

# Workshop on Structural Design for Coastal Flood Resilience



Funded by  
National Science Foundation  
Applied Technology Council  
Princeton University

## Applied Technology Council

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The Applied Technology Council (ATC) is an internationally recognized non-profit corporation founded by the Structural Engineers Association of California in 1973 to protect life and property through the advancement of science and engineering technologies. With a focus on seismic engineering, and demonstrated capabilities in wind, coastal inundation, and blast engineering, ATC develops state-of-the-art, user-friendly engineering resources and applications to mitigate the effects of natural and other hazards on the built environment. ATC implements funded research and technology transfer projects through the development of nonproprietary consensus opinions on structural engineering issues. ATC also identifies and encourages needed research, and disseminates technological advancements through guidelines, manuals, seminars, workshops, forums, and electronic media.

ATC consists of a small group of in-house technical and support staff, assisted by highly qualified individuals engaged as consultants or subcontractors on specific projects. With this model, ATC is able to assemble teams of researchers and practitioners in diverse areas of expertise that would not otherwise be available through any one organization. Funding for ATC projects comes from federal, state, and local government entities, or from the private sector in the form of tax-deductible contributions to the ATC Endowment Fund.

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Cover image: Damaged building along the New Jersey Coast after Hurricane Sandy in 2012 (photo credit: Tori Tomiczek).

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ATC-164

# Workshop on Structural Design for Coastal Flood Resilience

Prepared by  
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# Preface

The Applied Technology Council (ATC) is a non-profit organization with a 50-year history in developing user-friendly engineering solutions for safer and more resilient communities. To date, ATC has prepared more than 300 publications serving the structural engineering profession, including technical guidance documents and tools to support implementation of performance-based seismic design of buildings. More recently, in accordance with the ATC Strategic Plan (2021-2025), the organization has initiated a series of efforts to support infrastructure resilience under future hazard conditions.

This report is the result of a workshop co-organized by the National Science Foundation (NSF), ATC, and Princeton University, where NSF supported the workshop through funding a project “Advancing Knowledge in Water-Shell Structure Interaction through Discovery of Efficient Hydrodynamic and Structural Thin-Shell Forms” with the primary objective to research efficient hydrodynamic thin-shell structural forms that have broad application to coastal resilience.

ATC is indebted to the Workshop Planning Committee that included Maria Garlock (chair), Lyle Carden, Negar Elhami-Khorasani, Ayse Hortacsu, Justin Moresco, David Prevatt, and Seth Thomas. ATC also gratefully acknowledges the session moderators, including Elizabeth English, Ali Farhadzadeh, Matt Gilbertson, Katerina Kyprioti, David Prevatt, and Landolf Rhode-Barbarigos, who facilitated engaged discussions during the two-day workshop. The session speakers, who are named on the title page, shared thoughtful and compelling material that was impressive for its breadth and depth.

The workshop would not have been as successful if not for the discussions prompted by questions from participants during the sessions or the comments and thoughtful conversations during the breakout groups. ATC is grateful for the participation of all workshop attendees, whose names and affiliations can be found in Appendix A.

Jon A. Heintz  
ATC Executive Director

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## Chapter 1

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# Introduction and Program

The Workshop on Structural Design for Coastal Flood Resilience organized by the National Science Foundation (NSF), the Applied Technology Council (ATC), and Princeton University Department of Civil and Environmental Engineering was held at Princeton University on May 16-17, 2024. The workshop brought together over 60 researchers, practitioners, stakeholders and other experts to discuss structural solutions for coastal flood resilience considering future conditions.

This report summarizes the workshop program and key takeaways from presentations and breakout discussions and highlights immediate outcomes from the workshop. It also includes slides of the workshop presentations and lists workshop participants.

### 1.1 Motivation and Objectives

Increases in intensity and frequency of hurricanes and storm surges have resulted in increased flooding, evacuation, and deaths for coastal communities, making structural design for providing flood resilience more critical for our coastal communities. However, the tools commonly utilized for flood design rely on historically available hazard information, not including recent increases in intensity and frequency and potential for additional changes in the future. Methods for incorporating these changes are under development. In addition, structural design for other hazards, specifically earthquakes, has benefited from 50 years of research and development, primarily funded by the National Earthquake Hazards Reduction Program (NEHRP), which has led to, among other innovations, the development and wide acceptance of performance-based seismic design approaches. It is envisioned that methods successfully developed for seismic design may provide a framework for advancing flood design.

Further, accelerated urbanization in areas that may be susceptible to flooding in the future creates a pressing challenge to improve the resilience of communities. Joint efforts among the governments of major cities, private industry, and research entities are needed to explore responses to this issue.

To aid in making our communities more resilient, the Planning Committee envisioned a workshop with a specific focus on improving coastal flood design practices by incorporating experiences from mitigation design, research, and implementation in flood and other hazard areas. The resulting workshop was designed with the following objectives: form connections, share experiences and resources, and foster collaborations among participants; identify deficiencies in flood design practices, gaps in basic science, and needs in codes and standards.

### 1.2 Workshop Program and Participants

The workshop took place over two days (May 16 and 17, 2024). The workshop program is presented in Figure 1-1.

## Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience



**May 16-17, 2024**  
Princeton University



Final version (May 14)

### Wednesday, May 15, 2024 (81 Alexander St)

6:00: PM - 8:00: PM Drop-in Hors d'oeuvres Reception at M. Garlock home (on campus, 81 Alexander St.)

### Thursday, May 16, 2024 (016 Robertson Hall )

8:00: AM - 9:00: AM Registration and Continental Breakfast (Robertson Hall 016)

9:00: AM - 9:30: AM	<b>OPENING REMARKS</b>	Welcome Welcome Overview of Workshop	Branko Glisic, Prof. & Chair CEE, Princeton Univ. Jon Heinz, Exec. Director ATC Maria Garlock, Professor, CEE, Princeton Univ.
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9:30: AM - 10:20: AM	<b>Theme 1</b> <b>STATE OF RESEARCH/PRACTICE</b> <b>(Part 1)</b>  (Moderator: Ali FarhadZadeh)	1a. Overview of Climate Change, Storm Surge and SLR Models  1b. Flood Hazard in the Built Environment  <i>(10 min) Questions</i>	Jayantha T. Obeysekera, Director of the Sea Level Solutions Center, FIU  Andrew Kennedy, Professor, Civil and Environmental Engineering and Earth Sciences, Notre Dame
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10:20: AM - 10:40: AM **BREAK**

10:40: AM - 11:55: AM	<b>Theme 1</b> <b>STATE OF RESEARCH/PRACTICE</b> <b>(Part 2)</b>  (Moderator: Elizabeth English)	1c. State of Structural Engineering Flood Practice 1d. Case studies: Damage Classification, Fragility Quantification 1e. NYC climate adaptation plans: NY & NJ Harbor & Tributaries Focus Area Feasibility Study (HATS)	Seth Thomas, Associate, KPFF Portland Structural Victoria (Tori) Tomiczek, Associate Professor, United States Naval Academy Bryce W. Wisemiller, U.S. Army Corps of Engineers
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*(15 min) Questions/Discussion: State of Research/Practice*

11:55: AM - 1:15: PM **LUNCH (Whig Hall, Senate Chamber, Top Fl.)**

1:15: PM - 2:10: PM	<b>Theme 2</b> <b>EXPERIMENTAL AND NUMERICAL</b> <b>CAPABILITIES/NEEDS</b>  (Moderator: Katerina Kyprioti)	2a. Experimental Facilities for Coastal Flood Resilience: State-of-Art and Needs 2b. Numerical Tools: Types, Pros/Cons, Needs  <i>(15 min) Questions/Discussion: Exp. &amp; Num. Cap. &amp; Needs</i>	Dan Cox, Professor, School of Civil and Construction Engineering, Oregon State  Patrick Lynett, Professor, USC
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**Figure 1-1 Workshop program.**

2:10: PM - 3:25: PM	<b>Theme 3 STRUCTURAL ENGINEERING DESIGN APPROACHES</b>  (Moderator: Landolf Rhode-Barbarigos)	3a. Coastal Bridges: Performance and Design for Coastal Resilience  3b. Elevated infrastructure: Performance and Design for Coastal and Offshore Resilience  3c. PBD Approach to Coastal Design of Structures  <i>(15 min) Questions/Discussion: Struc. Eng. Design Approaches</i>	Jamie Padgett, Chair, Department of Civil and Environmental Engineering, Rice Univ.  Claudia Reis, Assistant Professor of Civil and Environmental Engineering, Lehigh Univ  Trung Do, Assistant Professor, Univ. South Alabama
3:25: PM - 3:45: PM	<b>BREAK</b>		
3:45: PM - 5:00: PM	<b>Theme 4 PRACTITIONER PERSPECTIVES</b>  (Moderator: Matt Gilbertson)	4a. Perspectives from Structural Engineering Practitioners: Needs & Challenges  4b. Perspectives from Coastal Engineering Practitioners: Needs & Challenges  4c. Perspectives from Architect and Planning Practitioners: Needs & Challenges  <i>(15 min) Questions/Discussion: Practitioner Perspectives</i>	Bill Coulbourne, Coulbourne Consulting  Muthu Narayanaswamy, Director, Coastal and Compound Flood Risk, The Water Institute  Elizabeth Hodges McQuade, Director, Architecture Background Office
6:00: PM - 6:30: PM -	RECEPTION (Louis A Simpson International Building - Atrium) DINNER (Louis A Simpson International Building - Atrium)		
<b>Friday, May 17, 2024 (016 Robertson Hall)</b>			
7:30: AM - 8:30: AM	<b>Continental Breakfast</b>		
8:30: AM - 8:40: AM	<b>INTRODUCTION TO DAY 2</b>	Recap of Thursday, and Setting Goals for the Day	Maria Garlock, Princeton University
8:40: AM - 9:30: AM	<b>Theme 5 EDUCATIONAL EFFORTS</b> (Moderator: David Prevatt)	5a. New Class: Structural Engineering and the Ocean Environment  5b. An Interdisciplinary course: Building Design for Climate Change Adaptation  <i>(10 min) Questions/Discussion: Educational Efforts</i>	Shengzhe (Jackson) Wang, Assistant Professor of Civil and Environ. Engineering, Univ. Colorado Denver  Gordana Herning, Visiting Assistant Professor of Design & Engineering Studies, Wesleyan University
<b>IDENTIFYING GOALS AND GAPS</b>			
9:30: AM - 9:40: AM	Explain break out sessions and get in groups <i>coffee/snacks available, grab as needed during breakout</i>		
9:40: AM - 11:25: AM	Breakout groups: Identify GOALS & GAPS in research and practice		
11:25: AM - 11:40: AM	Groups summarize discussion to be presented to full participants		
11:40: AM - 12:00: PM	<b>Boxed Lunch</b>		
12:00: PM - 12:45: PM	Reporting of breakout groups: GOALS & GAPS in research, practice, and teaching		
12:45: PM - 1:00: PM	Closing		
~1:30 PM - ~3:00 PM	Optional: Historical and Architectural Tour of Princeton		

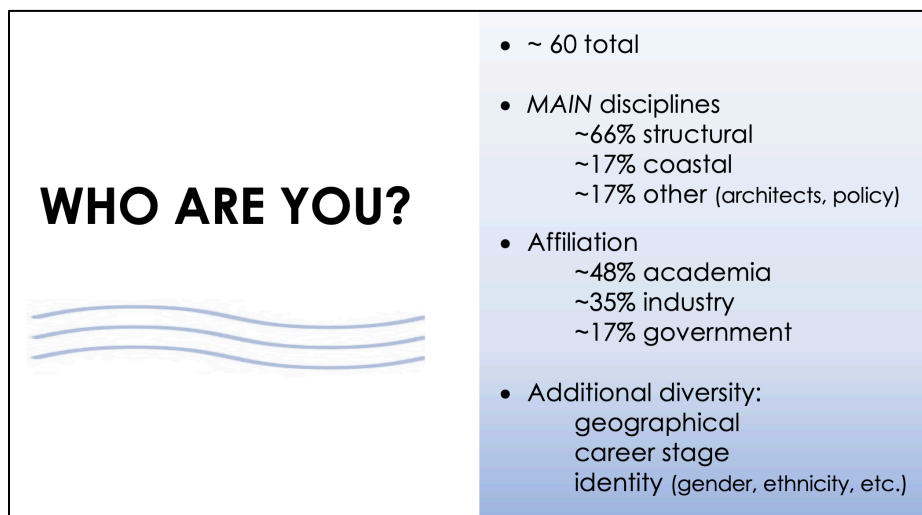
**Figure 1-1 Workshop program (continued).**

The event was organized into five sessions with the following themes:

- Theme 1: State of research and practice
- Theme 2: Experimental and numerical capabilities and needs
- Theme 3: Structural engineering design approaches
- Theme 4: Practitioner perspectives
- Theme 5: Educational efforts

Each session included several prepared presentations and a question-and-answer period facilitated by a moderator. After the conclusions of all presentations on the second day of the workshop, participants were asked to join one of three breakout discussion groups to explore a prepared set of questions. Each breakout group included a roughly equal distribution of researchers, practitioners, and government participants.

To fulfill the workshop objectives, over 60 people representing diversity in discipline, affiliation, geography, career stage, and identity participated. Figure 1-2 provides statistics about participant discipline and affiliation. The names of participants and their affiliations are included in Appendix A.



**Figure 1-2** Slide summarizing study discipline and affiliation of workshop participants.

### 1.3 Report Organization

This report summarizes the presentations, discussions, and key takeaways from the workshop.

Chapter 2 presents summary descriptions of each presentation for each of the five sessions.

Chapter 3 presents summary takeaways from breakout group discussions.

Appendix A presents the names of all workshop participants and their affiliations.

Appendix B presents a compilation of all presentations.

A list of cited references is provided at the end of the report.

### 2.1 Overview and Opening Remarks

This chapter summarizes the presentations given under each “theme” as shown in the workshop program (Figure 1-1). Images of the presentation slides are provided in Appendix B.

The workshop opened with brief remarks from Dr. Branko Glisic (Chair of the Department of Civil and Environmental Engineering at Princeton University), who welcomed the participants to Princeton and underscored the important subject to be addressed at the workshop. Mr. Jon Heintz, Executive Director of ATC, then gave an overview of ATC (inception, organization, and operation) and explained the motivation for ATC’s involvement in this workshop, which can be summarized as follows: the climate is the greatest challenge of the next generation, and ATC is prepared to bring their technical development model to the climate challenge (slides presented in Section B.1). Dr. Maria Garlock, Professor of Civil and Environmental Engineering at Princeton University (and Chair of the workshop), concluded the Opening Remarks session with an overview of the workshop (slides presented in Section B.2). Specifically, she introduced the organizing committee and discussed the composition of the audience, sponsors, and goals. The details of this overview data are given in Chapter 1.

### 2.2 Theme 1: State of Research and Practice

Five presentations launched the workshop in Theme 1 by presenting the state of research and practice. The presentation titles, presenter name and their affiliations, and location of the slides in Appendix B are shown in Table 2-1. The numbers associated with each presentation (first column) are referenced in the text that follows.

In Presentation 1a, Dr. Obeysekera presented a range of plausible consequences to the climate trends based on expert modeling. These consequences include warming (based on greenhouse gas emissions assumptions) and sea level rise (SLR). National climate assessment SLR scenarios were shown based on studies done by the National Oceanic and Atmospheric Administration (NOAA). There was discussion about nonstationarity, meaning that statistical characteristics of extreme events, such as floods and sea levels, vary with time; whereas a stationary hazard, which is typically used in building codes, the hazard is assumed to be constant over the design life. Failure to account for nonstationary risks may compromise the operational characteristics of existing and future infrastructure. Five resilience principles were recommended: (1) adopt a systems approach, (2) look at beyond-design events; (3) build and prepare infrastructure according to ‘remain functioning’; (4) increase recovery capacity by looking at social and financial capital; and (5) remain resilient into the future.

**Table 2-1 Presentations and Presenters in Theme 1: State of Research and Practice**

No.	App B.	Title	Presenter and Affiliation
1a	B.3	Overview of Climate Change, Storm Surge and SLR Models	Jayantha T. Obeysekera ('Obey') Director of the Sea Level Solutions Center, FIU
1b	B.4	Flood Hazard in the Built Environment	Andrew Kennedy Professor, Civil and Environmental Engineering and Earth Sciences, Notre Dame
1c	B.5	State of Structural Engineering Flood Practice	Seth Thomas Associate, KPFF Consulting Engineers
1d	B.6	Case Studies: Damage Classification, Fragility Quantification	Tori Tomiczek Associate Professor, United States Naval Academy
1e	B.7	NYC Climate Adaptation Plans: NY & NJ Harbor & Tributaries Focus Area Feasibility Study (HATS)	Bryce W. Wisemiller U.S. Army Corps of Engineers

Dr. Obeysekera provided the participants hyperlinks to the following list of resources to supplement his presentation:

- [Fifth National Climate Assessment Report](#) (Crimmins et al., 2023)
- [Sixth Assessment Report of the Intergovernmental Panel on Climate Change](#) (IPCC, 2023)
- [Climate Reanalyzer](#)
- [NASA Sea Level Change](#)
- [NOAA 2017 Global and Regional Sea Level Rise Scenarios for the United States](#) (NOAA, 2017)
- [NOAA 2022 Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines](#) (NOAA, 2022)
- [FIU Institute of Environment](#)

In Presentation 1b, Dr. Kennedy spoke about flood hazard in the built environment based on [ATC-149](#), *Coastal Inundation in Developed Regions: Experimental Results and Implications for Engineering Practice* (ATC, 2022). The presentation discussed research that enables better understanding of wave, current, and floodborne debris effects in and around buildings (i.e., developed regions) subject to coastal inundation events. The parameters studied were depths, velocities, and loads throughout a structural array and behind a sheltering wall. Floodborne debris paths and impact loading were also studied. All results showed strong decreases in loading with increased shelter. Debris loads have two major components: (1) debris impulse transferred to structural system, and (2) dynamic response of different components of a structural system. ASCE/SEI 7, *Minimum Design Loads and Associated*

*Criteria for Buildings and Other Structures* (ASCE, 2022), might be able to be put into this framework, but in some conditions, the standard may be unconservative. It was also found that debris loads are probabilistic, and will have x,y components even for unidirectional waves and currents.

In Presentation 1c, Mr. Thomas discussed the state of structural engineering flood practice. ASCE/SEI 7 Chapter 5 (Flood Loads) has remained essentially unchanged from 2005 to 2022 and has been lacking in providing requirements within the provisions (e.g., impact loads, sliding, buoyancy checks). In addition, the code has outdated wave loading equations. Updated codes and standards are (almost) available, specifically: [ASCE/SEI 7-22 Supplement #2](#) was published in May 2023, updated parallel requirements are nearing publication in the 2024 version of ASCE/SEI 24, *Flood Resistant Design and Construction* (ASCE, 2024), and an updated charging language is targeted for the 2027 version of the *International Building Code*. These new codes reflect significant changes to flood design methodology. The changes to ASCE/SEI 7 were discussed in detail and information is shown in the slides of Appendix B.

In Presentation 1d, Dr. Tomiczek discussed lessons learned from mostly residential infrastructure case studies such as: understanding hazard conditions and performance, developing structural fragility, standardizing damage assessment, and leveraging technology to capture ephemeral data. Previous studies showed that structures sheltered by dunes (and other structures) and/or emergent vegetation experienced less damage than unsheltered structures during storm events such as Hurricane Sandy and Hurricane Irma. Standardization of damage assessment methods is important if comparing across neighborhoods, geographies, and events; and emerging technology can increase geographical reach and impact of case studies. Coupling building fragility models with other models (e.g., transportation, evacuation) to inform communities about vulnerable locations was also presented as a need. Opportunities for ongoing and future case studies include longitudinal studies of damage and recovery, dataset expansion, cross-event and cross-geography comparisons of performance, virtual damage assessment, and coordination, collaboration, and data reuse. Additional work is necessary to address knowledge gaps and improve fragility estimation and community resilience in the face of climate change and coastal hazards.

In Presentation 1e, Mr. Wisemiller discussed New York City climate adaptation plans, referred to as "[HATS](#)": New York & New Jersey Harbor & Tributaries Focus Area Feasibility Study (USACE, 2024). Alternative plans, and the pros and cons of each, were mentioned, where the alternatives are summarized as:

- Alternative 1: No action
- Alternative 2: Harbor-wide storm surge barrier + shore-based measures
- Alternative 3A/B: Multi-basin storm surge barriers + shore-based measures
- Alternative 4: Single-basin storm surge barriers + shore-based measures
- Alternative 5: Shore-based measures only

Comparisons between alternatives included metrics such as percentage of area at reduced risk, years to fully construct, first cost, average annual cost, average annual benefits, net

benefits, and benefit to cost ratio. Alternative 3B is the tentatively selected plan. The features of this plan were discussed in detail and are shown in the slides of Appendix B. Public engagement and public comments were presented.

### 2.3 Theme 2: Experimental and Numerical Capabilities and Needs

The next session presented means for collecting experimental and numerical data and the state-of-the-art and needs in experimental and numerical approaches. The presentation titles, presenter name and their affiliations, and location of the slides in Appendix B are shown in Table 2-2. The numbers associated with each presentation (first column) are referenced in the text that follows.

