (direct and indirect)
Resilience – ability to remain functional even in presence of risks

Threat-Asset Pairs Analyzed

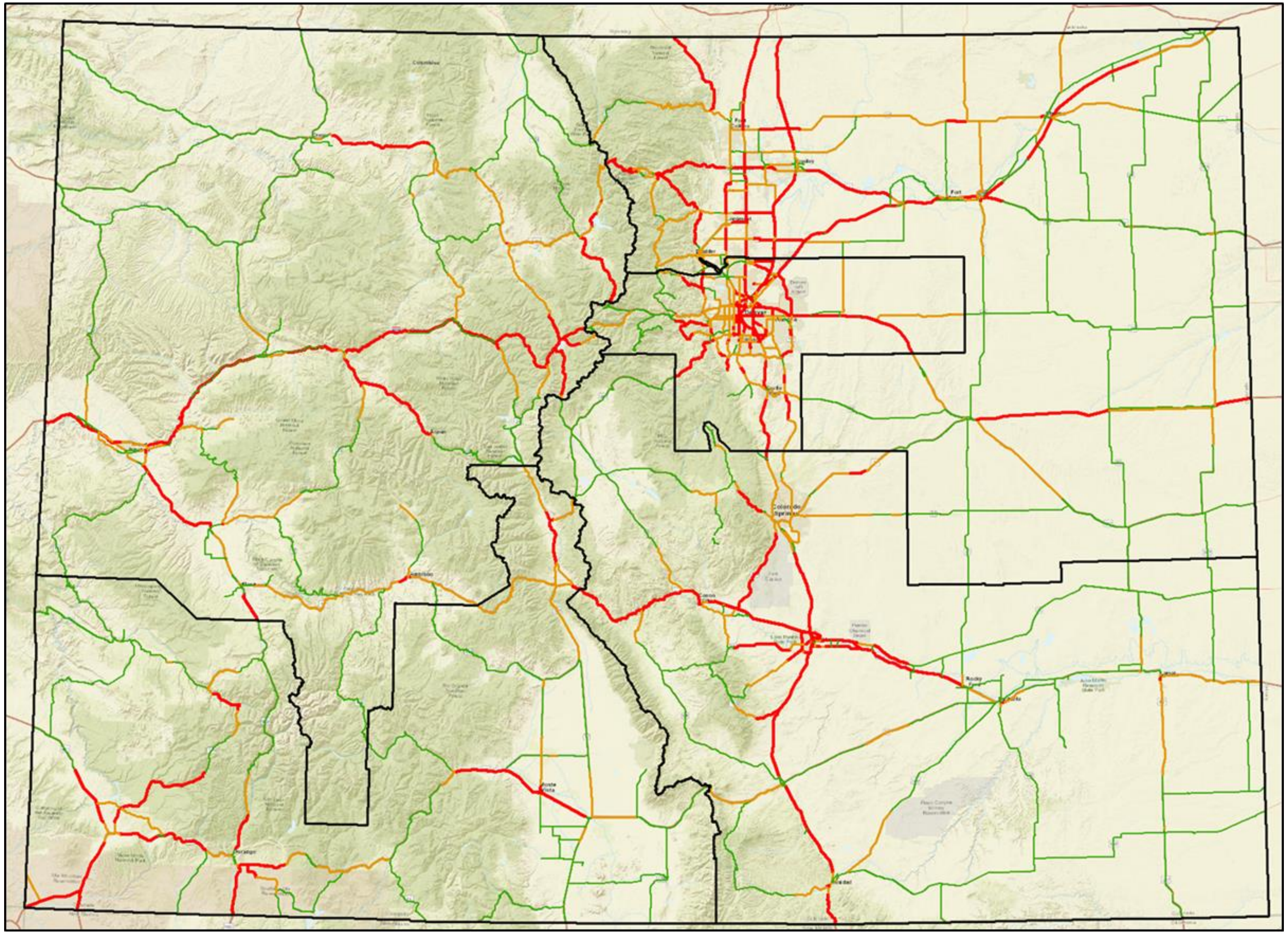
Threats	Assets
Avalanche	Bridges
Flood (scour)	Bridge Approaches
Flood (Overtopping / debris)	Roadway Prism
Fire (wildland)	Post Tension Concrete Slabs
Landslide	Tunnels
Rockfall	NBI Culverts
High wind (special wind zone)	Minor Culverts
Tornado	Walls
Bridge strike	ITS Devices

Criteria for Asset Criticality

Criteria	SOCIAL	ENVIRO	ECON
<u>Usage</u>: AADT + Roadway Classification	✓	✓	✓
<u>Economic Impact</u>: Freight value ($) + Tourism value ($)			✓
<u>Social Impact</u>: SoVI	✓		
<u>System Impact</u>: System Redundancy	✓	✓	✓

Equal weight assigned to each of the six selected variables.

Criticality Map for System Resilience



Equal Weight

- 53.8% Low
- 25.5% Moderate
- 20.7% High

AADT	16.7%
ASHTO Road Classification	16.7%
Freight $ (County)	16.7%
Tourism $ (County)	16.7%
SoVI	16.7%
Redundancy	16.7%

Reminder: Criticality reflects the importance of each asset to overall operations within CDOT's network as related to *system resilience only*. Criticality is part of Step 1 in a 7-step Risk and Resilience Analysis process.

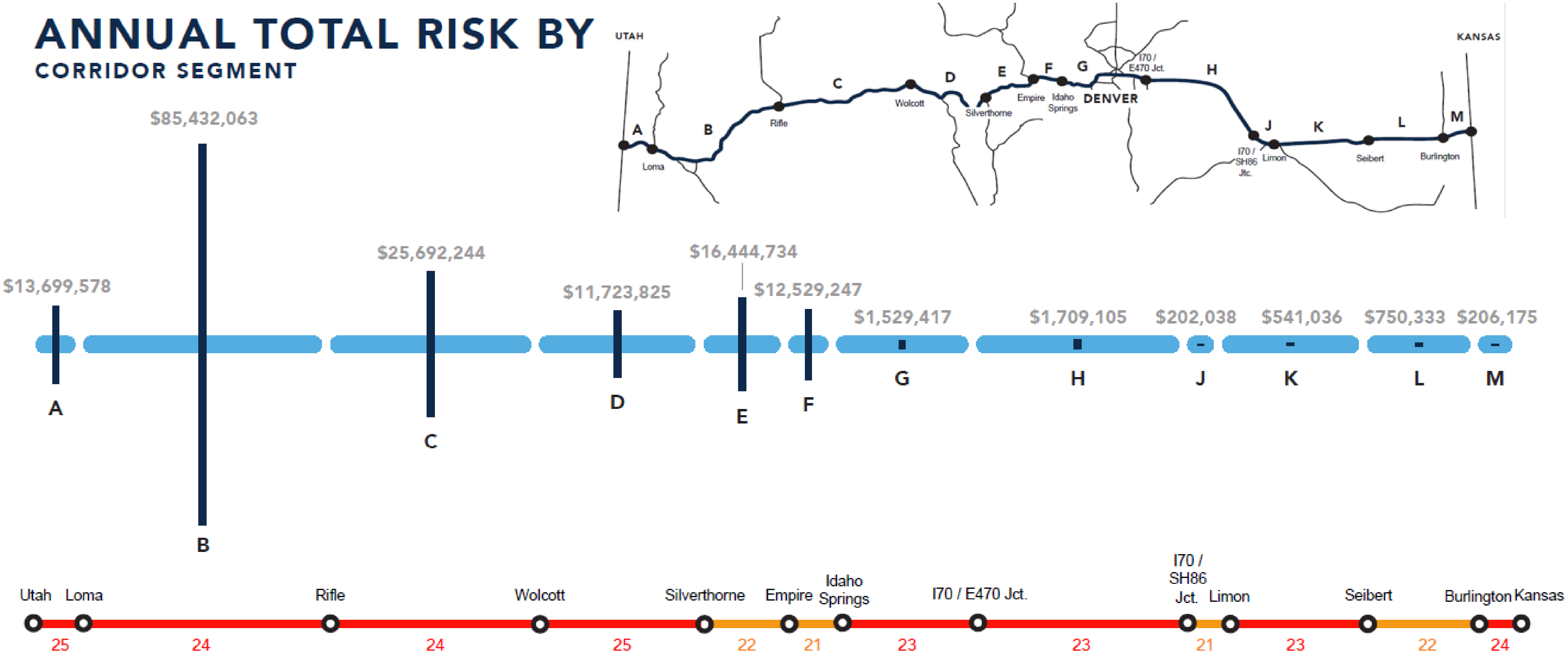
Consequence Analysis ($ per threat-asset pair)