**Table 2-2 Presentations and Presenters in Theme 2: Experimental and Numerical Capabilities and Needs**

No.	App B.	Title	Presenter and Affiliation
2a	B.8	Experimental Facilities for Coastal Flood Resilience: State-of-Art and Needs	Dan Cox Professor, School of Civil and Construction Engineering, Oregon State
2b	B.9	Numerical Tools: Types, Pros/Cons, Needs	Patrick Lynett Professor, USC

Presentation 2a started with an accelerated time video of a tropical storm washing away a wood-framed home. Dr. Cox asked the question: How can we study this event experimentally, and additionally at what time scale (where a wave impulse lasts ~0.01 seconds, a single wave can have up to a 10 second period, and the storm cycle ~100,000 seconds)? Further, the length scale can be at the structural elements level (1:1), isolated building level (1:6), or the community level (1:50). Results of how well the experiments captured the scenario and structure response are shown in Table 2-3.

In addition, Dr. Cox presented thoughts on needs for physical modeling for coastal community resilience and climate change, where four items were mentioned: (1) an experimental facility capable of combined waves and currents to model overland flow through urban coastal communities; (2) an experimental facility capable of combined wave- and current-induced erosion and scour in the presence of structures; (3) partnerships with unique coastal laboratories globally such as the U.S. Army Engineer Research and Development Center (ERDC) and Field Research Facility (FRF), the Large Wave Flume (Großer Wellenkanal, GWK) in Germany, and Port and Airport Research Institute (PARI) and Defense Policy Review Initiative (DPRI) in Japan; and (4) funding mechanisms to enable multi-institutional research campaigns since complex bathymetry is prohibitively expensive for single-investigator proposals.

**Table 2-3 Grade of Ability to Capture the Scenario and Response for Each Experimental Scale (Level) per D. Cox**

Scenario/ Response	Community level	Building level	Structure level
Flood hazards	A	A	A
Shielding	A	B+	C
Sediment erosion	C+	B+	C
Sediment scour	C	B+	A
Pressure/force	B	A	A
Structure response	C-	B	A
Destructive testing	D	B-	C
Debris transport	A	B	C

In Presentation 2b, Dr. Lynett presented an overview of coastal modeling (e.g., theories, approximations, numerical approaches). For example, wave equation models (e.g., nonlinear shallow water, Boussinesq) are best for: coastal process characterization for civil works projects, “filling in the gaps” for experimental (lab & field) studies, providing boundary conditions for refined three-dimensional (3D) simulation and experimental studies, fast and reasonable characterization for experimental design, computational expense, and practicality of usage. On the other hand, fluid dynamics models (e.g., Euler/potential flow) are best for: understanding the 3D properties of complex flows, including multi-phase and multi-material, high-fidelity transport, when coupled with proper turbulence models, users with large computational resources, and discovery, if done with great care. Recent advancements in numerical modeling include machine-learning, where the primary goal is to provide a solution more quickly. This area is currently exploding, but it is still difficult to apply for complex physics. Physics-informed neural networks can minimize error with governing equations during training.

Dr. Lynett also discussed some challenges in numerical modeling , which include: capturing uncertainty in detailed (i.e., 3D) flow structure modeling and modeling well-established trial-to-trial variance in wave impact loads (in well controlled experiments), hydro-morpho-ecosystems modeling, transport during extreme events in the built environment (such as fundamental issues with numerical modeling of kinematics at the scales relevant for transport, and cyclone and tsunami events, floating debris in mixed wave-current-wind, material properties of the debris), groundwater-ocean mixing (saline intrusion on various time scale), and configurations with multiple materials and/or multiple phases.

## 2.4 Theme 3: Structural Engineering Design Approaches

The third theme attempted to answer questions such as: Are there innovative structural solutions that better serve the community, landscape, and environment? How can we build a performance-based-design framework for coastal structures? The presentation titles, presenter name and their affiliations, and location of the slides in Appendix B are shown in Table 2-4. The numbers associated with each presentation (first column) are referenced in the text that follows.

**Table 2-4 Presentations and Presenters in Theme 3: Structural Engineering Design Approaches**

No.	App B.	Title	Presenter and Affiliation
3a	B.10	Coastal Bridges: Performance and Design for Coastal Resilience	Jamie Padgett Chair, Department of Civil and Environmental Engineering, Rice Univ.
3b	B.11	Elevated infrastructure: Performance and Design for Coastal and Offshore Resilience	Claudia Reis Assistant Professor of Civil and Environmental Engineering, Lehigh Univ
3c	B.12	Performance Based Design (PBD) Approach to Coastal Design of Structures	Trung Do Assistant Professor, Univ. South Alabama

In Presentation 3a, Dr. Padgett made the case that coastal bridges are an important infrastructure, yet they are often cited as some of the most vulnerable components of a network in extreme events. Past studies have pointed to the negative impact of climate change on coastal transportation infrastructure. Images of typical coastal bridge failure modes during tropical cyclones were shown, where failures were due to impact, scour, wind-water, surge and wave induced damage. These experiences led to anecdotal evidence, best practices, and numerical and experimental campaigns.

Quantifying resilience requires one to evaluate the potential for damage, restoration and recovery. One tool is fragility analysis, which can be empirical, analytical, or simulation based. Features emerging and requiring attention for resilience analysis include: multiple failure modes, correlated failures and spatial variability, coupled aging and deterioration, and alternative design details and retrofits. Bridge resilience has a direct impact on transportation network resilience and other community impacts; therefore, one must consider enhanced bridge design through a broader sustainability lens (including hazard resilience). Some practical considerations when pursuing resilient bridges (and systems that depend upon them) include design selection for heightened performance (e.g., new materials and systems), innovative adaptive structures, design decisions on sacrificial bridges or bridge elements, retrofit decisions on high priority bridges, post-event resource allocation, post-event budget requests, recovery/repair incentives, and pre-event staging of materials and contracts.

Dr. Padgett provided the following additional information to supplement her presentation:

- [\*Guide Specifications for Bridges Vulnerable to Coastal Storms\*](#) (AASHTO, 2008)
- [\*Selected Bibliography of Hydraulic and Hydrologic Subjects\*](#) (FHWA, 2024)
- [\*Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2–Task 2: Climate Variability and Change in Mobile, Alabama\*](#) (USDOT, 2013)

In Presentation 3b, Dr. Reis started by presenting environmental challenges as related to the performance and design for coastal and offshore resilience such as frequent and extreme loads. Often neglected considerations include: time-dependent variations (e.g., sea level rising and topo-bathymetric conditions), fluid(s)-solid(s) interactions (e.g., hydrodynamic loading, supra-structure, infra-structure, soil), and compatibilities between the performance criteria of cyber and physical components. Critical infrastructure challenges include: (1) the need for better understanding of coupled aero-hydro-geotechnical-structural interactions, and (2) acknowledging the major source of uncertainty in the natural conditions in short and long time periods.

The performance criteria for the design of these structures should include elements of risk management such as consideration of hazard, vulnerability, exposure, and mitigation. It should be noted that the expected infrastructure behavior is different for different infrastructure. Important considerations are: to (1) bridge the gap among recommendations from different design codes and standards for regular structures, and (2) target hazard assessment to define loading patterns for critical infrastructure. Two European test cases were presented to illustrate the meaning of what is discussed above. One of the test cases was regarding the expansion of a container terminal in one of the busiest European ports, while the other was regarding the design consideration for a mega-data center. In both cases, and considering the critical nature of the infrastructure, the contractual agreement was to characterize design loading patterns due to cascading earthquake and tsunami multi-hazards and to provide design recommendations. The approach to meet the objectives included tasks related with deterministic multi-hazard characterization and structural performance criteria for critical infrastructure.

In Presentation 3c, Dr. Do presented a methodology (flowchart) for a means to develop fragility curves for buildings subject to waves and surge. The methodology includes using Ansys FLUENT and Monte Carlo simulations with 10,000 samples. A fragility surface, measuring probability of failure, is generated based on significant wave height and surge level. Buildings on grade have a significantly higher probability of failure compared to buildings elevated 3 meters. Numerical wind-wave tunnels can be used for a broader view: the vulnerability of the structural components is calculated from the surge-wave and wind fragilities, and the vulnerability of the interior contents is calculated from the flood fragility.

## **2.5 Theme 4: Practitioner Perspectives**

In the fourth session, a structural engineer, a coastal engineer, and an architect/planner shared their experiences and discussed where they see needs, challenges, and further research. The presentation titles, presenter name and their affiliations, and location of the

slides in Appendix B are shown in Table 2-5. The numbers associated with each presentation (first column) are referenced in the text that follows.

**Table 2-5 Presentations and Presenters in Theme 4: Practitioner Perspectives**

No.	App B.	Title	Presenter and Affiliation
4a	B.13	Perspectives from Structural Engineering Practitioners: Needs & Challenges	Bill Coulbourne Coulbourne Consulting
4b	B.14	Perspectives from Coastal Engineering Practitioners: Needs & Challenges	Muthu Narayanaswamy Director, Coastal and Compound Flood Risk, The Water Institute
4c	B.15	Perspectives from Architect and Planning Practitioners: Needs & Challenges	Elizabeth Hodges McQuade Director, Architecture Background Office

In Presentation 4a, the practicing structural engineer’s perspective was given by Mr. Coulbourne. He began with showing home damages from Hurricanes Michael and Ian in Florida and noting that despite Florida having the strongest building codes in the nation for protection from high winds and storm surge, irreparable damage still occurs. He then pointed to the publication [Measurement Science R&D Roadmap for Windstorm and Coastal Inundation Impact Reduction](#) (NIST, 2013), which includes four topic areas that relate to coastal inundation: Coastal Inundation Hazards, Coastal Inundation Loads, Resistance to Coastal Inundation, and Performance-based Design for Coastal Inundation. Each of the topics has specific research ‘projects’ identified that are deemed important to the coastal hazards community. Mr. Coulbourne also discussed the opportunities via the NSF-funded program [National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Surge, and Wave Events](#) (NICHE). This program is developing testing protocols and methods for a full-scale facility that can generate 200 mph wind in a water basin to simulate storm surge and wave action. He also presented an innovation called [High Tide Homes](#), where the home foundations can lift when there is danger of flooding.

Finally, Mr. Coulbourne ended his presentation with a list of 10 needs and challenges:

- Find better ways to estimate wave metrics: wave height, period, and velocity that are useable for all practitioners during design phase, not just modelers or researchers.
- Develop ways for practitioners to estimate structural reliability in order to practice performance-based design for coastal structures; this is in order to connect reliability to performance.
- Consider ways to require all coastal structures to be designed using performance methods instead of prescriptive metrics; this will require performance-based design processes to be developed.
- Develop methods to estimate building water leakage during coastal flooding.
- Improve building attachment methods to foundations.
- Improve foundation performance during and after coastal erosion occurs.

- Develop solutions to coastal storm problems that are not static; i.e., create ways for buildings to adapt to changing environmental conditions including increased water levels or wave heights.
- Develop design solutions with materials that can resist the environmental harshness of coastlines.
- Develop design methods that can either resist flood debris or perform with structural redundancy to prevent collapse.
- Design such that there is less reliance on beach re-nourishment projects to keep buildings from collapsing.

Dr. Narayanaswamy started Presentation 4b with a list of challenges for practicing coastal engineers:

- Guidelines and manuals have inconsistent metocean design criteria and definitions for current conditions (e.g., DOT design Manuals, FHWA Design Manuals, AASHTO studies, USACE CEM).
- Numerous varying estimates of sea level rise and guidance on incorporation of sea level rise, which makes for difficult choices for practicing engineers and difficult conversations with clients.
- No guidance currently exists for meaningful assessment and incorporation of compounding impacts of surge and pluvial/fluvial events.
- Challenging to quantify future precipitation and antecedent conditions.

A related list of needs was then given:

- Embrace and communicate uncertainty in design guidance with: (1) an intentional move away from event-based, prescriptive design criteria, and (2) best practices on adaptive design.
- Unified guidance on sea level rise, including process to develop annual exceedance probability (AEP) curves for desired time horizons including uncertainty bounds.
- Guidance on incorporation of compounding flood hazards due to pluvial, fluvial, and coastal flooding into design.
- Guidance on approaches to develop future antecedent conditions and future precipitation estimates for generating compound flood hazard data.
- Guidance on future rainfall and winds for hydrodynamic and wave modeling within inland water bodies
- Facilitation of tight coupling between research findings and design guidance.
- Consistent guidance across federal and state levels for coastal design criteria (i.e., single X-year response for example) would increase efficiencies and reduce design costs.

Dr. Narayanaswamy mentioned that Texas likely has the best state department of transportation guidance on incorporation of coastal wave and hydrodynamics data for current and future conditions. The document he referred to is the [Hydraulic Design Manual](#) (TxDOT, 2019).

The presentation then turned to compound flooding, which has no existing design guidance. Assessment of compounding impacts is critical for scour and structural design—using surge-only or riverine-only criteria is inefficient and risk prone. Transportation design in Florida has inadequate guidance on future sea level rise for resilient design—future rainfall distributions are important but guidance is unavailable. The lack of consistent information can lead to widely varying design and planning guidance at a single location.

In Presentation 4c, Ms. McQuade focused on studies in New York City (NYC). She presented many books and reports published since 2002 envisioning the NYC waterfronts given rising waters. She then discussed post-disaster experience based on Hurricane Sandy where NYC was awarded \$15 billion for Hurricane Sandy recovery projects from FEMA, U.S. Department of Housing and Urban Development, and other government agencies. The limiting factors for post-disaster rebuilding were benefit-cost analysis (BCA) constraints, uncertain design criteria, and long timeframes. Concerning mitigation, federal grants are an opportunity, and an extensive study that was recently done provides alternatives: USACE NY/NJ harbor and tributaries study (see Presentation 1e). Mitigation constraints are conditional funds, unclear timelines, the need for BCA scores greater than 1, local cost share, feasible construction, environmental review, and complexity due to dense waterfront.

## 2.6 Theme 5: Educational Efforts

The fifth theme presents efforts to educate students (in higher education) on the theme of the workshop. The first presentation discusses a course taught to structural engineering students and is a more technical and focused course than the second presentation, which is interdisciplinary and less technical. Thus, a diverse perspective on education was presented. The presentation titles, presenter name and their affiliations, and location of the slides in Appendix B are shown in Table 2-6. The numbers associated with each presentation (first column) are referenced in the text that follows.

**Table 2-6 Presentations and Presenters in Theme 5: Educational Efforts**

No.	App B.	Title	Presenter and Affiliation
5a	B.15	New Class: Structural Engineering and the Ocean Environment	Shengzhe (Jackson) Wang Assistant Professor of Civil and Environ. Engineering, Univ. of Colorado, Denver
5b	B.16	An Interdisciplinary Course: Building Design for Climate Change Adaptation	Gordana Herning Visiting Assistant Professor of Design & Engineering Studies, Wesleyan University

In Presentation 5a, Dr. Wang emphasized that the structural engineering profession must play an active role in shaping the built environment for climate adaptation with social and environmental considerations in mind. Thus, more innovative approaches to structural engineering education must be sought to equip graduates with a more holistic “toolbox” for design (from a technical or policy perspective). He pointed to ASCE’s Committee for the Reform of Structural Engineering Education (CROSEE) report to the SEI Board of Governors (April 2022) with a recommendation to “Develop a repository of curricular materials that

support structural engineering relevant topics and skills to address climate change.” Further, the goal is “By 2040 climate change understanding, mitigation and adaptation will be a central part of structural engineering curriculum.”

At the University of Colorado, Denver, Dr. Wang teaches a course called “Structural Engineering and the Ocean Environment,” which serves as an introduction for students in structural engineering and has three main categories:

- Wave mechanics (6 topics, including wave theory, wave energetics, and irregular waves)
- Fixed structures (5 topics, including wave forces on walls and piles, and tsunami forces)
- Floating structures (4 topics, including stability and rigid body dynamics)

Dr. Wang has developed notes for this class that are [publicly available](#) (Wang, 2024). The course is open to senior undergraduate and graduate students and taught every fall. A basic understanding of structural mechanics and partial differential equations is required, but no prior knowledge of fluid/wave mechanics or physical oceanography is needed. More information on evaluation, mid-term project, course delivery, and course evaluations is given in the slides in Appendix B.

In Presentation 5b, Dr. Herning stated that climate action and sustainability have long been a concern for the Olin College community, leading to campus infrastructure changes and development of related academic programs. Olin’s “College as a Living Lab” framework positions Olin as an experimental testbed for reinvention and sustainability, and for transformation within and outside of Olin. Within this framework, Olin is working to provide an impact-centered education that connects theoretical principles with real-world experiences in order to graduate engineers who are systems thinkers, solve problems by understanding people’s needs, and are inclined to serve society and the planet.

Within this context, Dr. Herning co-taught “Building Design for Climate Change Adaptation” with Claire Rodgers, adjunct instructor as well as associate director for sustainability and campus engineering. A summary of the course is given in a [news article](#) posted on the Olin College of Engineering website (Olin College, 2024). This course: (1) introduces interdisciplinary perspectives of challenges and opportunities in developing energy-efficient and resilient infrastructure; (2) explores designs for improving the environmental performance of buildings and infrastructure in the context of climate resilience and adaptation; and (3) presents concepts related to regional energy grid operation, renewable energy generation, and efficient use of water, energy, and materials that serve to develop design and operation strategies for implementing Olin College’s Climate Action Plan. The course considers building materials and building codes (through design exercises), introduces fundamental engineering concepts (e.g., stress, load paths, geometry), and discusses real-world projects such as multifunctional roofs. Student evaluations and example projects are given in the slides in Appendix B.

## Chapter 3

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# Discussion Summary and Conclusions

When the presentations of the five themes concluded, the participants separated into three groups to discuss the vision, needs, and implementation methods for structural design for coastal flood resilience. The participants were organized into groups in advance so that there was roughly equal distribution of researchers, practitioners (coastal/structural), and government representatives. During breakout sessions, a moderator prompted questions that were prepared in advance by the organizing committee; thus, each group had the same prompts for discussion. A notetaker recorded the discussion following each question.

This chapter summarizes discussions by the three breakout groups with an emphasis on the common themes that emerged across the groups. Brief concluding remarks are also provided.

All of the questions discussed in the breakout groups were related to the future direction of structural design for coastal flood resilience. To avoid repetition, the term “coastal flood resilience” is frequently omitted from the descriptions below.

### 3.1 Breakout Topic: Vision

#### **Question 1: What are the near-term and long-term objectives for research and practice? What should we aim to achieve?**

##### **Common Themes**

- Buy-in from stakeholders (e.g., designers, planners, general population) to develop flood-resilient communities.
- Guidance for treatment of future hazard conditions (e.g., sea level rise, incorporation of uncertainty) that account for nonstationarity and that are consistent across hazards.
- Development of codes, standards, and guidelines that enable the design and construction of flood-resilient communities.

##### **Other Themes**

- Performance-based design guidelines.
- Consistent hazard definitions.
- Collaboration across engineering disciplines to ensure that all lifeline infrastructure is contributing to resilience.
- Recognition in development of public policies about how decisions affect future risks.

## **Question 2: What are key challenges to achieving these objectives?**

### **Common Themes**

- Lack of engagement between engineers and other stakeholders, such as homeowners and lenders, to better understand their tolerance for risk and to raise awareness among the public about the risks associated with current design codes and standards.
- Performance-based design for flood is not defined well enough for implementation.

### **Other Themes**

- Lack of efficient approach to quantify in probabilistic terms the impacts of compounding events.
- Lack of guidance on how to characterize time-dependent variables (e.g., climate change, population) that affect hazard and risk assessment.
- National Flood Insurance Program requirements that do not reflect the effects of climate change.
- Community resilience is not addressed by design codes or standards.
- Lack of guidance for how to retrofit existing buildings.
- Effective flood design is viewed as too costly by building owners.
- Homeowners are unaware of the risks associated with current design codes and standards.

## **3.2 Breakout Topic: Needs**

### **Question 3: What are the key research and practice needs to address the noted challenges?**

#### **Common Research Themes**

- Improved characterization of overland flow using numerical modeling and physical testing.
- Improved understanding of debris sources.
- Development of a new methodology that accounts for nonstationary hazards in structural reliability calculations.
- Improved probabilistic modeling techniques, including compounding effects (e.g., surge, tides, waves) and cascading events, to predict impacts of future events.
- Benchmarking of models with field data and experimental studies.
- Benchmarking of fragility curves to define damage level based on hazard, i.e., flood depth based on historical observations.
- Improved quantification of uncertainty.

## **Common Design and Implementation Themes**

- Establishment of performance objectives and design criteria to achieve those performance objectives (see Engagement with Stakeholders).
- Development of performance-based design guidelines.
- Development of retrofit guidelines.
- Nonstationary hazard data and structural reliability targets for ASCE/SEI 7.
- Improved tools for quantifying costs and benefits of different performance objectives, including quantification of embodied carbon.

## **Common Communication and Education Themes**

- Dialogue with stakeholders to understand their expectations and preferences for performance objectives.
- Development and sharing of stories from case studies that illuminate success, failures, and costs and benefits of different decisions and actions.
- Education of communities about risk, including through early education.
- Interdisciplinary training for engineers, in particular more emphasis on social science perspectives.