Given the worst reasonable event, what are the consequences? ($)

- Owner Cost
  - Asset Replacement Cost
- User Cost
  - Value of time (delay/detour)

I-70 Pilot Results

ANNUAL TOTAL RISK BY
CORRIDOR SEGMENT



SEGMENT CRITICALITY SCORE

CORRIDOR TOTAL ANNUAL RISK: $170.5 M

ANNUAL RISK SUMMARY BY THREAT

TOTAL RISK I-70

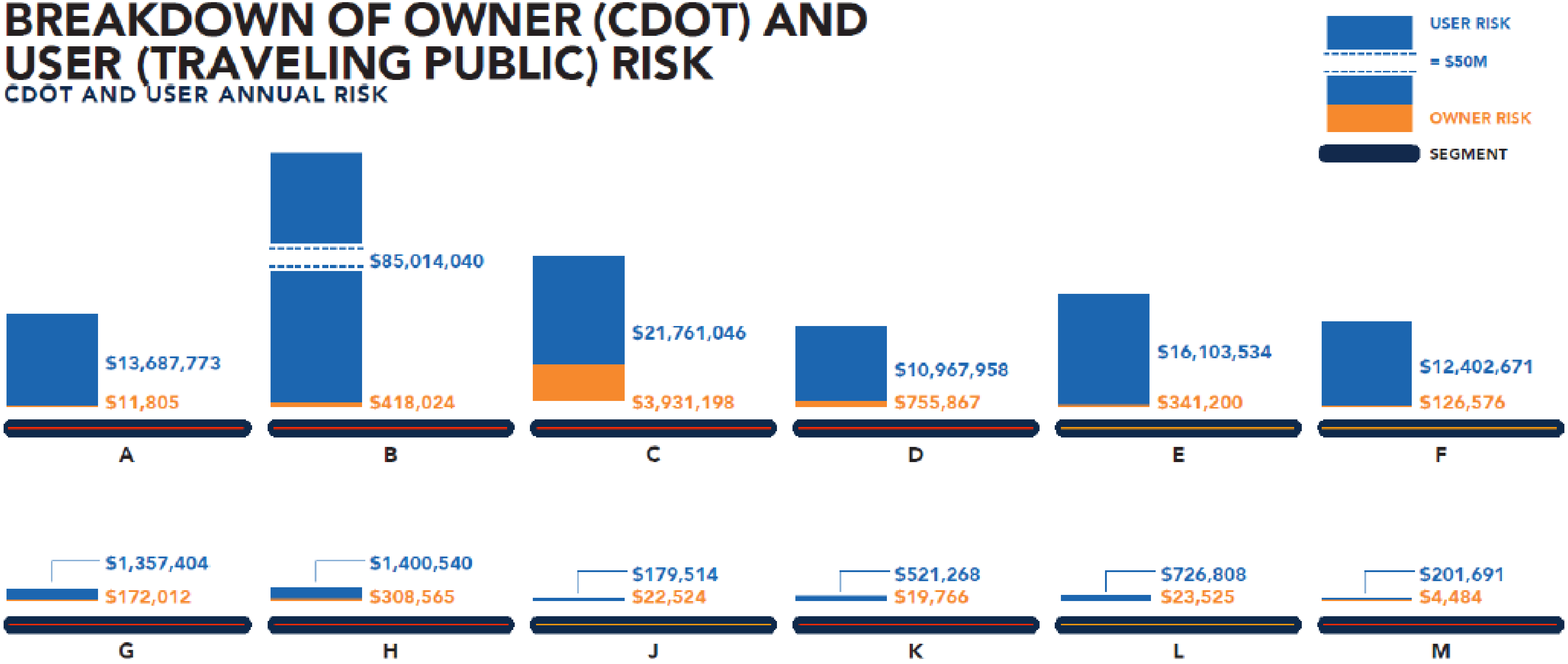
USER RISK · OWNER RISK

Threat	User Risk	Owner Risk
FLOOD	$117,857,395	$1,344,101
ROCKFALL	$35,781,405	$3,835,682
AVALANCHE	$8,516,684	$216,093
LANDSLIDE	$2,161,863	$723,814
HIGH WIND & RELATED WEATHER	$8,475	$310
BRIDGE VEHICLE STRIKE	$6,901	$15,853
TOTAL SYSTEM RISK (TOTAL)	$164,324,248	$6,135,544

TOTAL = $170.5 M

BREAKDOWN OF OWNER (CDOT) AND USER (TRAVELING PUBLIC) RISK

CDOT AND USER ANNUAL RISK



ANNUAL RISK SUMMARY BY THREAT

SEGMENT C -- HIGH CRITICAL

TOTAL RISK USER RISK OWNER RISK

ROCKFALL

$16,977,067
$13,174,605
$3,802,462

FLOOD

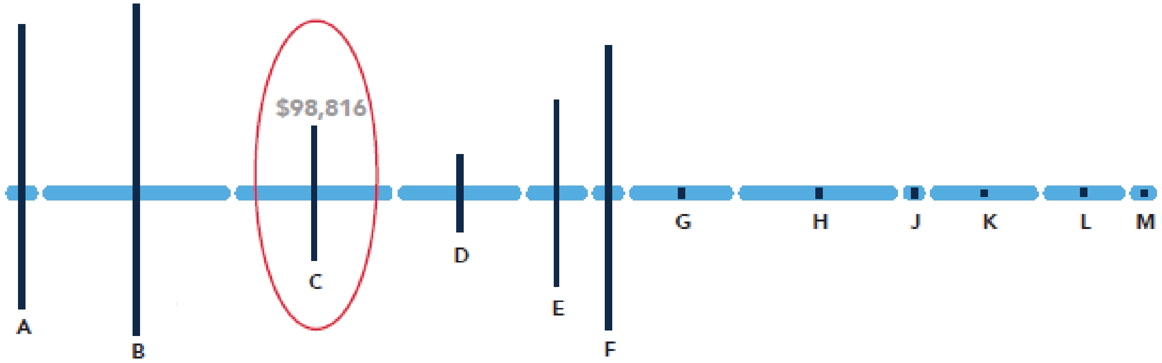
$8,713,721
$8,586,235
$127,486

BRIDGE VEHICLE STRIKE

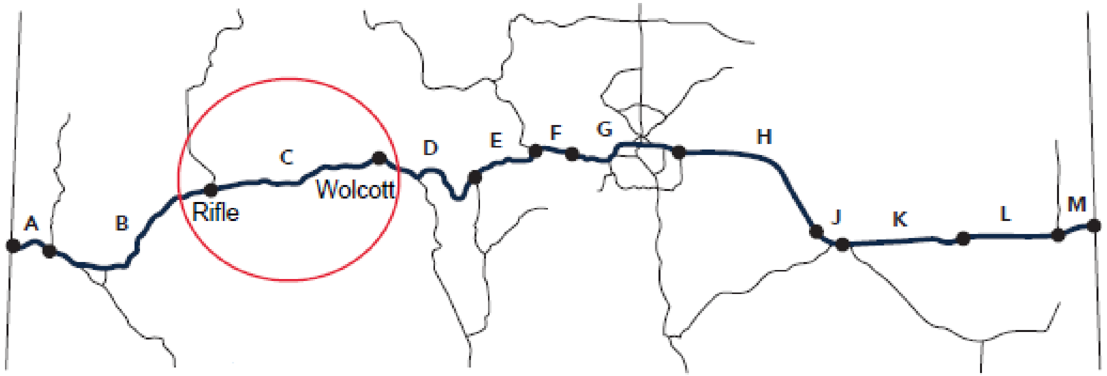
$1,456
$206
$1,250

TOTAL SYSTEM RISK

$25,692,244
$21,761,046
$3,931,198



TOTAL RISK FROM ALL THREATS PER LANE MILE



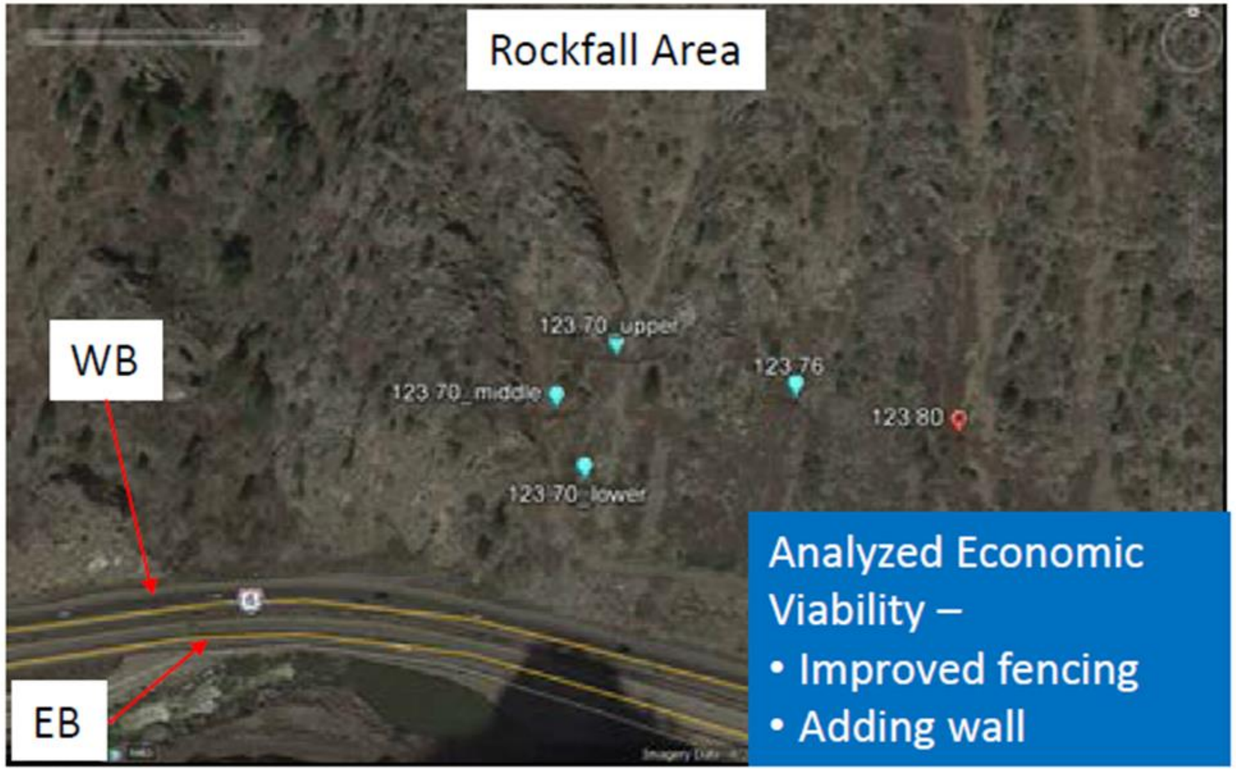
Final Step – A Deeper Dive at 5 Specific Sites

Evaluate alternative mitigation measures to improve future resiliency at five locations – diverse locations and threat/asset combinations:

1. Flood – Bridge
2. Rockfall – PTCS
3. Flood – Bridge Approach
4. Flood – non-NBI Culvert
5. Landslide – Roadway Prism

Example 2: PTCS – Rockfall

Location	Milepost	Region	Resilience Segment	Criticality	Total Annualized Risk
Glenwood Canyon	123.7	3	C	High	$ 1,233,853



Analyzed Economic Viability –
- Improved fencing
- Adding wall

Example 2: PTCS – Rockfall

Proposed Mitigation	Description	Cost of Mitigation
Option 1	Replacement of existing 2,000 KJ fences with 5,000 KJ fences (5 fences total)	$ 290,000/fence $ 1,450,000/site
Option 2	New 140 feet wall to Existing site with 2,000 KJ fences	$ 350,000

Example 2: PTCS – Rockfall: Summary

Mitigation	Reduction in Annualized Owner Risk	Reduction in Annualized User Risk	Reduction in Annualized Total Risk	B/C Owner Risk	B/C Total Risk
Option 1	$ 69,912	$ 388,113	$ 458,025	0.41	2.7
Option 2	$ 36,839	$ 268,225	$ 305,064	2.56	21.2

Contact Information

Project Management Team

Lizzie Kemp-Herrera, CDOT Region 1 Planning & Program Management
elizabeth.kemp@state.co.us (303) 829-0274

Heather Paddock, PE, CDOT Region 4 Central Program Engineer
heather.paddock@state.co.us (970) 290-8723

Project Team

Aimee Flannery, Ph.D., P.E., Program Manager, AEM Corporation
aimee.flannery@aemcorp.com (703) 328-2423 (cell)

Joe Garcia, P.E., Senior Manager, AEM Corporation
joseph.garcia@aemcorp.com (719) 250-3442 (cell)

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FHWA Approaches for Addressing Resilience to Extreme Weather Events

Mr. Robert Kafalenos
FHWA

U.S. Department of Transportation
Federal Highway Administration

U.S. Department of Transportation
Federal Highway Administration

FHWA Approaches for Addressing Resilience to Extreme Weather Events

Tran-SET

September 19, 2018

Robert Kafalenos
Office of Natural Environment
FHWA

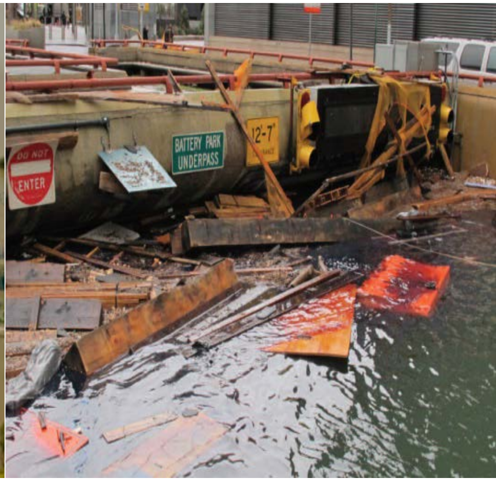
Summary

1) FHWA approach and policies
2) Ongoing pilot projects
3) FHWA resources

(1) What is *Resilience*?