### **Question 4: Among the needs identified, which should be prioritized?**

- Development of a new methodology for nonstationarity and reliability calculations.
- Improved probabilistic modeling techniques, including compounding effects (e.g., surge, tides, waves) and cascading events, to predict impacts of future events.
- Benchmarking of models with field data and experimental studies.
- Improved quantification of uncertainty.
- Establishment of performance objectives and design criteria to achieve those performance objectives.
- Development and sharing of stories from case studies that illuminate success, failures, and costs and benefits of different decisions and actions.
- Education of communities about risk, including through early education.

### **3.3 Breakout Topic: Implementation**

#### **Question 5: What are the key tasks necessary to address one or more of the prioritized needs?**

Due to time constraints, breakout groups did not have enough time to thoroughly respond to this question. The following are initial thoughts recorded by one breakout group for one prioritized need.

#### **Prioritized Need: Development and Sharing of Stories from Case Studies**

- Identify appropriate archetype communities for post-event assessment.
- Identify and document actions of early adopters of flood-resilient approaches.

- Leverage remote-sensing tools in the collection of pre- and post-event data.

### **3.4 Conclusions**

The breakout groups identified several needs to achieve the vision and goal of coastal resilience as related to structural design. The advancement of codes, standards, and performance-based guidelines considering future conditions can enable the design and construction of flood-resilient communities. However, there are many knowledge gaps that are preventing this advancement, such as a need for improved understanding of overland flow and debris sources and development of methodologies and models that better account for nonstationary hazards and uncertainty in structural reliability calculations.

Current efforts for advancing codes and standards are limited in their application to new design, and hazard mitigation for existing structures should also be considered as existing structures located in highest flood hazard zones comprise our Nation's largest exposure to flood hazards. Further, implementation and enforcement of updated building codes and standards are very important to improving coastal resilience; accordingly, it is important to encourage stronger communication between engineers and stakeholders about current risks and expected structural performance. This communication can be strengthened by demonstrations of cost effectiveness associated with technical advancements. Further, this collaboration can lead to realistic expectations following future flood events and could help grow broader support for improvements in structural design for flood resilience.

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# Presentation Slides

This appendix includes presentation slides shared at the Workshop in the following order:

- Opening Remarks
  - B.1: Jon A. Heintz, Applied Technology Council
  - B.2: Maria Garlock, Princeton University
- Theme 1, State of Research/Practice
  - B.3: Jayantha Obeysekera, Florida International University
  - B.4: Andrew Kennedy, University of Notre Dame
  - B.5: Seth Thomas, KPFF Portland Structural
  - B.6: Victoria (Tori) Tomiczek, United States Naval Academy
  - B.7: Bryce W. Wisemiller, U.S. Army Corps of Engineers
- Theme 2, Experimental and Numerical Capabilities/Needs
  - B.8: Dan Cox, Oregon State
  - B.9: Patrick Lynett, University of Southern California
- Theme 3, Structural Engineering Design Approaches
  - B.10: Jamie Padgett, Rice University
  - B.11: Claudia Reis, Lehigh University
  - B.12: Trung Do, University of South Alabama
- Theme 4, Practitioner Perspectives
  - B.13: Bill Coulbourne, Coulbourne Consulting
  - B.14: Muthu Narayanaswamy, The Water Institute
  - B.15: Elizabeth Hodges McQuade, Architecture Background Office
- Theme 5, Educational Efforts
  - B.16: Shengzhe (Jackson) Wang, University of Colorado Denver
  - B.17: Gordana Herning, Wesleyan University

## B.1 Heintz




**Applied Technology Council**  
*Who We Are and Why We're Here*

**Jon A. Heintz**  
*Executive Director*

NSF-ATC Climate Workshop  
May 16-17, 2024

### Outline

- Who We Are
  - Inception, organization, and operation
- Why We're Here
  - A new strategic plan and the idea that we can help



2

## Inception

- 1971 San Fernando earthquake
- SEAOC formed a three-person ad-hoc committee
  - New organization to speed up transfer of research to practice
  - Different from current code-development efforts
  - Supported through procurement of federal funding
  - Compensated (rather than volunteer) committee members



Rol Sharpe    John Wiggins    Steve Johnston



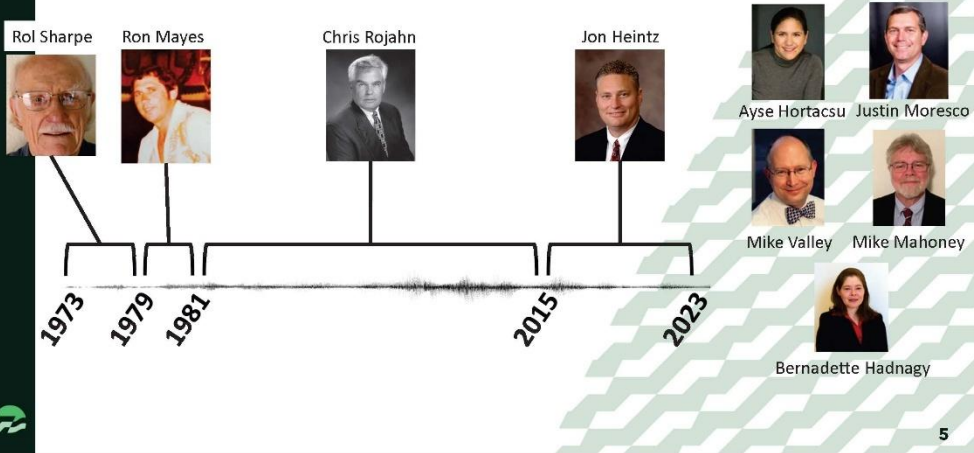
3

## Project Delivery Model

- Small In-house Technical Staff
  - Direct projects, prepare products and reports
- Large Pool of Technical Consultants
  - Structural engineers from diverse firms, researchers from diverse institutions
  - Conduct project work
- Products
  - Non-proprietary, objective, and reflect a broad spectrum of engineering opinion
  - Immediately accepted by the profession, and hold lasting value

4

## Leadership and Operation

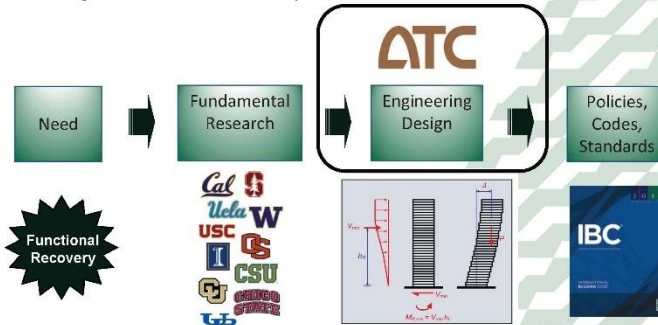


## ATC Board of Directors (2024-2025)



## Role in Technology Development

- We view ourselves as being in service to the profession, and place a high value on making the world a safer place



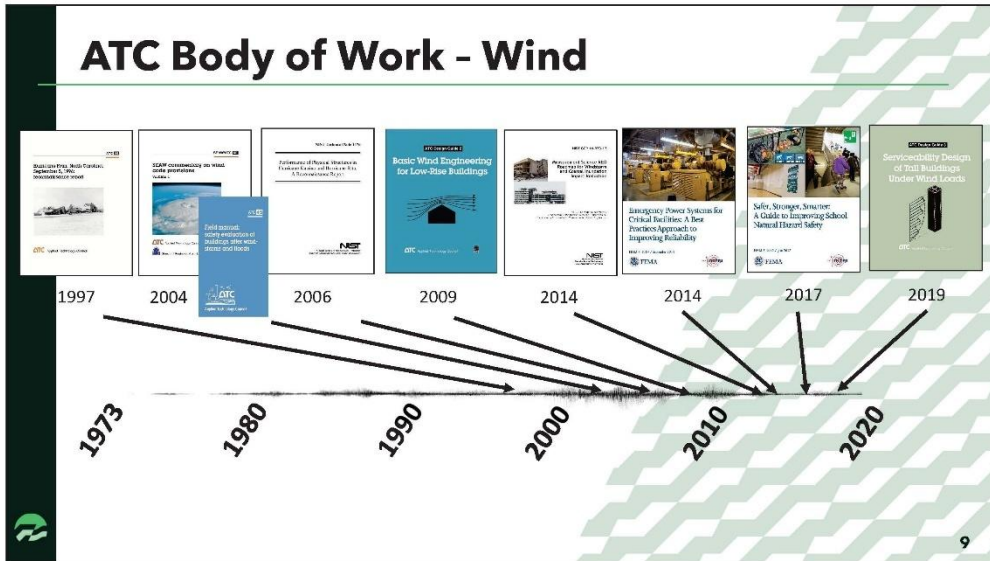
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## ATC Body of Work - Seismic Legacy Reports

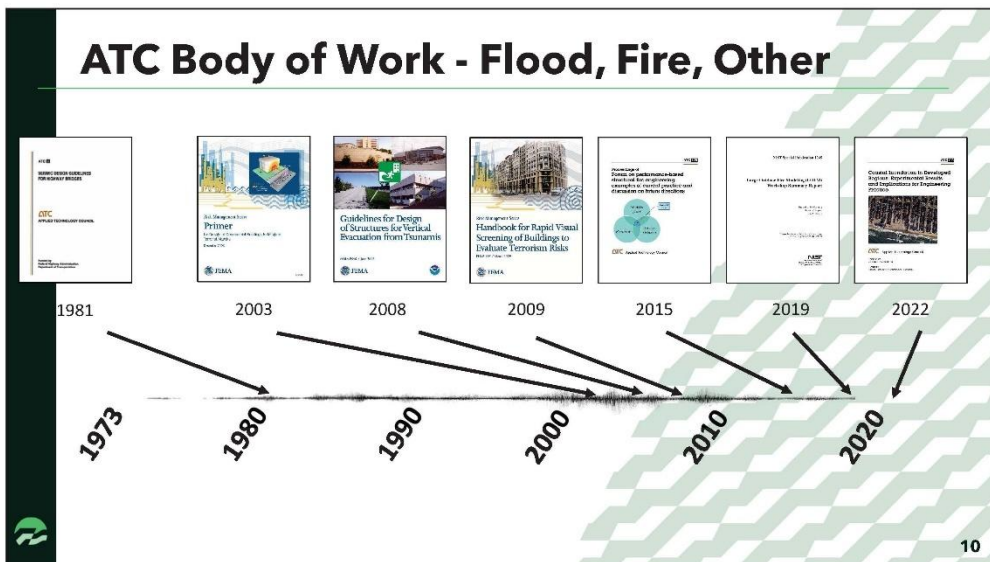


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## ATC Body of Work - Wind



## ATC Body of Work - Flood, Fire, Other



## Why We're Here

### New Strategic Area - Climate

- Greatest challenge of the next generation
- Climate Action Plan - organizes ATC's thoughts and actions on mitigation and adaptation
  - Climate Needs Workshop
- Looking to bring ATC's technical development model to the climate change problem



## Concluding Thoughts

- Formed by engineers for engineers
- Born in California with an earthquake focus, but are now national/international working in all hazard areas
- Our 50 years of history has included transformational concepts and practical guidance
- Looking to take on the next generation's engineering challenges and begin work on climate adaptation and mitigation concepts



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Section 3

# Thank you!

## B.2 Garlock

**Climate Adaptation Workshop: Structural Design for Coastal  
Flood Resilience**





May 16-17, 2024  
Princeton University

# OVERVIEW OF WORKSHOP

**Maria E. Moreyra Garlock**  
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1

## ORGANIZING COMMITTEE



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(Martin, Chock, & Carden)
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(ATC, Director of Projects)
- Justin Moresco  
(ATC, Director of Projects)
- David Prevatt  
(University of Florida)
- Seth Thomas  
(KPF Consulting Engineers)

2

# WHO ARE YOU?



- ~ 60 total
- *MAIN* disciplines
  - ~66% structural
  - ~17% coastal
  - ~17% other (architects, policy)
- Affiliation
  - ~48% academia
  - ~35% industry
  - ~17% government
- Additional diversity:
  - geographical
  - career stage
  - identity (gender, ethnicity, etc.)

3

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## NSF BRITE Pivot

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This Boosting Research Ideas for Transformative and Equitable Advances in Engineering (BRITE) **Pivot** project will *lead to scientific discoveries in water-structure interaction, that will enable innovative approaches to coastal resilience.*

### **Pivot Track**

is intended to enable researchers to ... leverag[e] their experience when pursuing a pivot into a field of research where they have no proven track record...

5

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## NSF BRITE Pivot

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### **BRITE Pivot: Advancing Knowledge in Water - Shell Structure Interaction Through Discovery of Efficient Hydrodynamic and Structural Thin-shell Forms**

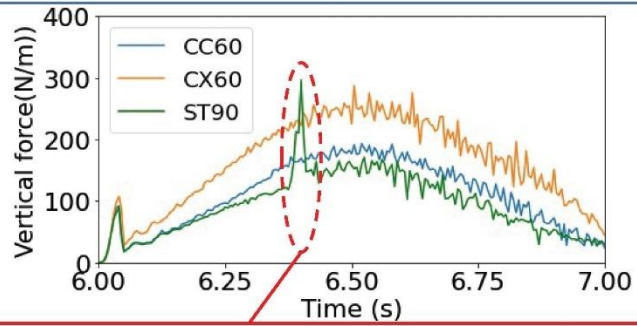
The research objective is to enable *aquatectural engineering* and *adaptable aquatecture* design goals through the advancement of fundamental knowledge in water - shell structure interaction

Specifically, the research will discover efficient hydrodynamic thin-shell structural forms that have broad application to coastal resilience (e.g. seawalls/floodbarriers, breakwaters, coastal bridges, and coastal building facades).

6

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## NSF BRITE Pivot



SPH Numerical Simulation



## NSF BRITE Pivot

- ✓ Experiments:
  - 1:10 scale @SBU (June '24)
  - 1:5 scale @OSU (Apr '25)
- ✓ More parameters:
  - wave characteristics
  - 3D forms/patterns

SBU  
(25 m)

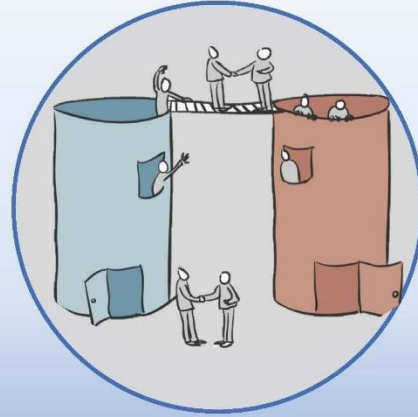


OSU  
(104 m)



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# BARRIERS & BRIDGES



icon; [https://www.cleanpng.com/png-silo-collaboration-organization-clip-art-business-7179125/#google\\_vignette](https://www.cleanpng.com/png-silo-collaboration-organization-clip-art-business-7179125/#google_vignette)

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## BARRIERS & BRIDGES

Potential **BARRIERS** to Coastal Flood Resilience?



How to **BRIDGE** over barrier?



Prescriptive Methods



Performance-based Design (PBD)



Siloed Disciplines



Integrated Disciplines  
(in education & practice)



Narrow Focus on Traditional Approaches

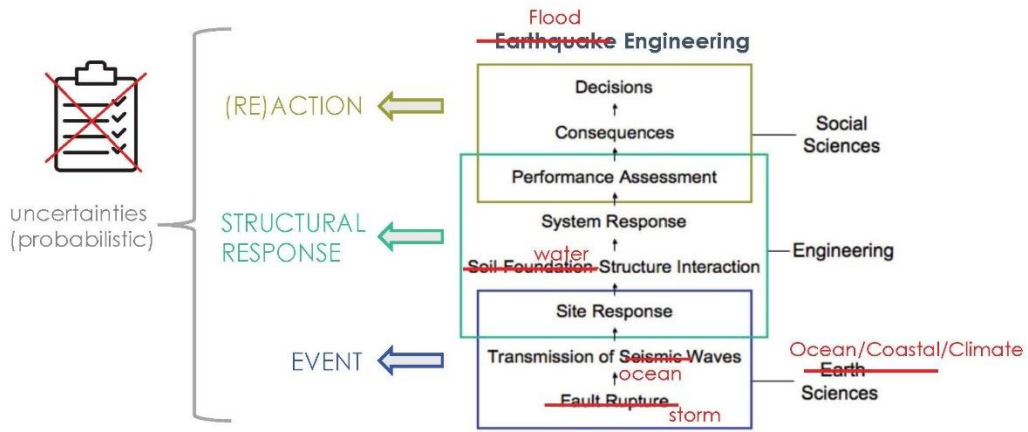


ADD an "Audacious" Vision  
(without restriction to prior ideas)

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# BARRIERS & BRIDGES // PRESCRIPTIVE → PBD

Overall PBD Framework

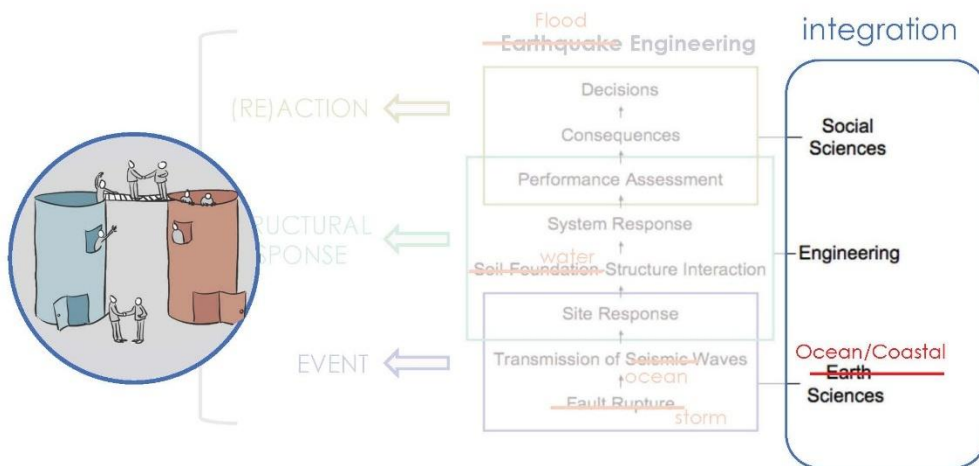


<https://peer.berkeley.edu/research/pbee-methodology>

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# BARRIERS & BRIDGES // SILOED → INTEGRATED

Integration

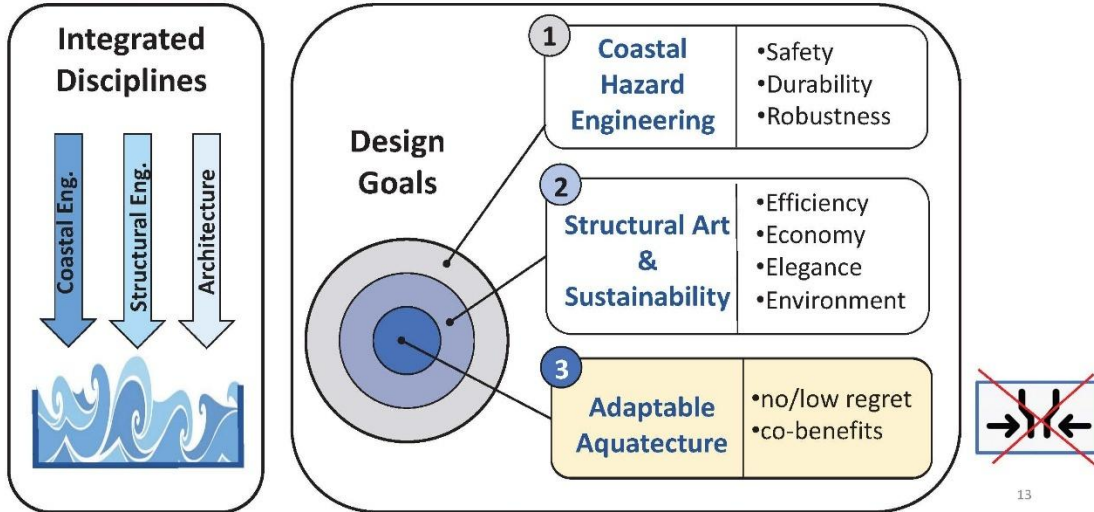


<https://peer.berkeley.edu/research/pbee-methodology>

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# BARRIERS & BRIDGES // SILOED → INTEGRATED

“Aquatectural Engineering”



## BARRIERS & BRIDGES // TRADITIONAL → AUDACIOUS

Monmouth Beach, NJ



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## BARRIERS & BRIDGES // TRADITIONAL → AUDACIOUS

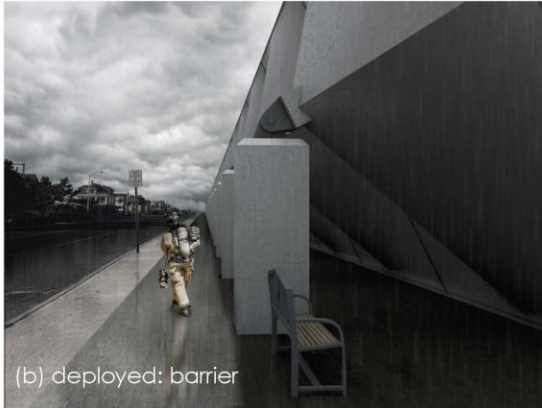
Monmouth Beach, NJ



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## BARRIERS & BRIDGES // TRADITIONAL → AUDACIOUS

Adaptable Aquatecture

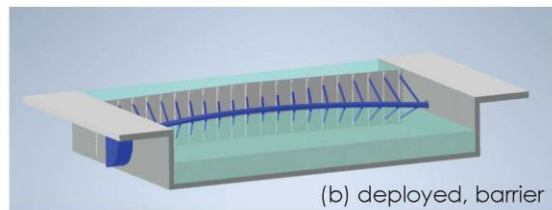
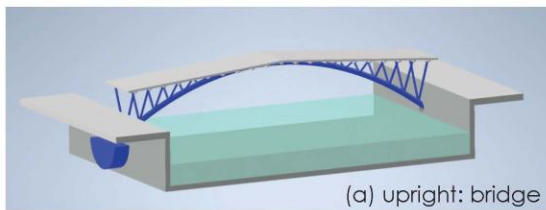


17

## BARRIERS & BRIDGES // TRADITIONAL → AUDACIOUS

Adaptable Aquatecture

Ajigawa  
Suimon Gates  
(JAPAN)



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## BARRIERS & BRIDGES // TRADITIONAL → AUDACIOUS

Traditional



Audacious



Amphibious Construction

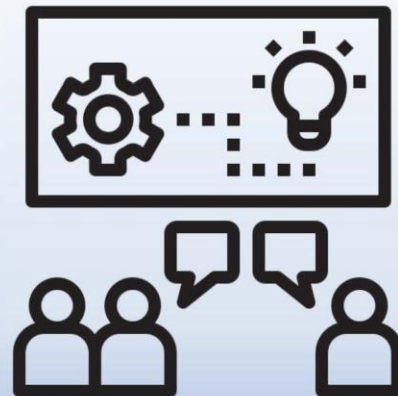
Buoyant Foundation Project  
(Elizabeth English)

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## WORKSHOP GOALS & OUTCOMES



icon by noomtah on <https://www.freepik.com>



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## WORKSHOP GOALS

- Identify barriers
- Build bridges over those barriers!