Resilience: the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions

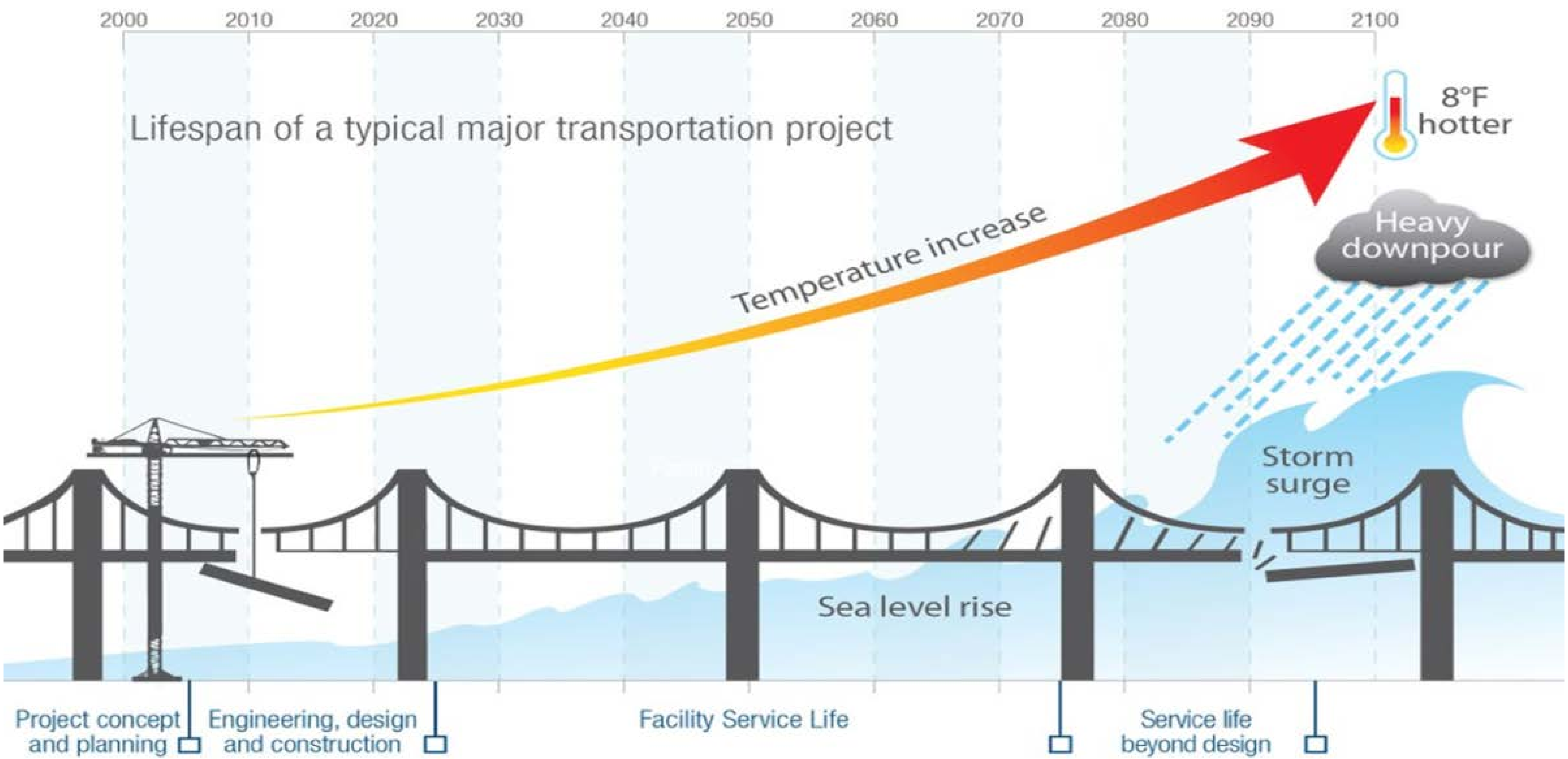
Adaptation: adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects



Importance of Resilience

Story Created: Jul 4, 2008 at 5:07 PM PDT
Story Updated: Jul 4, 2008 at 5:25 PM PDT

Why Consider Changing Conditions?



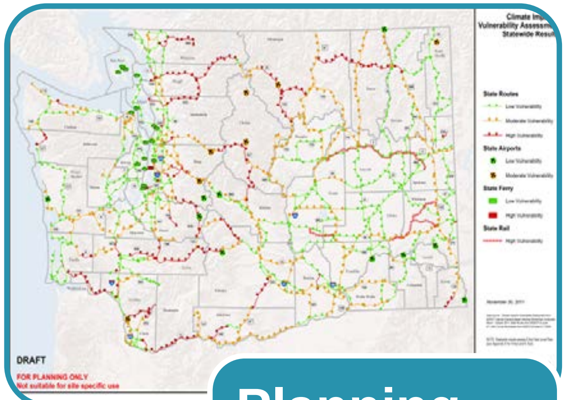
Impacts of a changing climate are being felt now, and will accelerate significantly in the future.

– National Academy of Sciences and National Climate Assessment

Integrating Resilience

Goal: Integrate consideration of resilience in transportation decision making

- In support of 23 U.S.C. § 503(b)(3)(B)(viii), which directs the U.S. Department of Transportation "to carry out research and development activities … to study vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities."



Planning

- Long Range Transportation Plans
- Asset Management Plans

Project Level

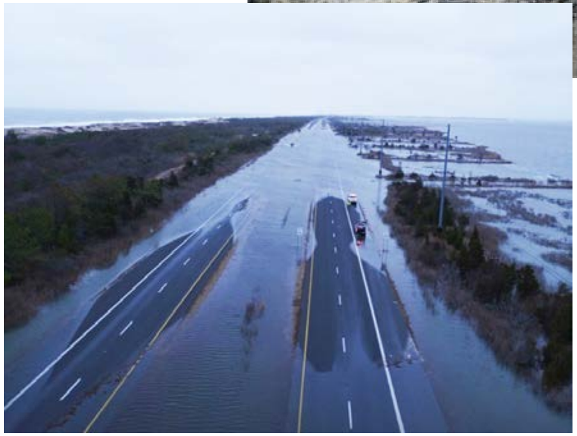
- Environmental Processes
- Engineering
- Design