The overall objective of the workshop is to gather academics, practitioners, stakeholders, and other experts to discuss climate adaptable structural solutions for coastal flood resilience

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## WORKSHOP GOALS

### Workshop Outcomes:

- form connections
- foster collaborations
- sharing experiences and resources
- identifying the following:
  - ✓ deficiencies in flood design practices
  - ✓ gaps in basic science
  - ✓ needs in codes and standards
- A workshop report will be distributed to the participants (and public) following the event.

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## WORKSHOP GOALS

### Thursday

Theme 1: STATE OF RESEARCH/PRACTICE

Theme 2: EXPERIMENTAL AND NUMERICAL CAPABILITIES/NEEDS

Theme 3: STRUCTURAL ENGINEERING DESIGN APPROACHES

Theme 4: PRACTITIONER PERSPECTIVES

### Friday

Theme 5: EDUCATIONAL EFFORTS

Breakout Sessions: IDENTIFYING GOALS AND GAPS

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## WORKSHOP GOALS

### Discussion Questions: Thoughts in Advance

To have everyone's voice heard, and to make the breakout sessions on Friday more efficient, share with us your thoughts on the questions below. Here are some means to share:

- Hand-write thoughts on this sheet and share during discussion/breakout time;
- Hand in to Maria or any of her students anytime;
- And/or use this QR code to type in your responses directly (preferred).



#### General Question:

What does "Coastal Flood Resilience" look like to you?

#### Theme 1: State of Affairs

- In light of the presentations on the state of affairs related to climate change, storm surge and flood hazard, and structural engineering practice, what should be our key objectives in research and practice over the next 5-10 years?

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# Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience



May 16-17, 2024  
Princeton University

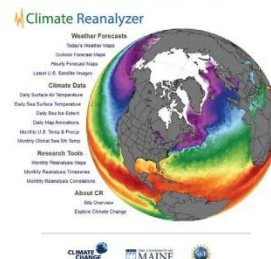
## Overview of Climate Change, Storm Surge, and SLR Models

Jayantha Obeysekera ('Obey'), Ph.D., P.E.  
Director and Research Professor  
Sea Level Solutions Center  
Institute of Environment

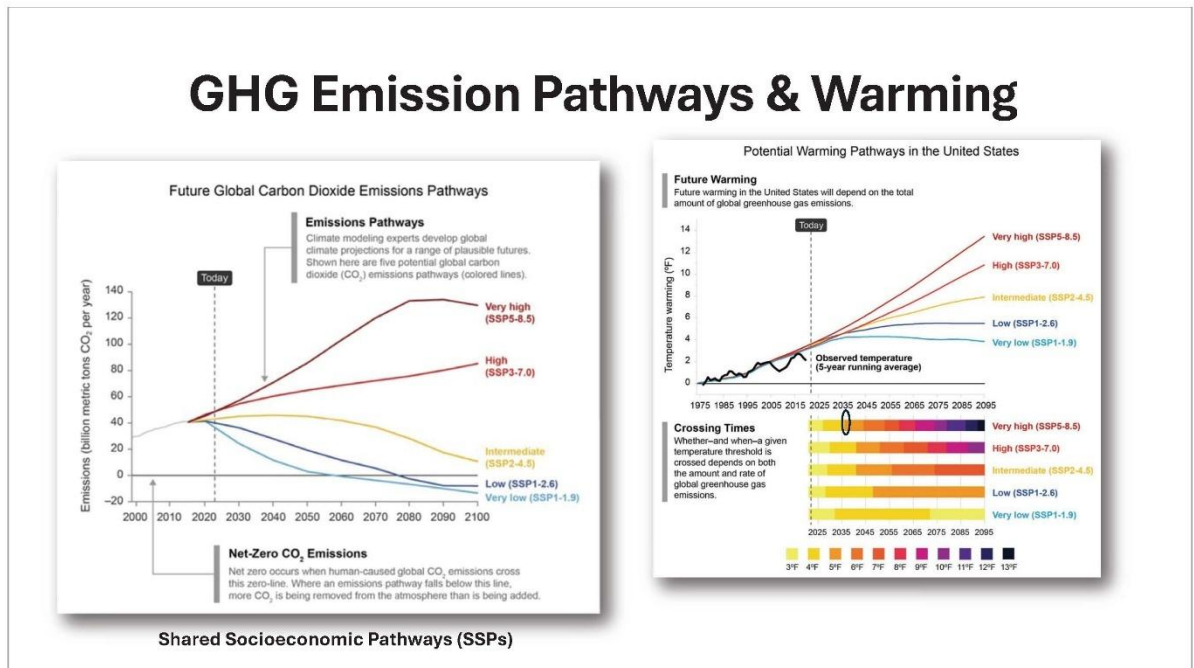
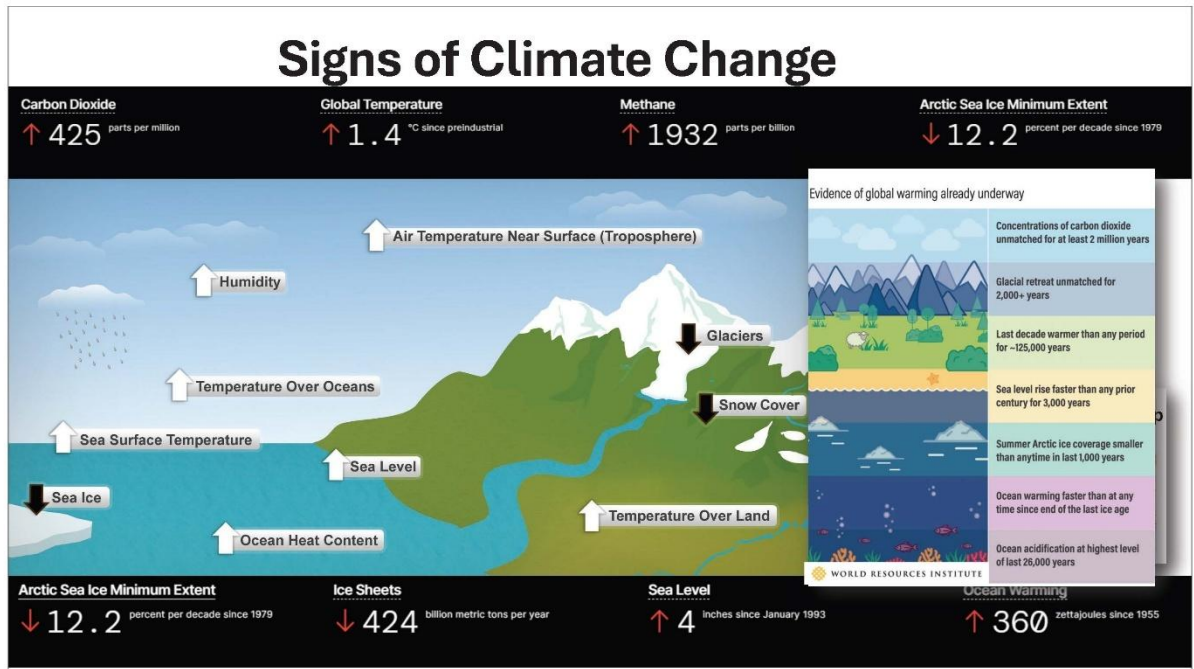


## Resources

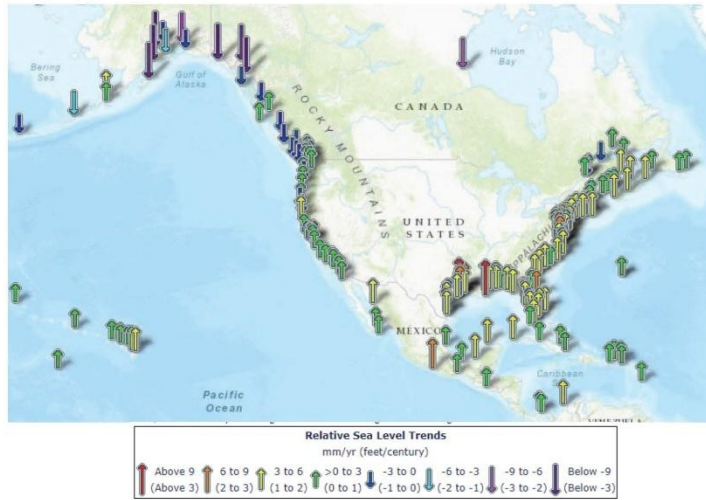
- <https://nca2023.globalchange.gov/>
- <https://www.ipcc.ch/assessment-report/ar6/>
- <https://climatoreanalyzer.org/>
- <https://sealevel.nasa.gov/>
- [https://drsl.serdp-estcp.org/Docs/CARSWG\\_SLR.pdf](https://drsl.serdp-estcp.org/Docs/CARSWG_SLR.pdf)



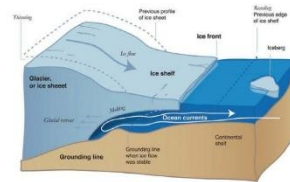
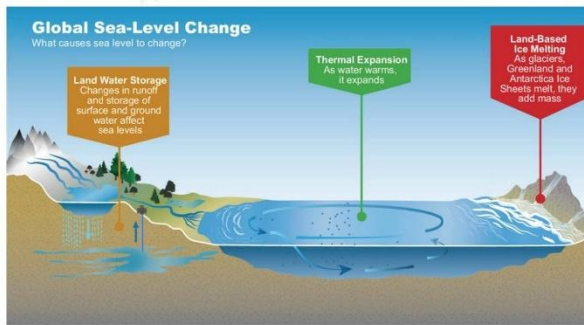
### B.3 Obeysekera



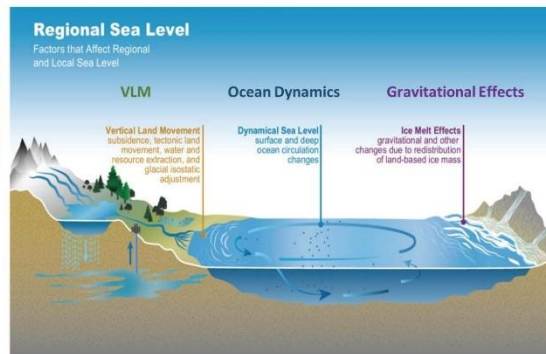
# Sea Level Trends in the United States



# Global and Regional Sources of Sea Level Change



Marine Ice Sheet and Ice Cliff Instability (MISI & MICI)



## Δ Relative Sea Level (RSL) (Sweet et al., 2017)

$$\Delta RSL = \Delta GMSL + \Delta RSL_{\text{climatic}} + \Delta RSL_{\text{non-climatic}}$$

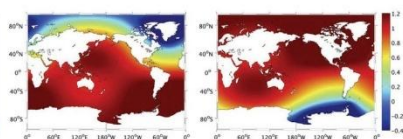
Global Mean Sea Level (GMSL) Scenarios for 2100:

- Low (0.3)
- Intermediate-Low (0.5 m)
- Intermediate (1.0 m)
- Intermediate-High (1.5 m)
- High (2.0 m)
- \*Extreme (2.5 m)

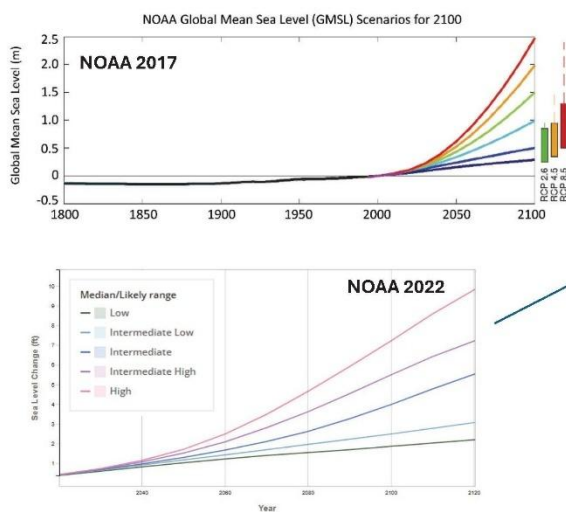
- 1) Δ Ice Mass w/ gravity 'fingerprints' of Mitrovica et al. (2011):
- 2) Δ Oceanographic Processes (thermal expansion, dynamics from CMIP5 models)
- 3) Land-water storage based upon empirical relationships

GIA, tectonics, sediment compaction, anthropogenic factors:

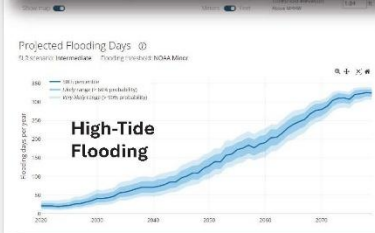
- Spatiotemporal model of tide gauge data with 3 modes: 1) globally uniform sea level change, 2) a **constant-rate average, long-term, regionally varying trend**, and 3) temporally and spatially varying regional sea-level contributions



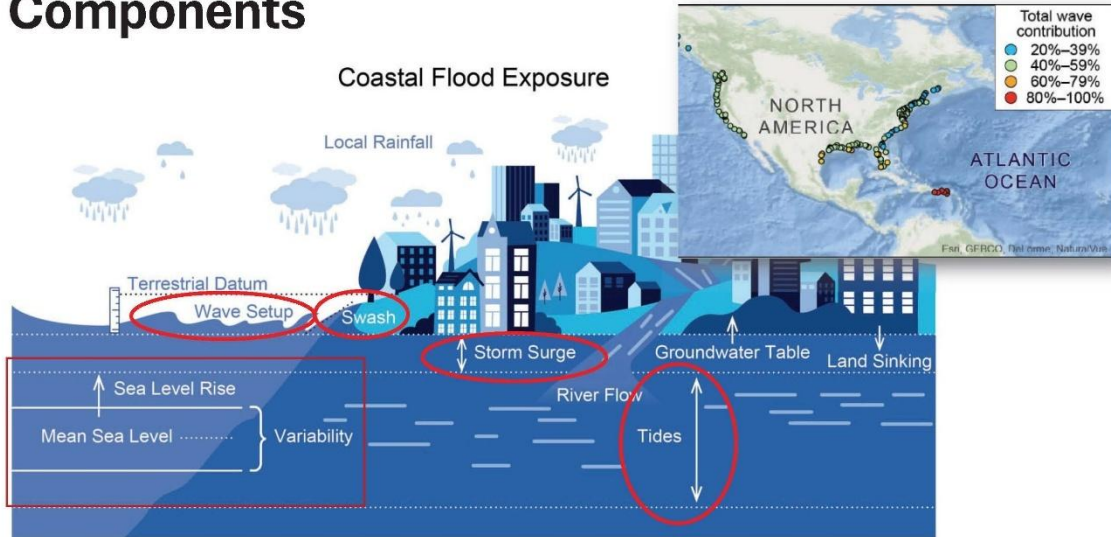
## National Climate Assessment SLR Scenarios



Global Mean Surface Air Temperature 2081–2100 Projection	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	Unknown Likelihood, High Impact – Low Emissions	Unknown Likelihood, High Impact – Very High Emissions
Closest Emissions Scenario-Based GMSL Projection	Low (SSP1-2.6)	Low (SSP1-2.6) to Intermediate (SSP2-4.5)	Intermediate (SSP2-4.5) to High (SSP2-7.0)	High (SSP2-7.0)	Very High (SSP4-5)	Low (SSP1-2.6), Low Confidence processes	Very High (SSP5-8.5), Low Confidence processes
Total (2050)	0.18 (0.16–0.24)	0.20 (0.17–0.24)	0.21 (0.18–0.23)	0.22 (0.19–0.25)	0.25 (0.22–0.30)	0.20 (0.16–0.24)	0.24 (0.20–0.40)
Total (2100)	0.44 (0.34–0.59)	0.51 (0.40–0.69)	0.61 (0.50–0.81)	0.70 (0.58–0.92)	0.81 (0.69–1.05)	0.45 (0.32–0.79)	0.88 (0.63–1.60)
Bounding Median Scenarios in 2100	Low to Intermediate-Low	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Intermediate-Low to Intermediate	Low to Intermediate-Low	Intermediate-Low to Intermediate
Probability > Low (0.3 m) in 2100	52%	98%	>99%	>99%	>99%	89%	>99%
Probability > Int.-Low (0.5 m) in 2100	37%	50%	82%	97%	>99%	49%	96%
Probability > Int. (1.0 m) in 2100	<1%	2%	5%	10%	23%	7%	49%
Probability > Int.-High (1.5 m) in 2100	<1%	<1%	<1%	1%	2%	1%	20%
Probability > High (2.0 m) in 2100	<1%	<1%	<1%	<1%	<1%	<1%	8%

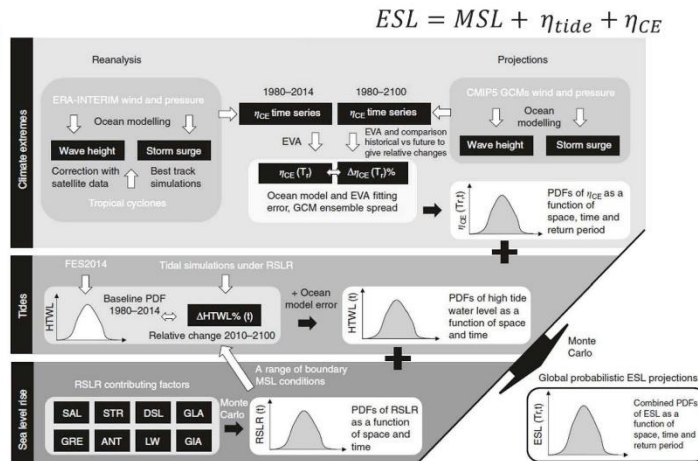


# Coastal Flooding: Total Water Level Components



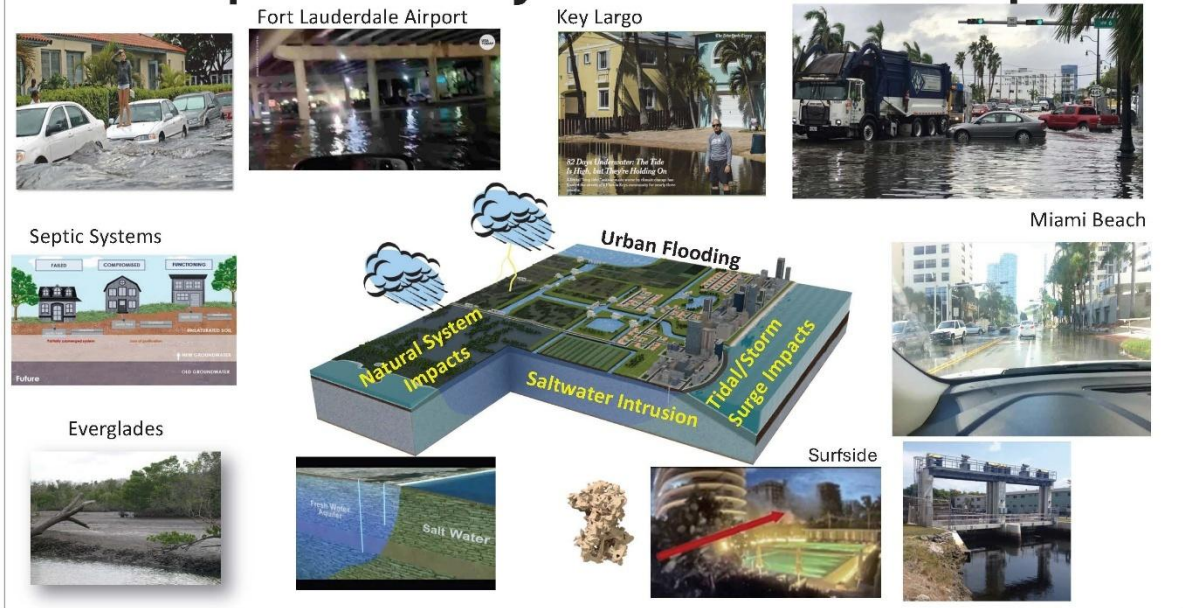
## Selected Datasets Available

Dataset	Surge+	Wave Effects		TCs
	Tides	Setup	Swash	
USACE Coastal Hazards System (CHS)	Yes	Yes	No	Yes
USGS Coastal Storm Modeling System (CoSMoS)	Yes	Yes	No	Yes
Vousdoukas et al. (2018)	Yes	Yes	No	Yes
Muis et al. (2020)	Yes	No	No	No
Kirezcki et al. (2020)	Yes	Yes	No	No



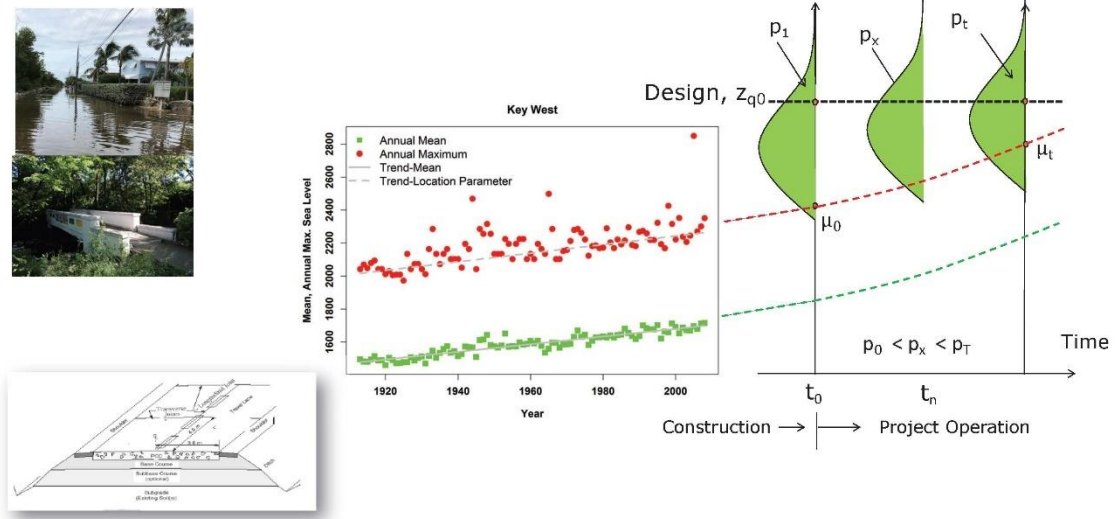
Vousdoukas et al. 2018

# SLR Impacts already: South Florida Example

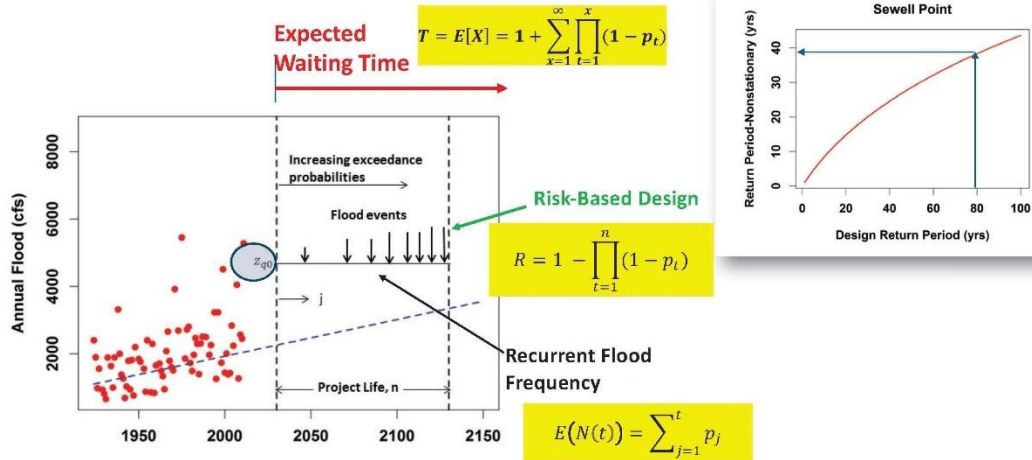


## Nonstationary Paradigm

- Statistical characteristics of extremes (floods, sea levels) vary with time



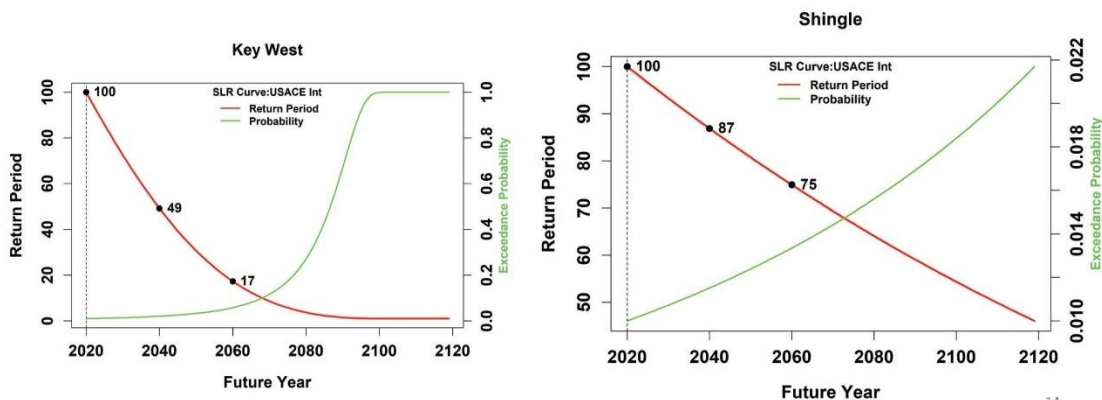
# Hydrologic Design considering Nonstationarity



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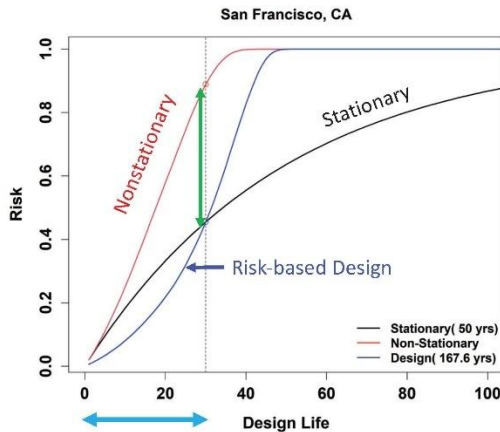
## WHY SHOULD NONSTATIONARITY MATTER?

“Climate change introduces nonstationary risks such as sea level and temperature rise, and changes in timing and distribution of precipitation, snowpack, and snowmelt (USGCRP 2017, 2018). Failure to account for such nonstationary risks may compromise the operational characteristics of existing and future transportation infrastructure” (NCHRP1561, 2019)



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# Revisiting Risk Under Nonstationarity

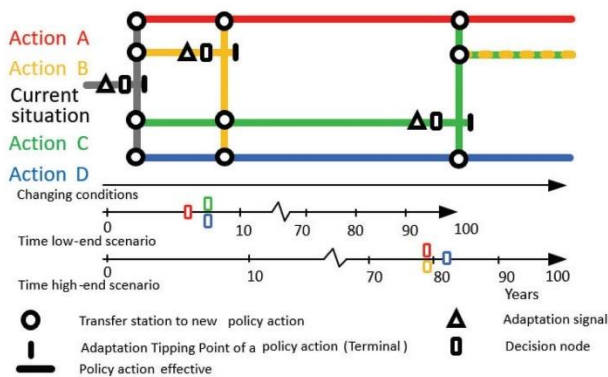


- Future Risks and Damages are dynamic (nonstationary)
- Nonstationary Risk Formula:

$$R = 1 - \prod_{t=1}^n (1 - p_t)$$

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# Embracing Uncertainty Adaptively (Dynamic Adaptive Policy Pathways)

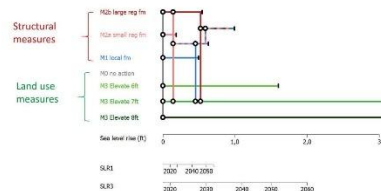
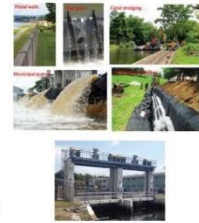


“Different roads leading to Rome”

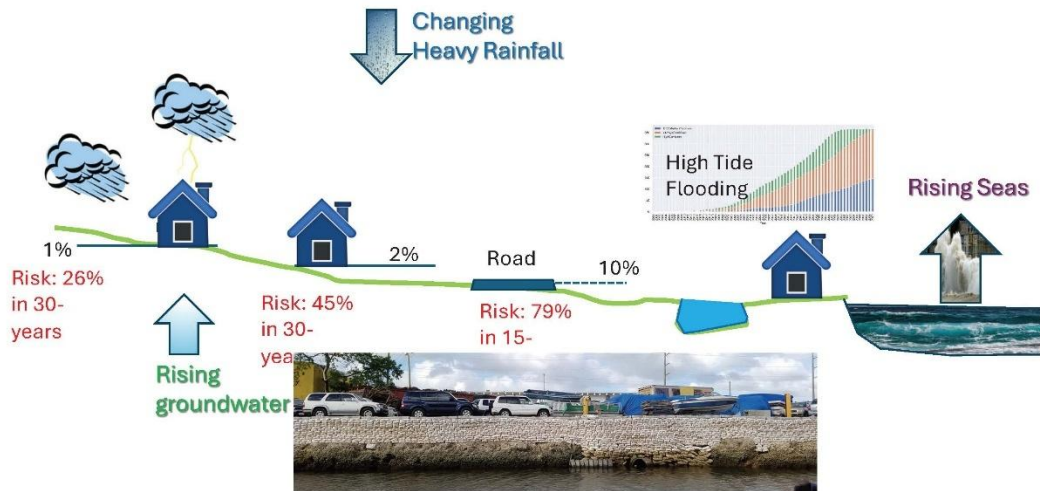
## Example: Little River Basin

### Level II: Portfolio of Measures

- M0 – No action
- M1 – Local flood mitigation: flood walls, exfiltration trenches, flap gates, and local pumps
- M2 – Regional flood mitigation: forward pumps at S-27 coastal structure (small & large pumps)
- M3 – Land-use mitigation: raise roads and buildings to 6, 7 or 8 feet elevation



# Increasing Risk of Flooding: Compounding Effects of Threat Multipliers



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## Compound Flooding in a Non-stationary World: A primer for practice (ASCE ~2024) CACC/HYDEA Committee~2024)

### Editors

Rolf Olsen, Julie Pietrzak, Jayantha Obeysekera

### 2. Background

Poulomi Ganguli, pganguli@agfe.iitkgp.ac.in (lead author)  
Shaleen Jain, Carlo De Michele, Gianfausto Salvadori

### 3. Hydrodynamic Process-Based Models of Compound Flooding

Liv Herdman, (lead author)  
Matthew Bilskie, Antonia Sebastian, Ning Lin, Miguel Medina, Teng Wu

### 4. Statistical Models of Compound Flooding

Carlo De Michele, (co-lead author)  
Gianfausto Salvadori, (co-lead author), Thomas Wahl, Amir AghaKouchak, Robert Jane, Emanuele Bevacqua, Ivan Haigh, Ferdinand Diermanse

### 5. Joint Probability Method

Norberto Nadal, (lead author)  
Michelle Bensi, Madison Yawn, Victor Gonzalez

### 6. Linking Statistical and Hydrodynamic Process-Based Models

Hamed Mofkakhari, Amir AghaKouchak, David Muñoz, Ning Lin, Ferdinand Diermanse,

### 7. Analysis of Changing Conditions

Rolf Olsen, (co-lead author)  
Julie Pietrzak, Jayantha Obeysekera, Gerarda Shields, Poulomi Ganguli, Avi Gori Ning Lin, Mohammad Reza Najafi, Miguel Medina, Teng Wu

### 8. Risk and Uncertainty Analysis

Gerarda Shields, (co-lead

author)  
Jayantha Obeysekera, Rolf Olsen, Julie Pietrzak, Poulomi Ganguli, Michelle Bensi, Antonia Sebastian, Miguel Medina, Carlo De Michele, Gianfausto Salvadori, Fabrizio Durante, Ferdinand Diermanse, Teng Wu, Aikaterini Kyprioti

### 9. Case Studies

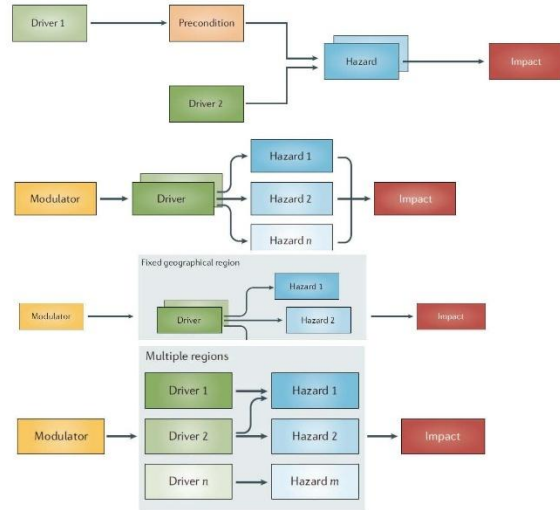
Shubra Misra, Norberto Nadal

Credit: MOP (in\_Prep)

ASCE AMERICAN SOCIETY OF CIVIL ENGINEERS

# Compounding Events: Typology

- **Sequential or preconditioned:**
  - Sequential or preconditioned hazards indicate a background climate or weather condition that leads to an amplified impact
- **Multivariate**
  - The coincidence of two or multiple hazards at the same location
- **Temporally compounding/Consecutive Hazard:**
  - Results from a sequence of hazards involving similar or dissimilar types of weather or climate events that have occurred in succession affecting a geographical region
- **Spatially compounding:**
  - Spatially compounding events results from accumulated impacts of the same or different hazards occurring in multiple connected locations within a short time window.



(Zscheischler et al., 2020).

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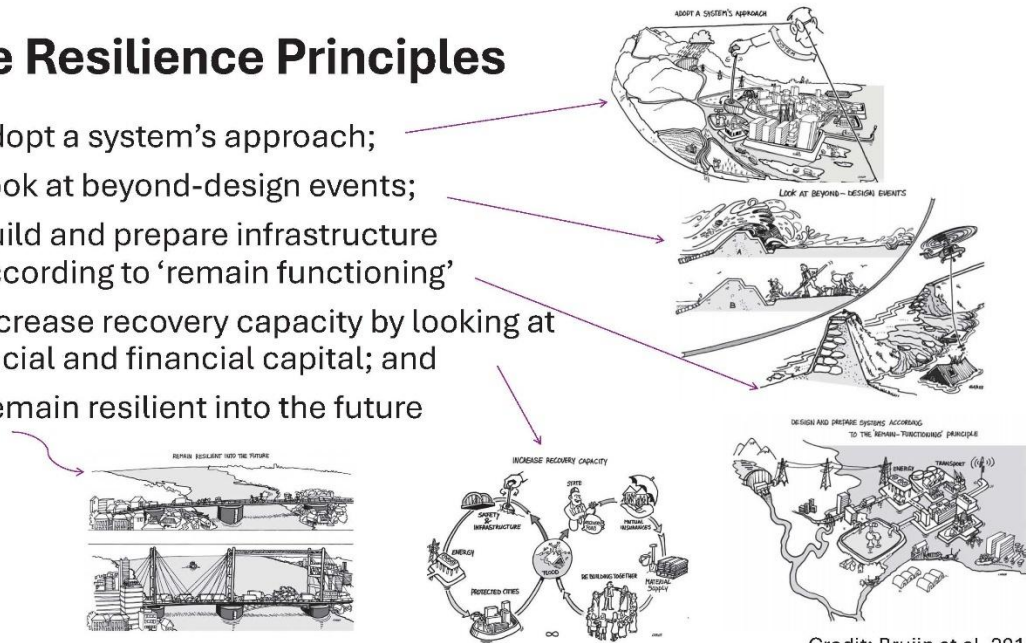
# Modeling Approaches

- Hydrodynamic Process-Based Models
- Statistical Models
- Hybrid: Linking Statistical and Process-Based Models
- AI/ML Methods (emerging)

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# Five Resilience Principles

- Adopt a system's approach;
- Look at beyond-design events;
- Build and prepare infrastructure according to 'remain functioning'
- Increase recovery capacity by looking at social and financial capital; and
- Remain resilient into the future



Credit: Bruijn et al. 2017

## Selected Papers

- J. Salas and Obeysekera, J. 2014. "Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events." *ASCE J. Hydrol. Eng.*, 19(3). (Received 3 awards for this paper including the 2015 ASCE Norman Medal and the 2015 Best Paper)
- J. Obeysekera, and Salas. 2014. "Quantifying the Uncertainty of Design Floods Under Non-Stationary Conditions." *ASCE J. Hydrol. Eng.*, 19(7).
- John A. Hall, S. Gill, J. Obeysekera, W. Sweet, K. Knauti, and J. Marburger. 2016. "Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide." U.S. Department of Defense, Strategic Environmental Research and Development Program". 224 pp. 2016. (peer reviewed)
- Jayantha Obeysekera, Jose Salas. 2016. "Frequency of Recurrent Extremes under Nonstationarity." *ASCE J. Hydrol. Eng.* 21(5).
- William V. Sweet, M. Menendez, A. Genz, Jayantha Obeysekera, J. Park, and J. 2016. In Tide's Way: Southeast Florida's September 2015 Sunny-Day Flood [in "Explaining Extremes of 2015 from a Climate Perspective". *Bull. Amer. Meteor. Soc.*, 97 (12), S14-S18, doi:10.1175/BAMS-D-16-0149
- William V. Sweet, R. Kopp, C. P. Weaver, J. Obeysekera, R.M. Horton, E. R. Thieler, C. Lervas. 2017. "Global and Regional Sea Level Rise Scenarios for the United States." NOAA Technical Report NOS CO-OPS 083.
- Salas, J.D., J. Obeysekera, and R. Vogel. 2018. Techniques for assessing water infrastructure for nonstationary extreme events: a review. *Hydrologic Science Journal*, Vol. 63, Issue 3. Published online: 27Feb2018
- John A. Hall, Christopher P. Weaver, Jayantha Obeysekera, Mark Crowell, Radley M. Horton, Robert E. Kopp, John Marburger, Douglas C. Marcy, Adam Parris, William V. Sweet, William C. Veatch & Kathleen D. White. 2019. Rising Sea Levels: Helping Decision-Makers Confront the Inevitable. *Coastal Management*. <https://doi.org/10.1080/08920753.2019.1551012>
- Jose Salas, J. Obeysekera. 2019. Probability Distribution and Risk of the First Occurrence of k Extreme Hydrologic Events. *ASCE Journal of Hydrologic Engineering*, 24(10).
- Jane, R., Cadavid, L., Obeysekera, J., Wahl, T., 2020. Multivariate statistical modelling of the drivers of compound flood events in south Florida. *Nat. Hazards Earth Syst. Sci.* 20, 2681–2699. <https://doi.org/10.5194/nhess-20-2681-2020>
- J. Obeysekera, and J. Salas. 2020. Hydrologic designs for extreme events under nonstationarity. In: *Engineering Methods for Precipitation under a Changing Climate*. Olsen, J.R. and K. T. Adamcc, Eds. American Society of Civil Engineers, 63–82. <http://dx.doi.org/10.1061/9780784415528.ch04>
- F. Peña, Nardi, F., Melesse, A., Obeysekera, J., Castelli, F., Price, R.M., Crowl, T., Gonzalez-Ramirez, N., 2021. Compound flood modelling framework for rainfall-groundwater interactions. *Nat. Hazards Earth Syst. Sci.* 2021, 1–38. <https://doi.org/10.5194/nhess-2021-259>
- Sweet William, Benjamin D Hamlington, Robert E Kopp, Christopher P Weaver, Patrick I Barnard, David Bekacrt, William Brooks, Michael Craghan, Gregory Dusek, Thomas Frederikse, Gregory Garner, Ayesha S Genz, John P Krasting, Eric Larour, Doug Marcy, John J Marra, Jayantha Obeysekera, et al. 2022. Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along US coastlines. National Oceanic and Atmospheric Administration.

# Questions?

Email:  
jobeysek@fiu.edu



# Acknowledgement

- <https://nca2023.globalchange.gov/>
- <https://www.ipcc.ch/assessment-report/ar6/>
- <https://climatereanalyzer.org/>
- <https://sealevel.nasa.gov/>
- [https://drsl.serdp-estcp.org/Docs/CARSWG\\_SLR.pdf](https://drsl.serdp-estcp.org/Docs/CARSWG_SLR.pdf)

**The Fifth National Climate Assessment**  
The Fifth National Climate Assessment is the US Government's preeminent report on climate change impacts, risks, and responses. It is a congressionally mandated interagency effort that provides the scientific foundation to support informed decision making across the United States.