Operations and Maintenance

- Emergency Relief
- Snow Removal Programs

Extreme Weather Resilience Policy

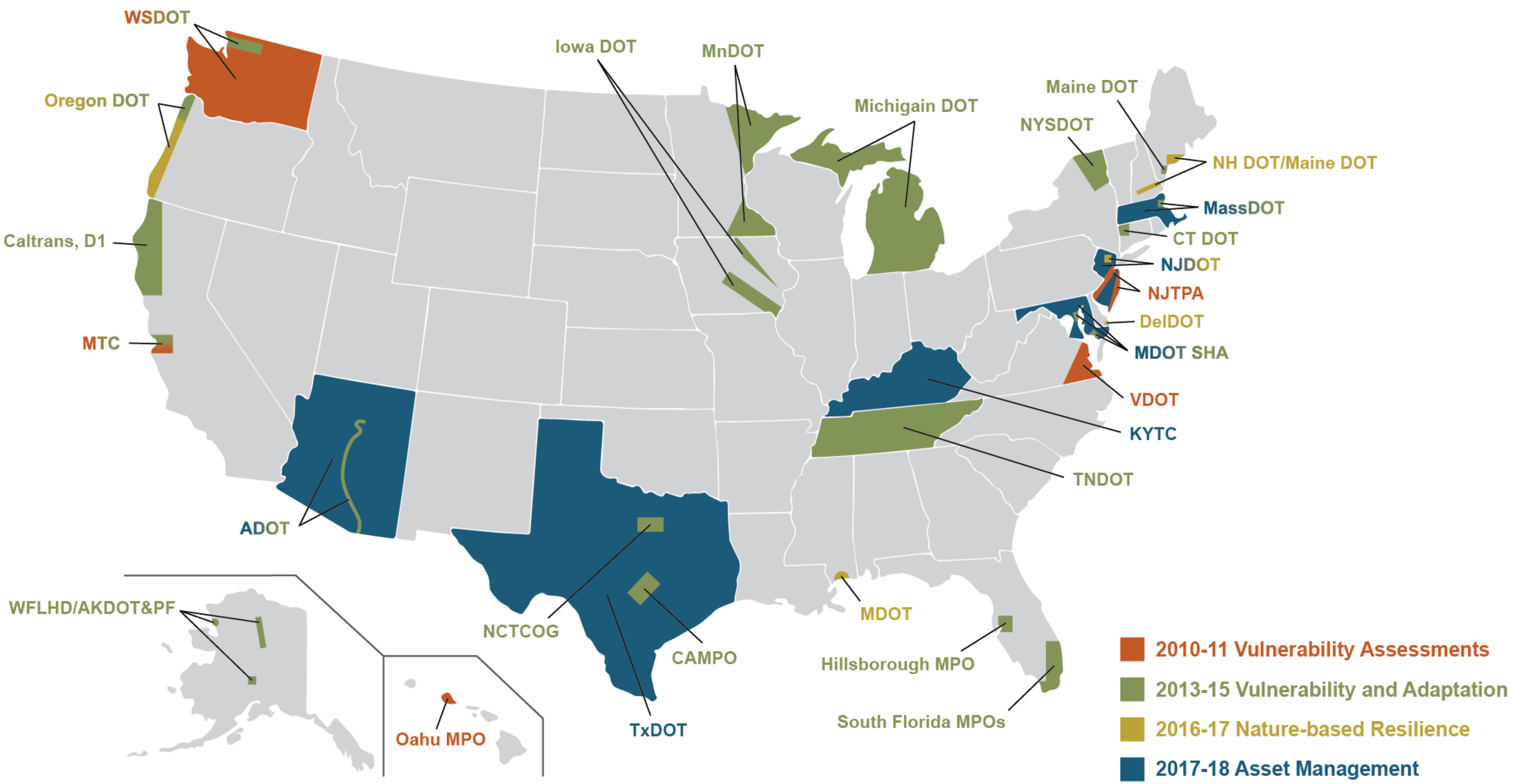
- USDOT FY 2018-22 Strategic Plan: "DOT will increase its effectiveness in ensuring that infrastructure is resilient enough to withstand extreme weather"
- FHWA Order 5520 commits FHWA to integrating EW risk consideration into programs
- EW resilience eligible for FHWA funds
- Emergency relief program guidance encourages cost-effective resilience strategies



Extreme Weather Resilience Related Regulations

- Risk-based **asset management** plans must address risks associated with current and future environmental conditions (23 CFR 515)
- Assets requiring repeated repair require **analysis of alternatives** (23 CFR 667)
- State and metropolitan **transportation planning** should now include resilience as a planning factor (23 USC 134, 23 CFR 450)
- **Metropolitan transportation plans** shall include an assessment of capital investment and other strategies to… reduce the vulnerability of the existing transportation infrastructure to natural disasters (23 CFR 450.324(f)(7))

(2) Resilience Pilot Projects



Nature-based Resilience Strategies

Why talk about nature-based solutions (also called **green infrastructure**)?

- May be cheaper; effective; more adaptable; co-benefits for habitat, fisheries, recreation

Integrated Approach:

- **Structural** (e.g. armoring, raise road, widen culvert, pavement materials)
- **Natural features**: (e.g. wetlands, dunes)
- **Nature-based features**: built in coastal areas by acting in concert with natural processes (e.g. wetland restoration, artificial reefs, beach nourishment)
- **Non-structural** (e.g. land use policies, infrastructure siting, insurance policies)

Rock revetment, Photo credit: Tina Hodges

Concept for protecting Bay Bridge, Oakland, CA, Credit: MTC

FHWA Project: Nature-based Resilience for Coastal Highways

- Goal: Provide research and technical assistance to help state DOTs and MPOs implement nature-based solutions to protect coastal highways from storm surge and sea level rise.
- Build off USACE and NOAA work
- 5 pilot projects completed
  - OR DOT
  - ME & NH DOTs jointly
  - MS DOT
  - DE DOT
  - US Army Corps of Engineers in NJ
- White paper, Winter 2018
- Regional peer exchanges, Spring 2018: AL, CA, DE, NC
- Implementation guide, 2019

Photo Credit: Tina Hodges

Map Credit: Google Earth

Asset Management & Resilience Pilots

Asset Management and Resilience Pilot Program

- AZ, TX, KY, MD, NJ, MA pilot projects
- Expected late 2018
- Guidebook on addressing resilience in Asset Mgt. (2019)

What is *Asset Management*?

- ***Asset Management*** is a systematic process of operating, maintaining, and improving physical assets to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired **state of good repair** over the **life cycle** of the assets at **minimum practical cost**.

TAMP Contents

- Asset Management Plan contents:
  - Pavement and bridge inventory and conditions on the NHS
  - Objectives and measures
  - Performance gap identification
  - **Lifecycle planning**
  - **Risk management analysis**
  - Financial plan
  - Investment strategies

Asset Management Plans: Extreme Weather Risks

Resilience focus in two sections:

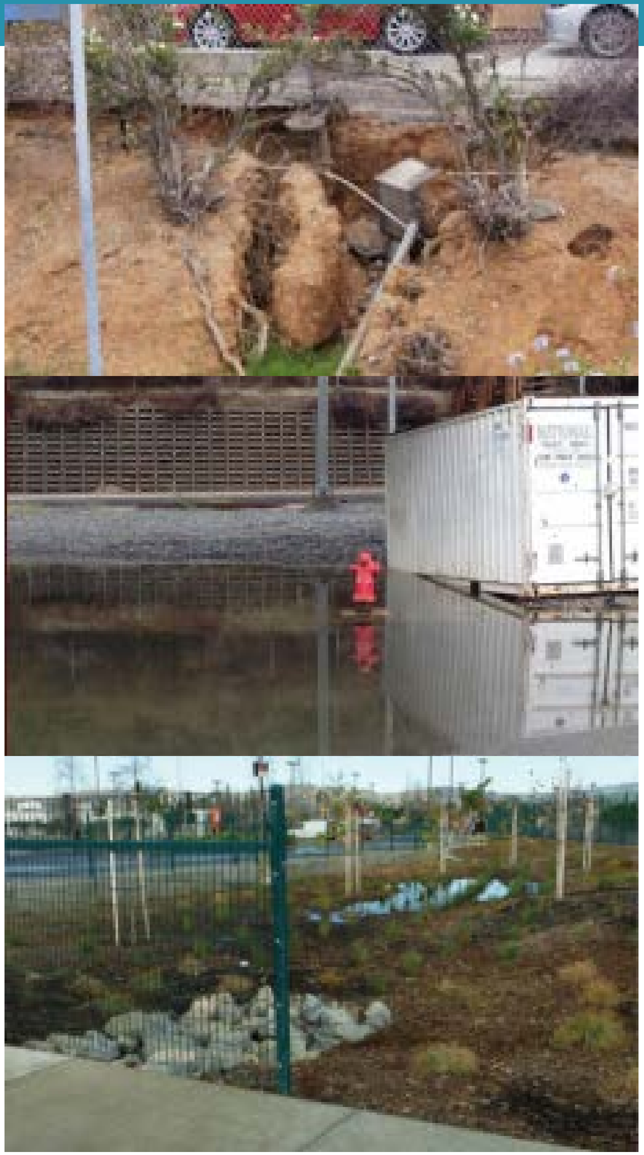
- **Risk management plan**…that identifies at a minimum risks associated with current and future environmental conditions, extreme weather events, etc. (23 CFR Part 515.7(c))
- **Life-cycle planning**, which should include a range of factors that could affect whole life cost of assets, including current and future environmental conditions, extreme weather events, etc. (23 CFR Part 515.7(b)

First complete TAMPs (due June 2019)