**Sixth Assessment Report**  
The Working Group I contribution was released on 9 August 2021. The Working Group II and III contributions were released on 28 February and 4 April 2022, respectively. The Synthesis Report was released on 20 March 2023.

**Climate Reanalyzer**  
Weather Forecasts  
Today's Weather Data  
Global Forecast Data  
Polar Forecast Data  
Latest U.S. Satellite Imagery  
**Climate Data**  
Daily Surface Air Temperature  
Daily Sea Level Pressure  
Daily Wind Speed  
Monthly U.S. Snow-Precip  
Monthly Global Sea Ice Extent  
**Research Tools**  
Monthly Temperature Data  
Monthly Precipitation Data  
Monthly Humidity Data  
Monthly Wind Speed Data  
**About CR**  
Site Overview  
Explore Climate Change

**GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES**  
NOAA  
SERDP  
ESTCP  
Regional Sea Level Rise Scenarios for Coastal Risk Management  
Global and Regional Sea Level Rise Scenarios for the United States

## B.4 Kennedy

Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience




   May 16-17, 2024  
Princeton University

### Flood Hazards in the Built Environment




Andrew Kennedy  
University of Notre Dame

Courtesy PLAN INTERNATIONAL

Roof






Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience

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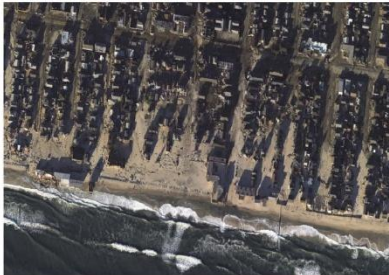
## Flood Hazards in the Built Environment

Andrew Kennedy  
University of Notre Dame



ATC 149

### Coastal Inundation in Developed Regions: Experimental Results and Implications for Engineering Practice



ATC Applied Technology Council

Prepared for  
University of Notre Dame

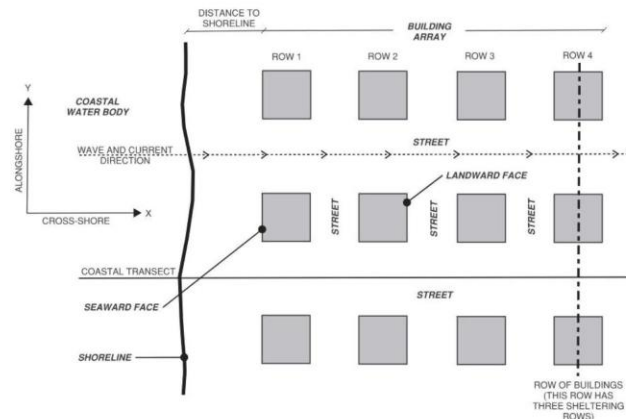
Funded by  
National Institute of Standards and Technology

- ATC-149 summarizes work by team: Jon Heintz, Chris Jones, Chris Cerino, Tony Dalrymple, Seth Thomas, Joaquin Moris, Andrew Kennedy
  - Laboratory experiments at Oregon State University Large Wave Basin
  - Additional analyses and interpretations
- Only addressing parts of this work.

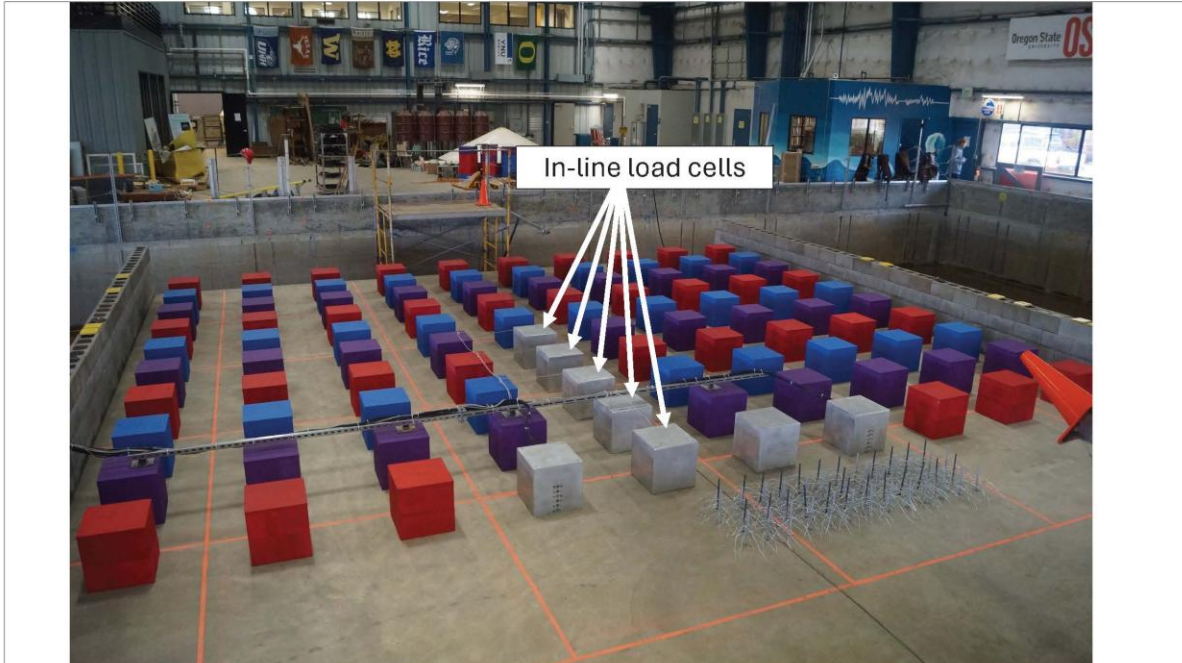


## Problem Statement and Topics

- Better estimates of wave, current, and floodborne debris effects are needed in developed regions subject to coastal inundation events
  - Depths, velocities, loads throughout a structural array, and behind sheltering wall
  - Floodborne debris paths and loading
  - Standards-based loads: similarities and differences



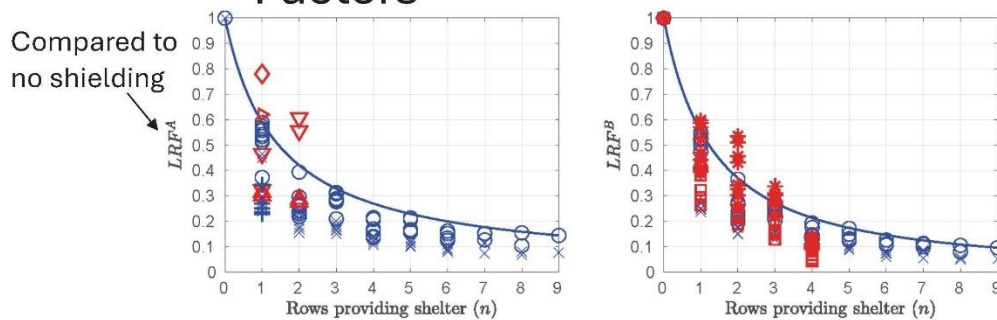
Nearshore structural array and definitions used here



## Error-Function-Type Wave Runup

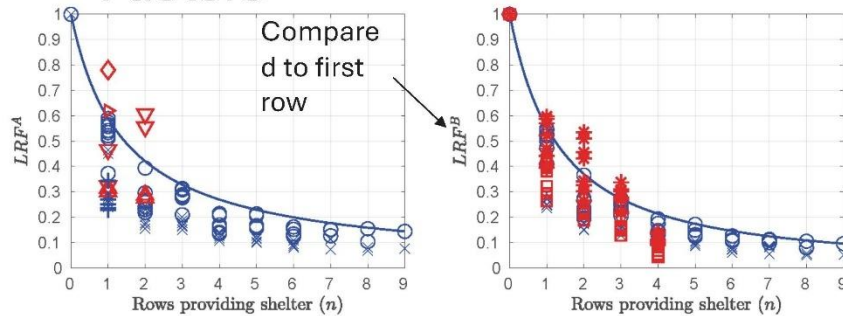


## Array Loading: Load Reduction Factors



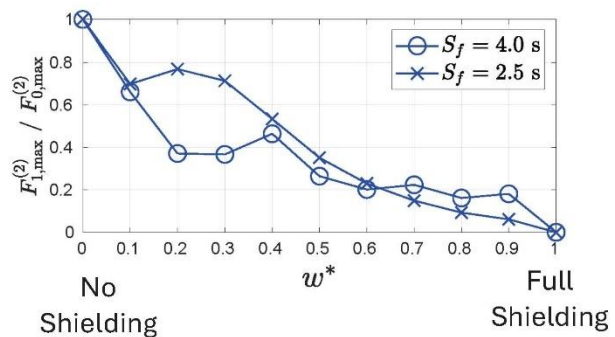
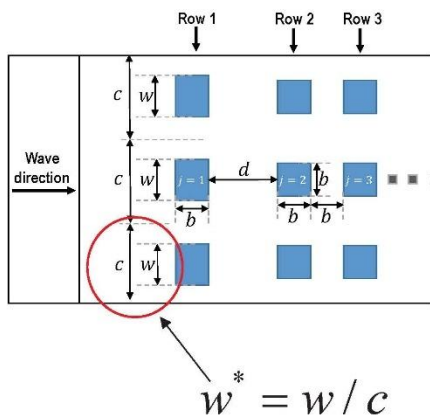
- Two Load Reduction Factors for regular array: depends on known quantities: Laboratory and computational data from numerous experiments
- All results show strong decreases in loading with increased shelter

## Array Loading: Load Reduction Factors

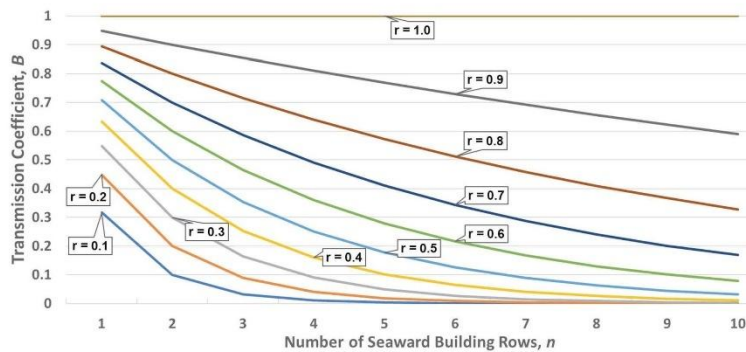


- Two Load Reduction Factors for regular array: depends on known quantities: Laboratory and computational data from numerous experiments
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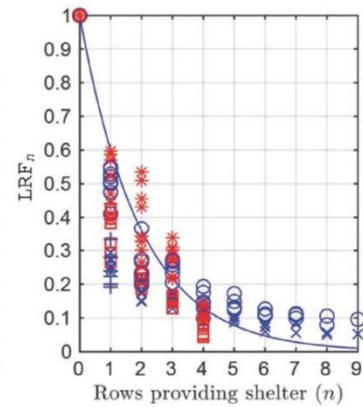
## Array Loading: Geometry Changes



# National Academy of Sciences Transmission Formula



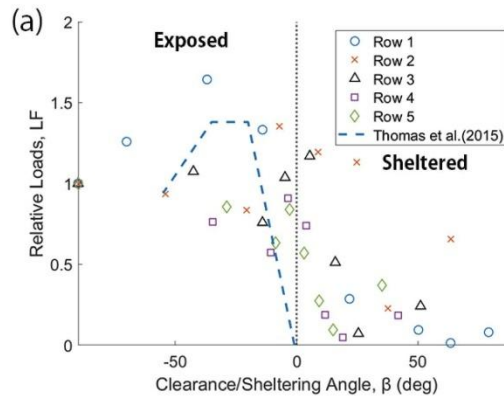
Conservation of Energy Flux-based NAS formula



Comparison with laboratory and computational data

## Summary of Loading in a Structural Array

- Channelization creates areas of strong flow where waves preferentially travel
- Blocking effects reduce all loading where one or more sheltering rows exist
  - Where buildings are offset due to irregular spacing in the alongshore direction, wave loads on row 1 also apply to row 2 buildings
- The NAS Formula for wave height reduction in a structural array gives reasonable results for the first few rows, for the cases tested.
- If waves are not parallel to the rows/streets, there may be some changes to loading
- **NOT DETAILED:** Sheltering/clearance angles from edges of walls explain much



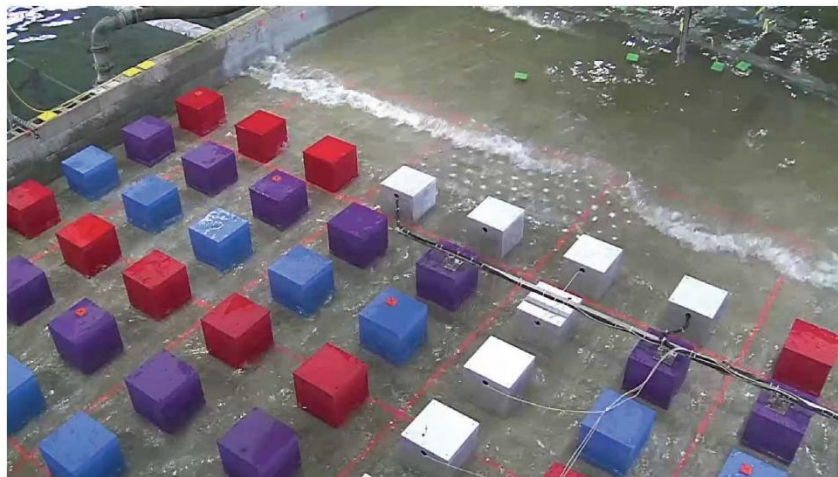
Sheltering effects on wave loads in a structural array

## Wave-Current-Debris Loading in a Building Array



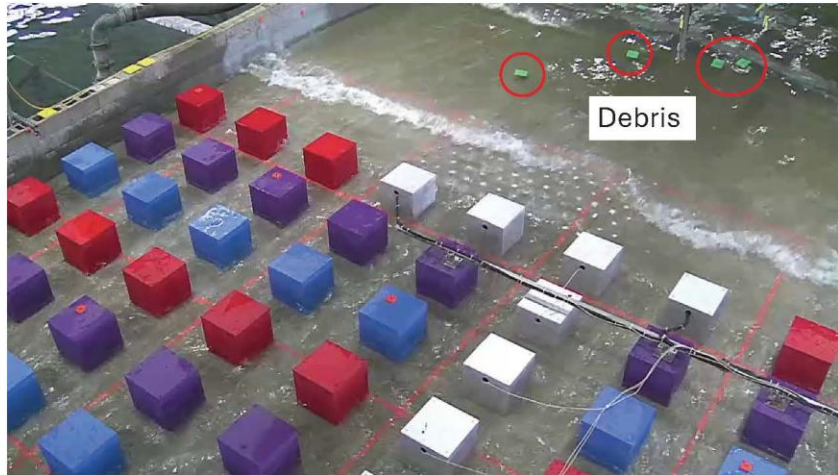
17

## Debris Transport and Collisions



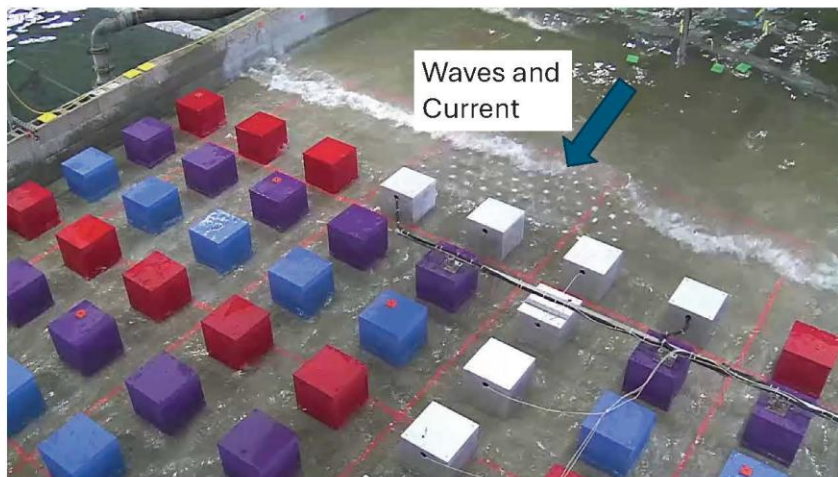
18

## Debris Transport and Collisions



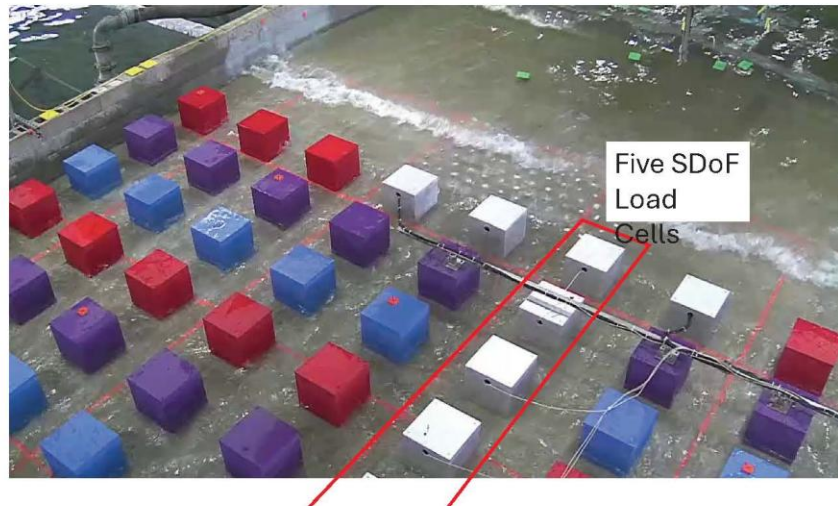
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## Debris Transport and Collisions



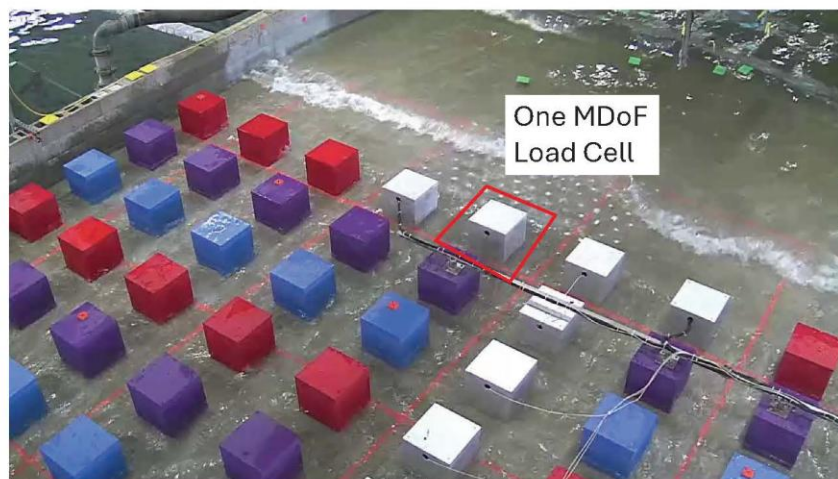
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## Debris Transport and Collisions



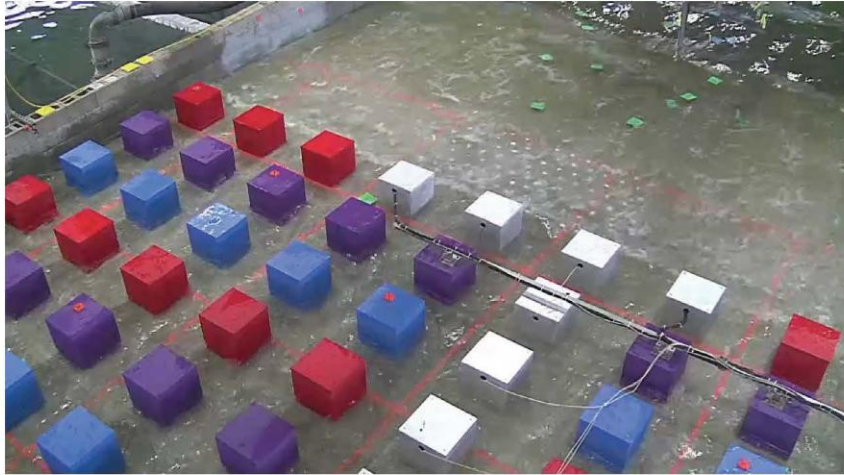
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## Debris Transport and Collisions



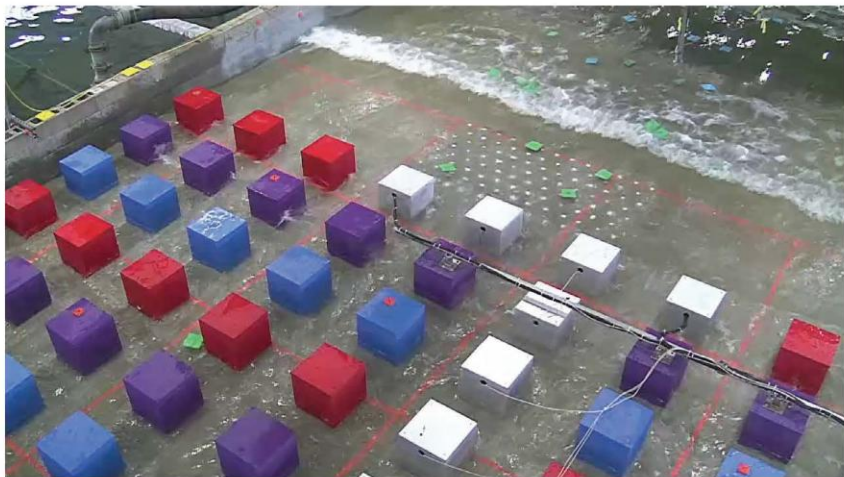
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## Debris Transport and Collisions