Asset Management & Resilience – Los Angeles

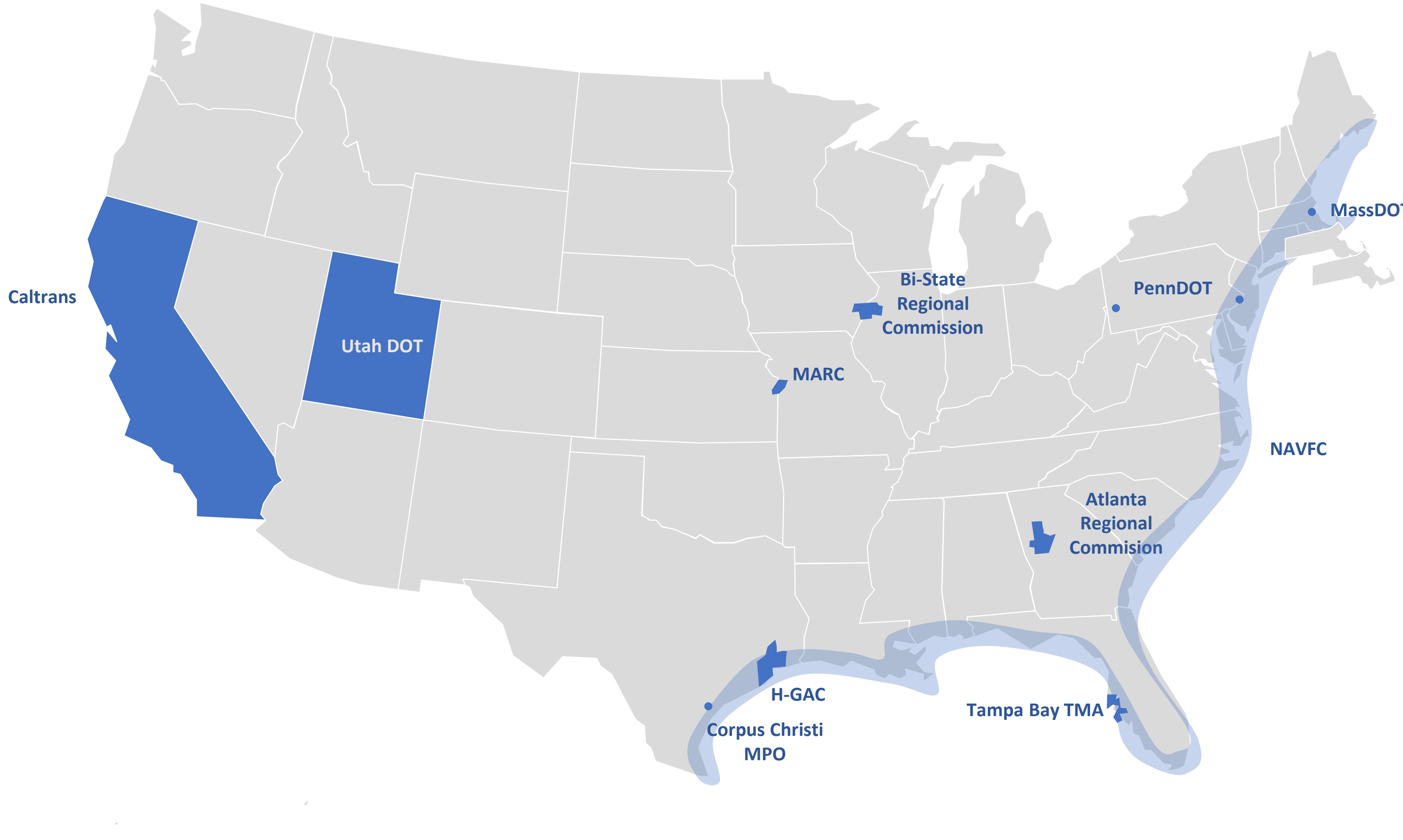
LA County Metropolitan Transportation Authority (Metro)

- Integrated climate risk into existing asset management system.
- Developed new data fields in the asset management system, and guidelines for assessing risk of the assets.



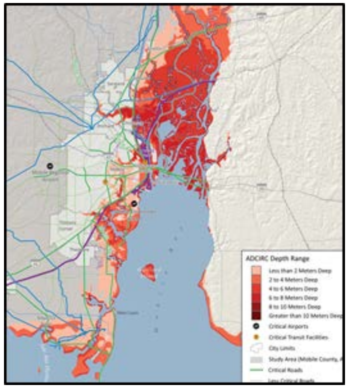
Source: Metro

2018 – 2020 Pilots

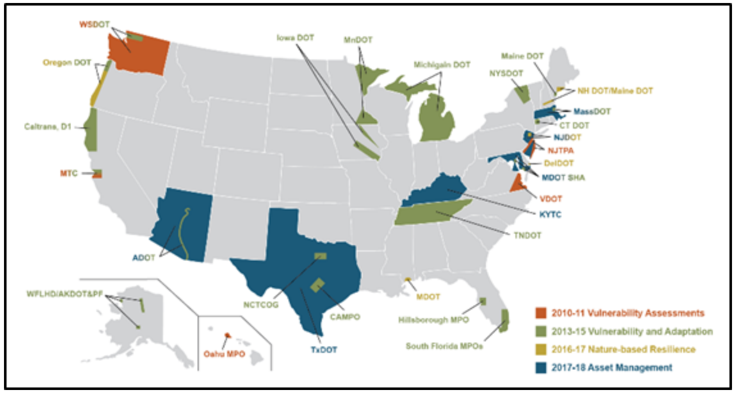


(3) FHWA Resilience Resources

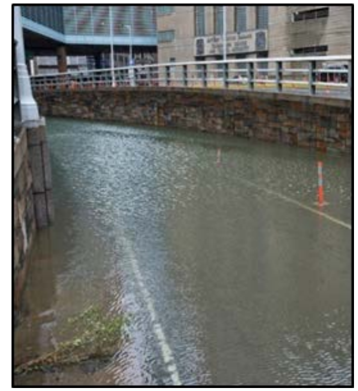
Gulf Coast 2 Study



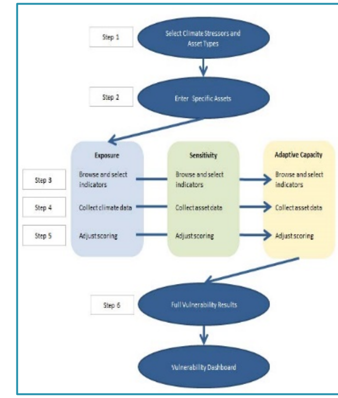
Resilience Pilots - State DOTs, MPOs, FLMAs



Hurricane Sandy Project



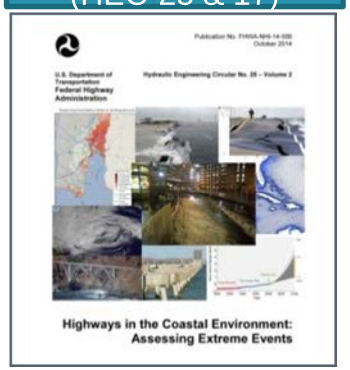
Tools



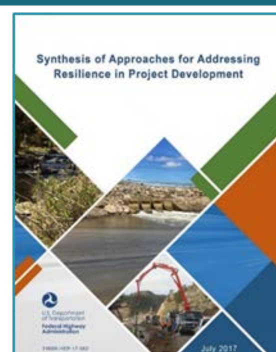
https://www.fhwa.dot.gov/environment/sustainability/resilience/

Vulnerability & Adaptation Framework

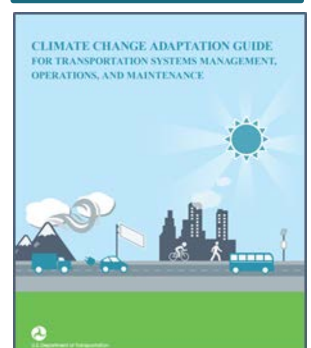
Engineering Guidance (HEC-25 & 17)