23

## Debris Transport and Collisions



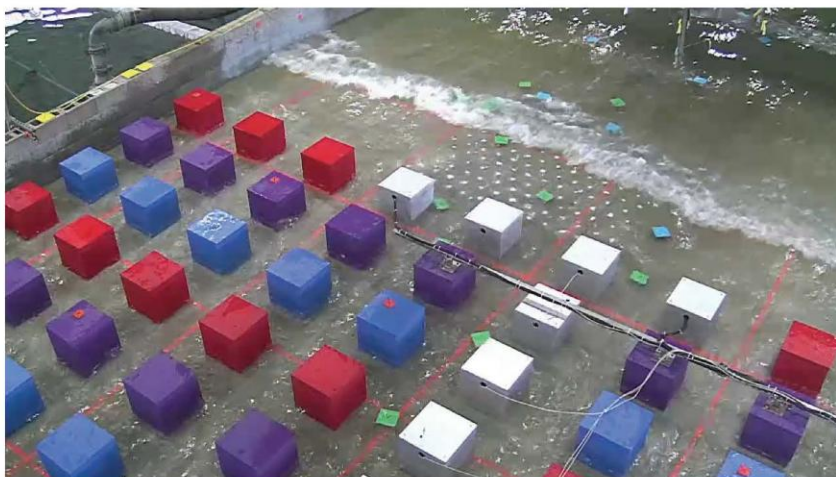
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## Debris Transport and Collisions



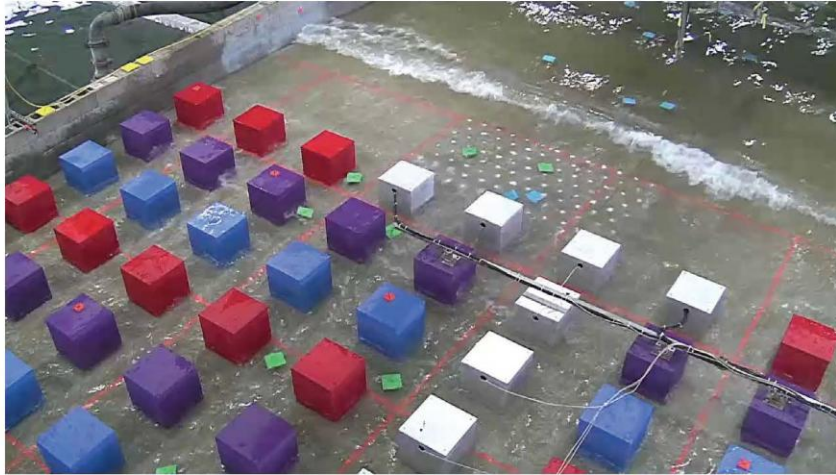
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## Debris Transport and Collisions



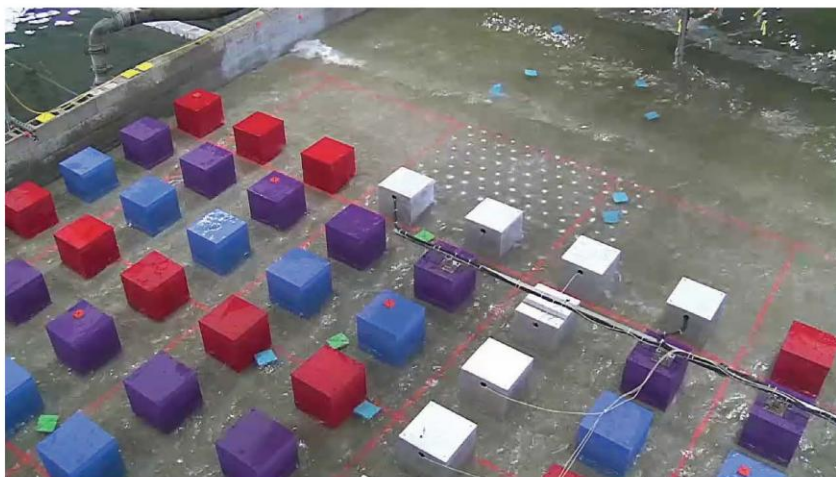
26

## Debris Transport and Collisions



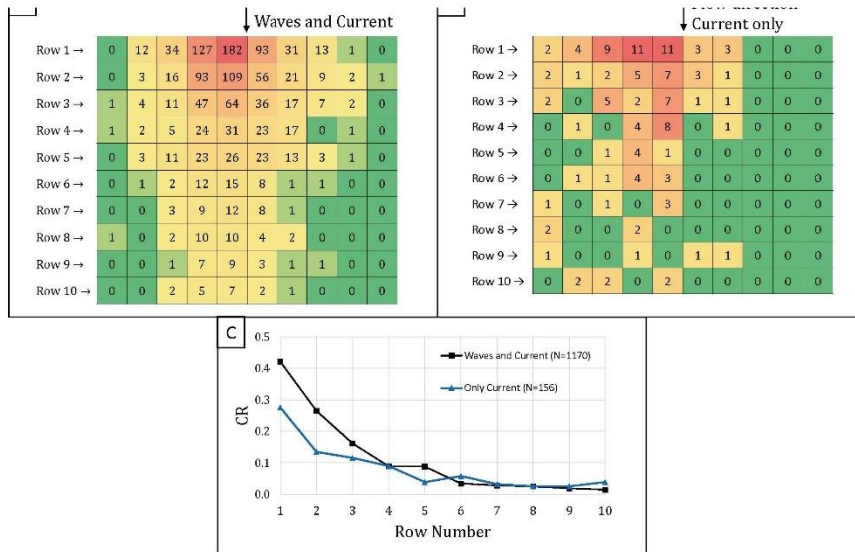
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## Debris Transport and Collisions

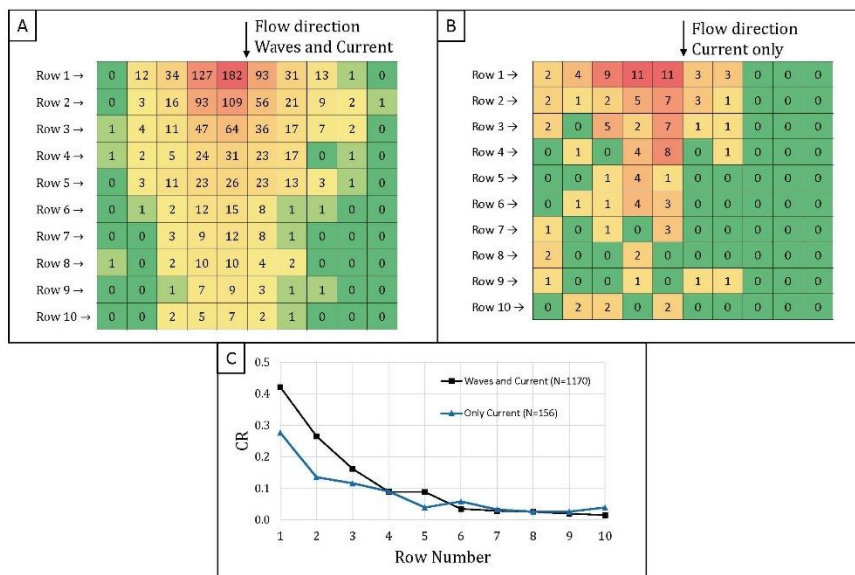


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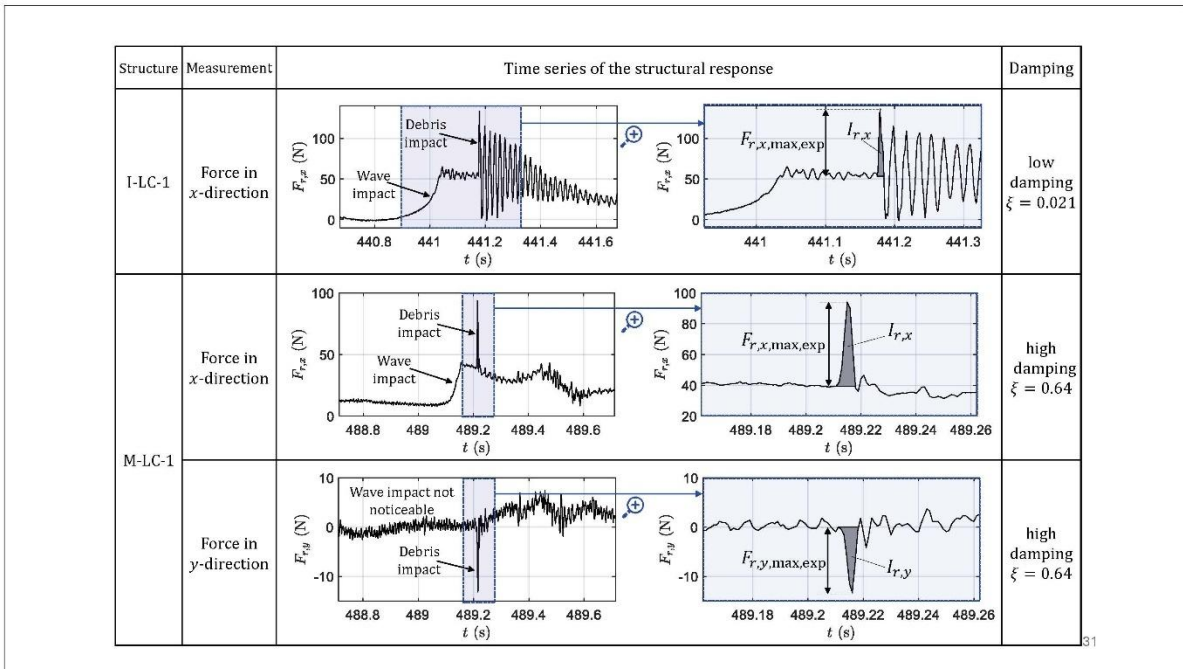
# Number of Collisions



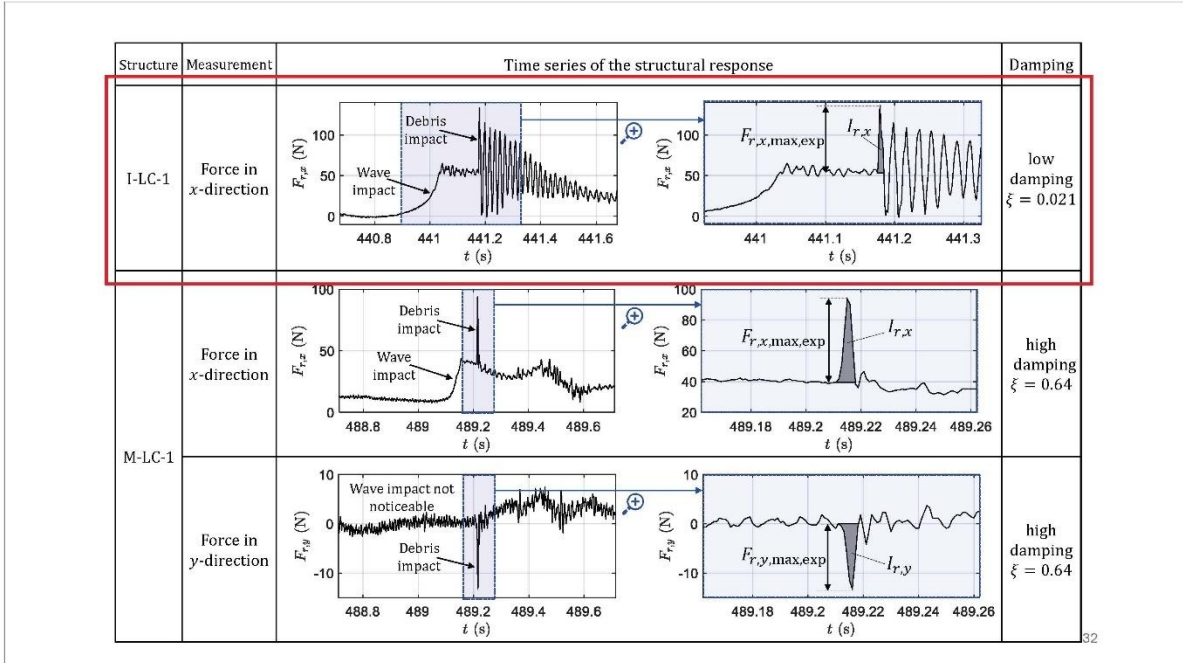
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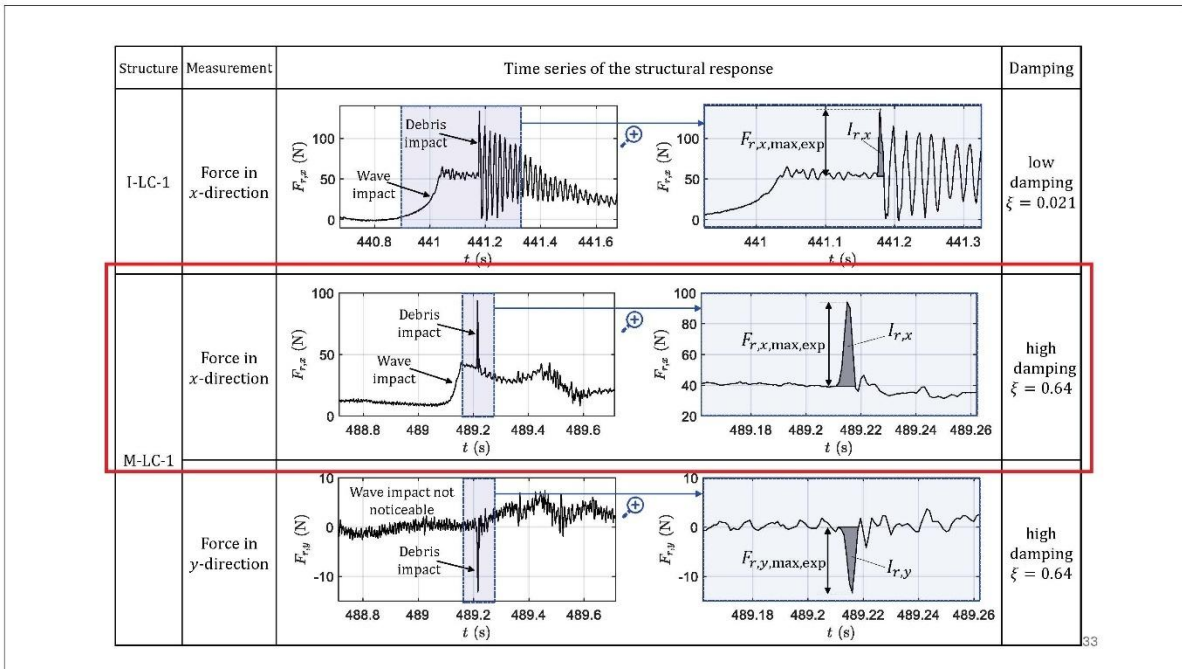
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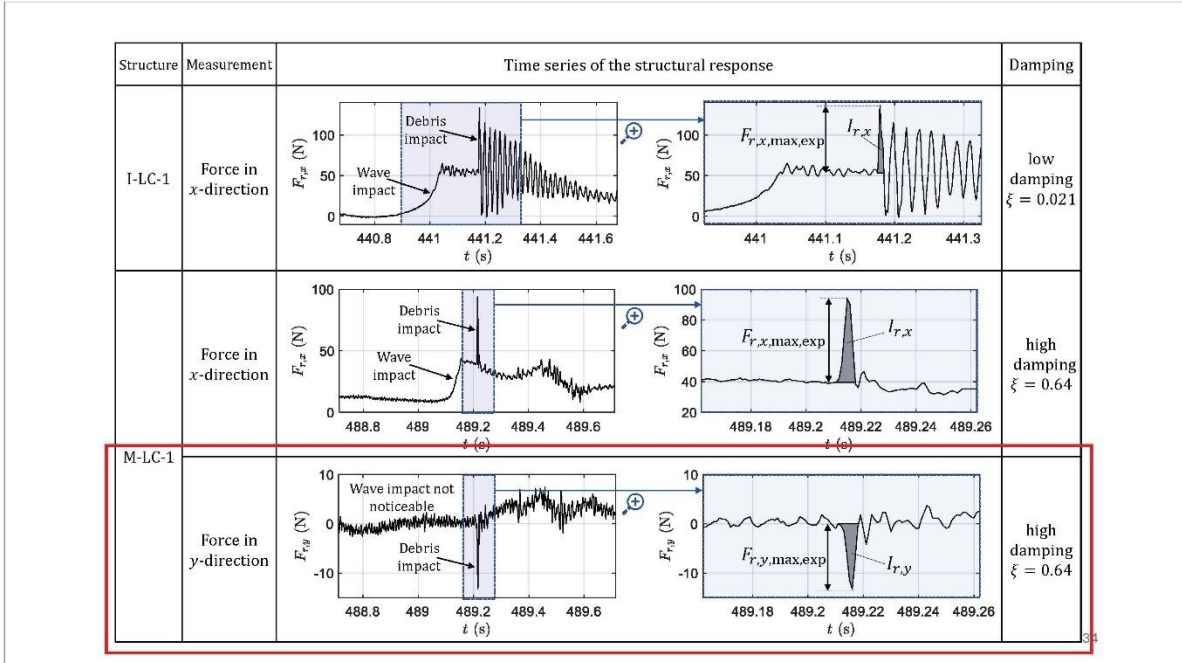
31



32



33



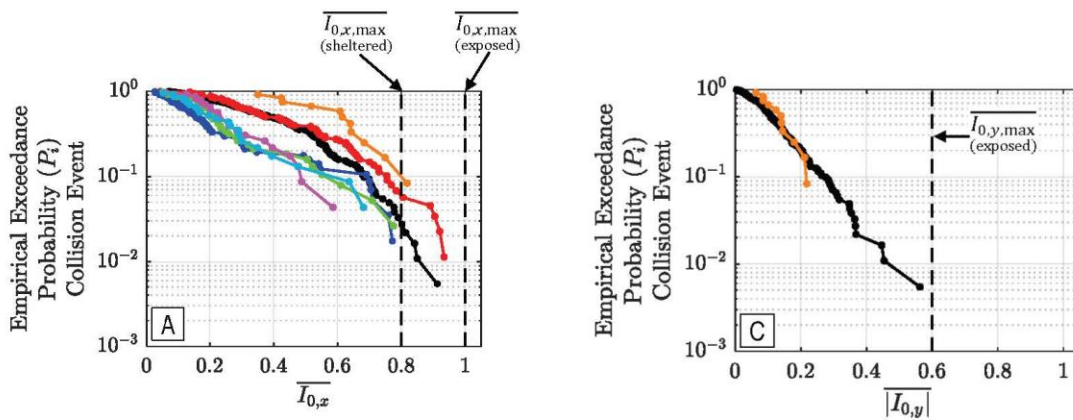
34

## Debris Loading

- Given a Collision Event (Debris impact), there are two components to loading:
  1. Impulse transmitted from debris to structure
  2. Effect of impulse on structural system considered
- Relate impulse to debris, hydrodynamic conditions
- Translate impulse to load through structural dynamics
- This sequence is different from how things are laid out in ASCE7