Project Development



Operations & Maintenance

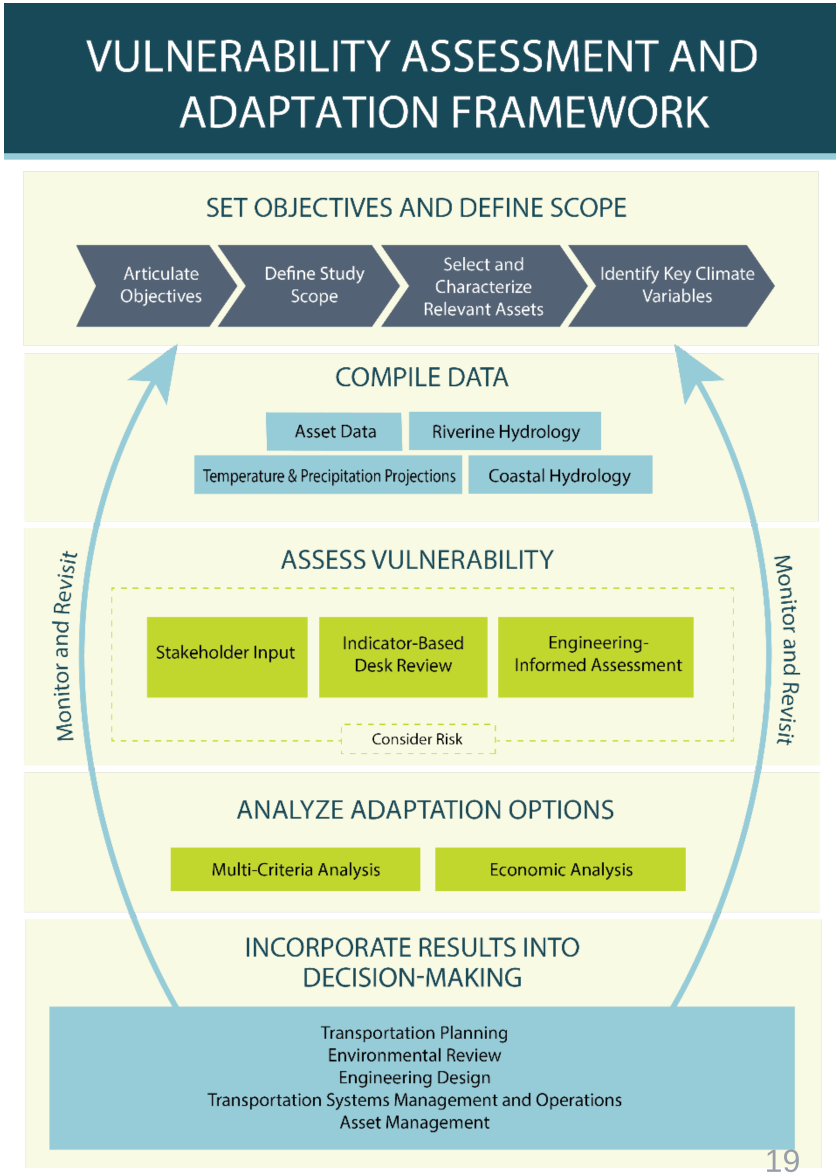


Guidebooks under development on integrating resilience in:

- Asset Management
- Transportation Planning
- Nature-based solutions

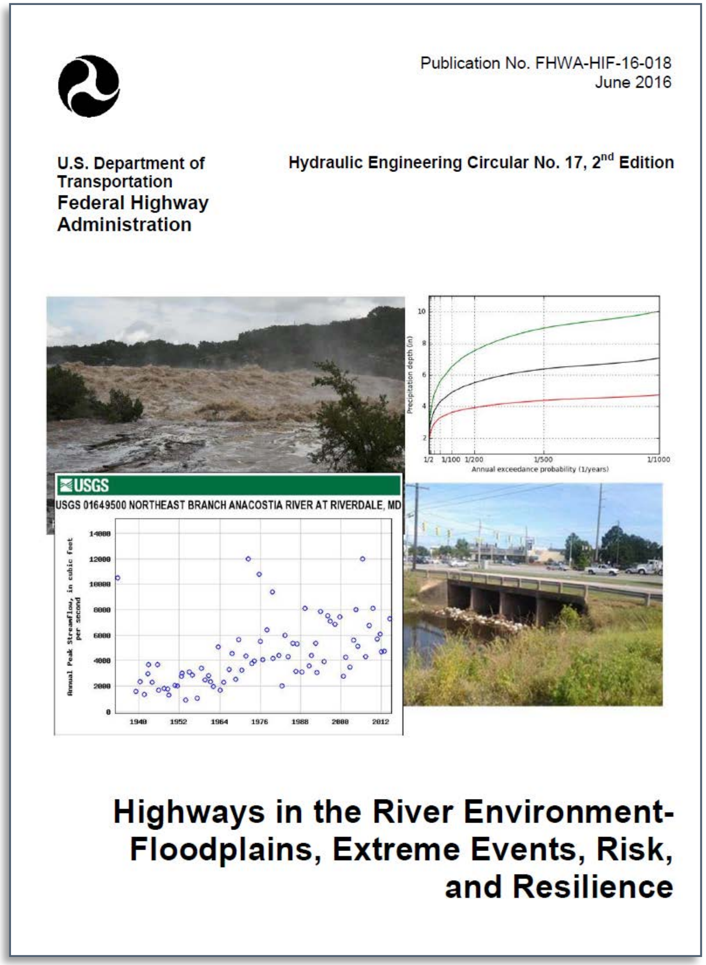
Vulnerability Assessment and Adaptation Framework, 3rd Edition

- Provides an in-depth and structured **process** for conducting a vulnerability assessment.
- Features **examples** from assessments conducted nationwide.
- Incorporates information from recent FHWA and other U.S. **partner projects**.
- Includes links to **resources and tools**.



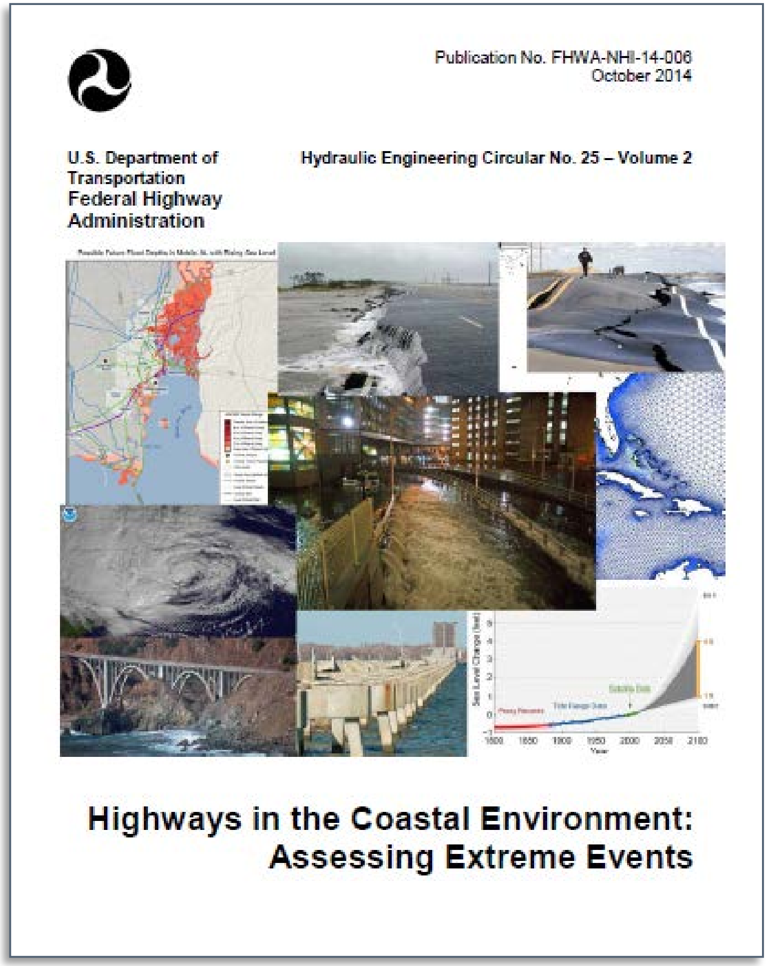
Riverine Hydrology

- **Hydraulics Engineering Circular 17**
  Highways in the River Environment - Floodplains, Extreme Events, Risk, and Resilience (Second Edition), June 2016



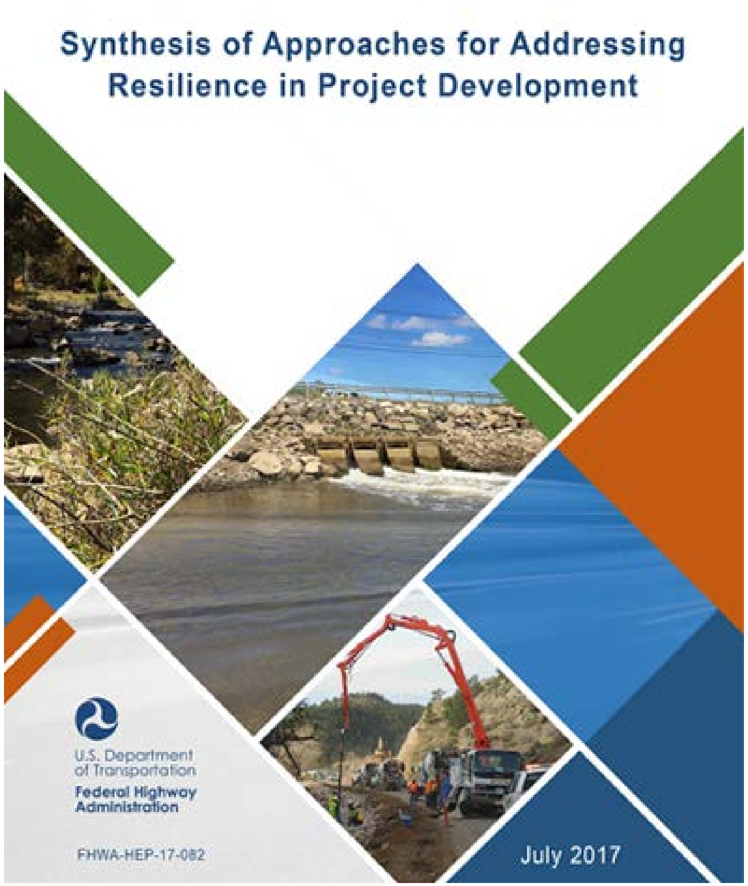
Coastal Hydrology

- **Hydraulics Engineering Circular 25, Volume 2** Highways in the Coastal Environment: Assessing Extreme Events, October 2014.
- Currently being updated

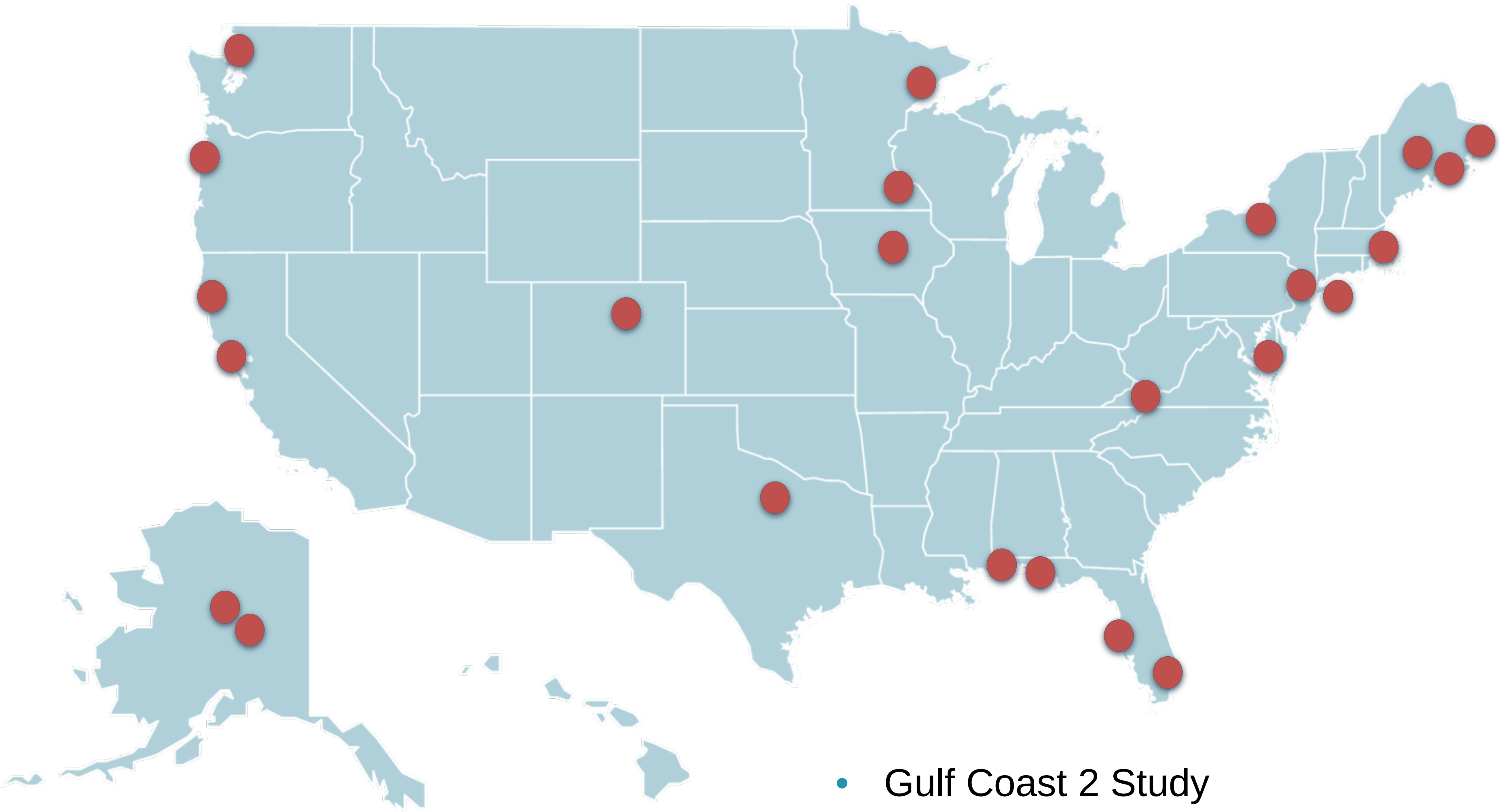


Synthesis of Approaches for Addressing Resilience in Project Development (2017)

- Lessons learned, etc., for four engineering disciplines
  - Coastal Hydraulics
  - Riverine Hydraulics
  - Pavement and Soils
  - Mechanical & Electrical Systems
  - Overall Lessons learned for engineering
- Addressing resilience in the project development process
- Economic analysis



Engineering-Focused Case Studies



- Gulf Coast 2 Study
- Adaptation Pilots
- Post-Sandy Resiliency Study
- TEACR

THANK YOU!

Contact Information: Robert.Kafalenos@DOT.gov

Website: https://www.fhwa.dot.gov/environment/sustainability/resilience/