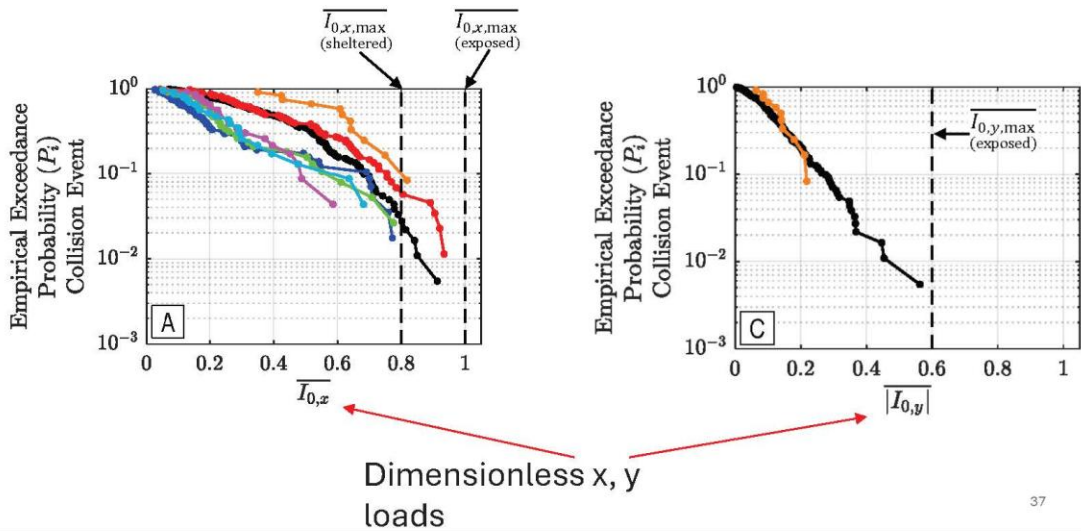
35

## Probabilistic Impulse

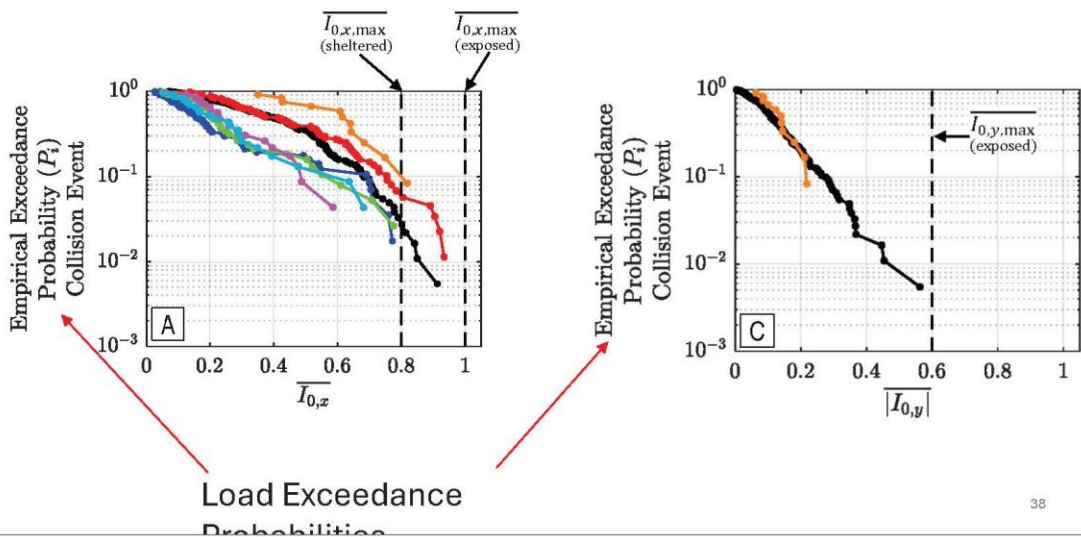


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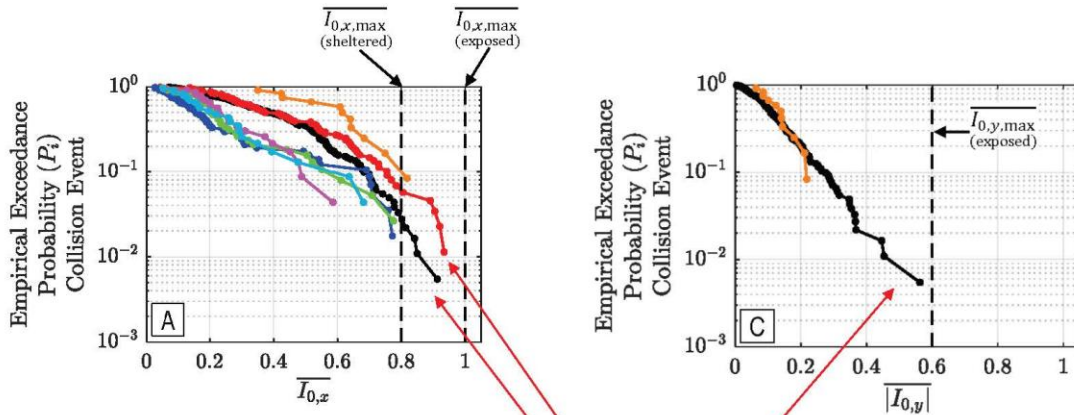
## Probabilistic Impulse



## Probabilistic Impulse



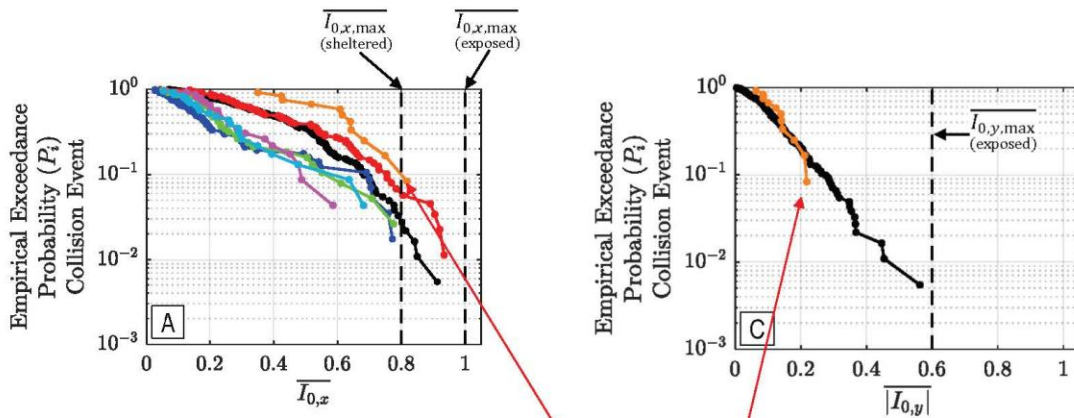
## Probabilistic Impulse



First Row Loads Wave-

39

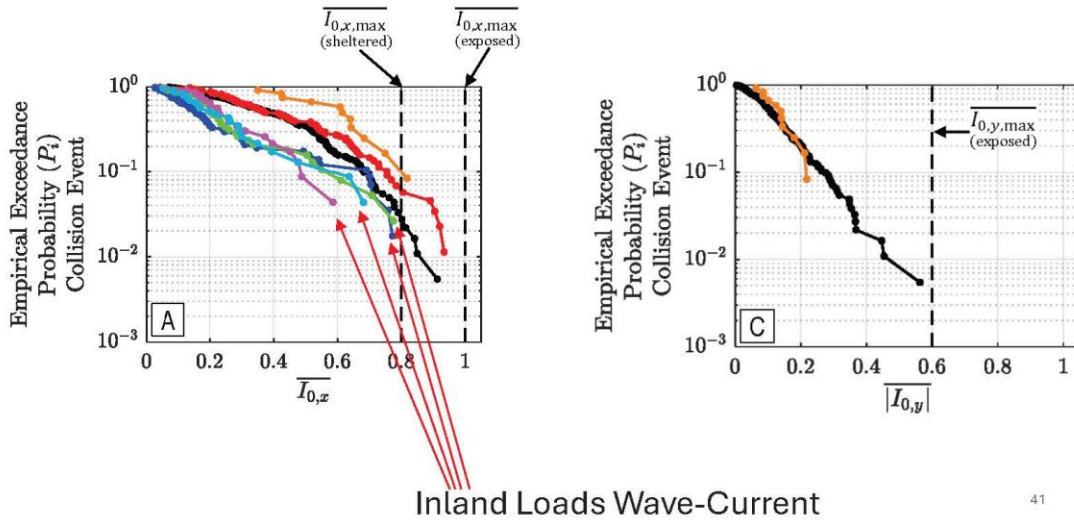
## Probabilistic Impulse



First Row Loads Current-

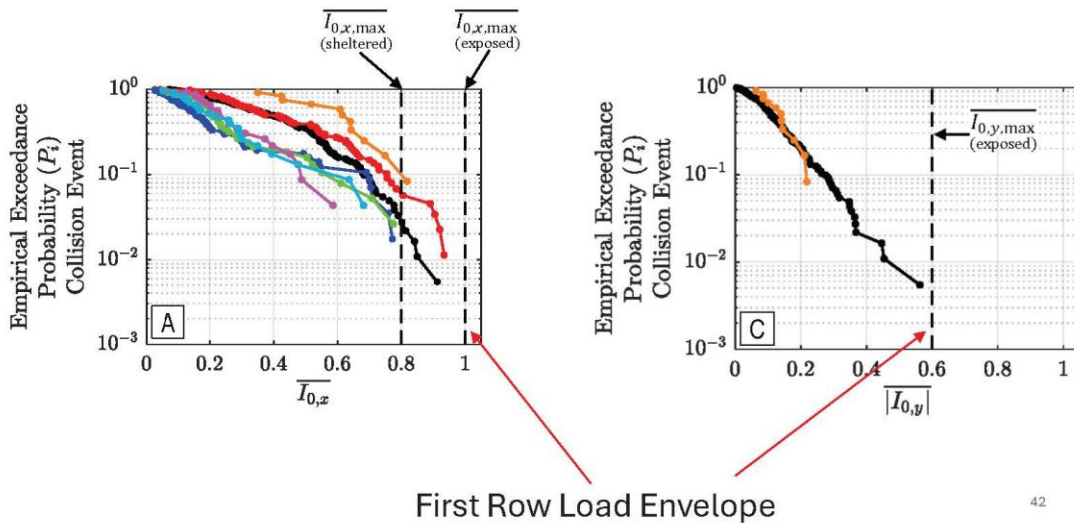
40

## Probabilistic Impulse



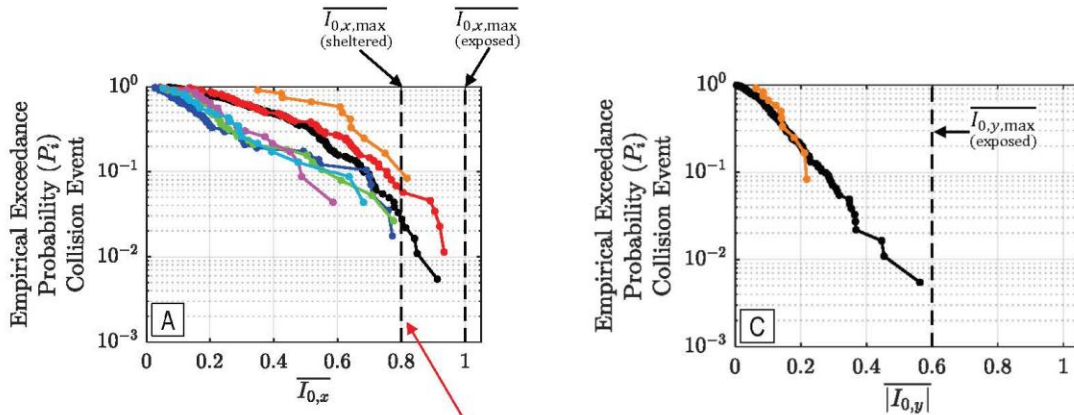
41

## Probabilistic Impulse



42

## Probabilistic Impulse



Inland Rows Load Envelope

43

## Envelope Debris Loads From Present Work

$$I_0 = \bar{I}_0 p_n$$

$$p_n = \mu u + m \frac{H_s}{2h} \sqrt{gh}$$

$\bar{I}_{0,x,max} = 1.0,$	First Row
$\bar{I}_{0,x,max} = 0.8,$	Sheltered Rows
$\bar{I}_{0,y,max} = 0.6,$	First Row

$$F_{r,x,max} = \frac{2\pi}{T_n} \bar{I}_{0,x,max} p_n \lambda(\xi) C_s$$

$$F_{r,y,max} = \frac{2\pi}{T_n} \bar{I}_{0,y,max} p_n \lambda(\xi) C_s \quad \lambda(\xi) = \exp\left(\frac{-\xi \cos^{-1} \xi}{\sqrt{1-\xi^2}}\right)$$

44

## Envelope Debris Loads From Present Work

$$I_0 = \bar{I}_0 p_n \qquad \bar{I}_{0,x,\max} = 1.0, \quad \text{First Row}$$

$$p_n = \mu u + m \frac{H_s}{2h} \sqrt{gh} \qquad \bar{I}_{0,x,\max} = 0.8, \quad \text{Sheltered Rows}$$

$$\qquad \qquad \qquad \bar{I}_{0,y,\max} = 0.6, \quad \text{First Row}$$

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45

## Envelope Debris Loads From Present Work

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$$F_{r,x,\max} = \frac{2\pi}{T_n} \bar{I}_{0,x,\max} p_n \lambda(\xi) C_s \quad \leftarrow C_s = 1.3$$

$$F_{r,y,\max} = \frac{2\pi}{T_n} \bar{I}_{0,y,\max} p_n \lambda(\xi) C_s \qquad \lambda(\xi) = \exp\left(\frac{-\xi \cos^{-1} \xi}{\sqrt{1-\xi^2}}\right)$$

$T_n = \text{Natural Period}$

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## ASCE7-22 Flood Loads

$$F = \frac{\pi W V_b C_I C_O C_D C_B R_{\max}}{2 g t_d}$$

47

## ASCE7-22 Flood Loads

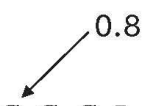
Often = 1


$$F = \frac{\pi W V_b C_I C_O C_D C_B R_{\max}}{2 g t_d}$$

48

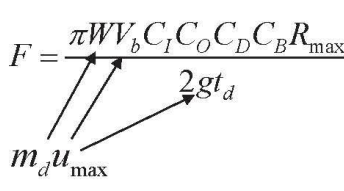
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## ASCE7-22 Flood Loads

$$F = \frac{\pi W V_b C_I C_O C_D C_B R_{\max}}{2 g t_d}$$


49

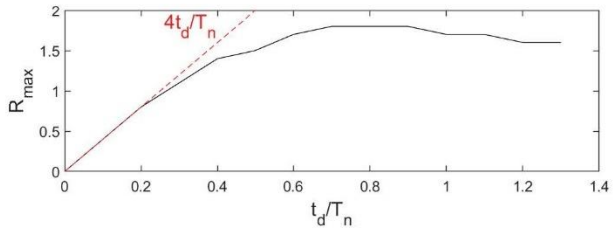
## ASCE7-22 Flood Loads

$$F = \frac{\pi W V_b C_I C_O C_D C_B R_{\max}}{2 g t_d}$$


50

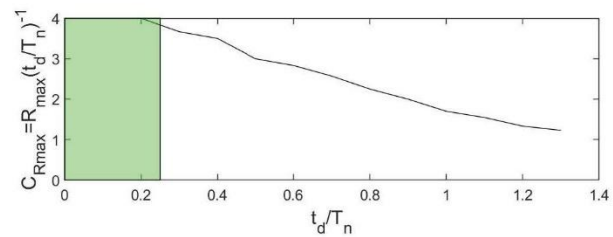
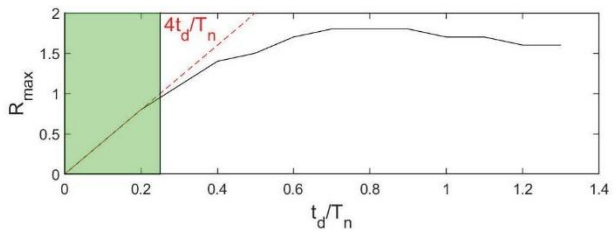
## ASCE7-22 Flood Loads

$$F = \frac{\pi W V_b C_I C_O C_D C_B R_{\max}}{2 g t_d} \rightarrow R_{\max}$$



## ASCE7-22 Flood Loads

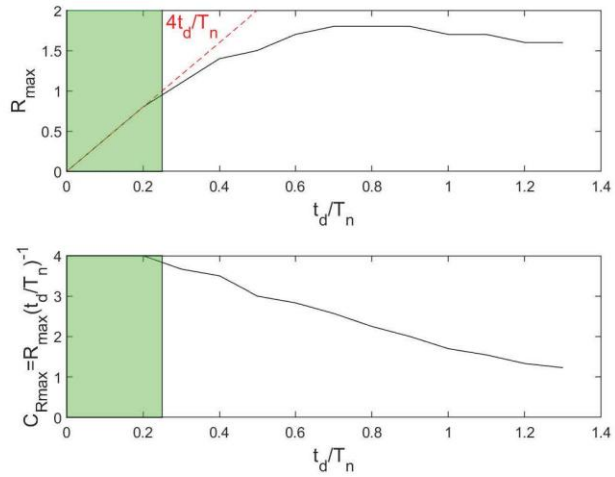
$$F = \frac{0.8 \pi m_d u_{\max} 4 t_d / T_n}{2 t_d} \rightarrow R_{\max}$$



## ASCE7-22 Flood Loads

$$F = \frac{0.8\pi m_d u_{\max} 4t_d / T_n}{2t_d} \rightarrow R_{\max}$$

$$F = \frac{1.6\pi m_d u_{\max}}{T_n} \approx \frac{5.03 I_0}{T_n}$$



## ASCE7-22 Tsunami Loads

$$\left. \begin{aligned} F_{ni} &= u_{\max} \sqrt{km_d} \\ F_{ni} &= 2m_d u_{\max} / t_d \end{aligned} \right\} \text{Maximum instantaneous load at point of impact}$$

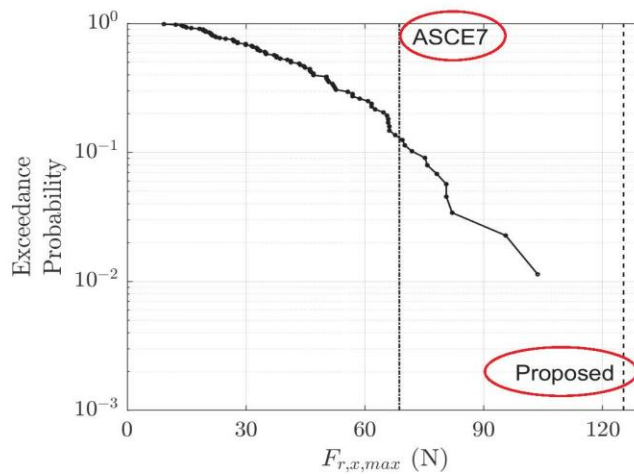
## Impulsive, Undamped Loads using $I_0=p_n$

Source	Simplified Equation for Impulsive Loading, Typical Coefficients, Undamped Structure
Derived from ASCE7-22 Flood	$F = 1.6\pi p_n / T_n \approx 5.03 p_n / T_n$
Derived from ASCE7-22 Tsunami	$F = 5.2 p_n / T_n$
Present recommendations	$F = 2.6\pi p_n / T_n \approx 8.17 p_n / T_n$

Coastal Inundation in Developed Regions: Experimental Results and Implications for Engineering Practice. ATC-149.

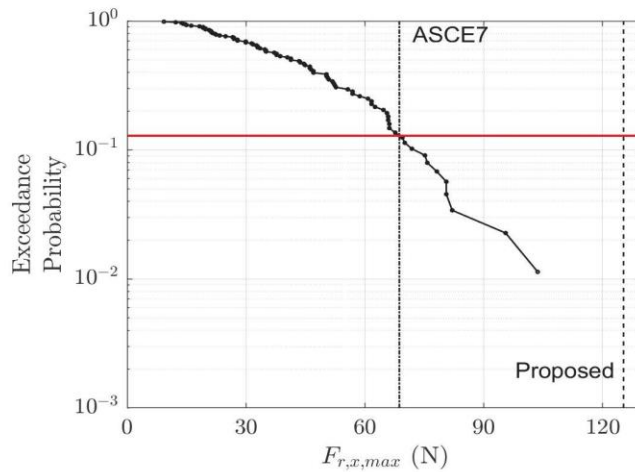
57

## Loads for First Row, Lightly Damped



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## Loads for First Row, Lightly Damped

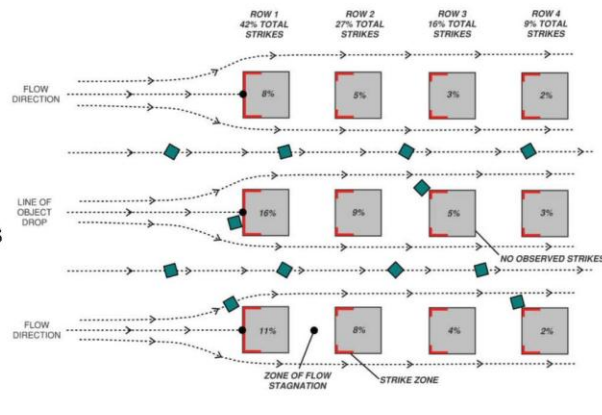


- ASCE7-22 flood equations are unconservative here at greater than 10%
  - Not acceptable
- Proposed relations appear conservative for low exceedance probabilities

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## Summary Debris Loading

- Debris loads have two major components:
  - Debris impulse transferred to structural system
  - Dynamic response of different components of structural system
- ASCE7 can sort of be put into this framework, but unconservative in its loads
- Debris loads are probabilistic, and will have x,y components even for unidirectional waves and currents



Cartoon of debris impacts

## Questions?



Funding for this work was provided by the National Science Foundation (Grants Numbers 1661015, 1727662) and the National Institute of Standards and Technology Grant Number 70NANB17H278).

## B.5 Thomas

### Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience



May 16-17, 2024  
Princeton University

## State of Structural Engineering Practice



Seth Thomas, P.E., S.E.  
KPFF Portland | SETH.THOMAS@KPFF.COM | 503-764-0554

## Outline

- Flood Load Code Structure
  - ASCE 7, ASCE 24, IBC
- Past/Current Design Requirements
  - ASCE 7-22/ASCE 7-14 and before
- Historical Code Design Issues
- Current practice
  - Local AHJ and Client approaches
- The Present & Near Future
  - ASCE 7-22/ASCE 24-24/IBC 2027
- Summary/Next Steps

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## Flood Load Code Structure

- Design of structures is controlled by three documents
  - IBC (or locally adopted version)
  - ASCE 7
  - ASCE 24



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## Flood Load Code Structure

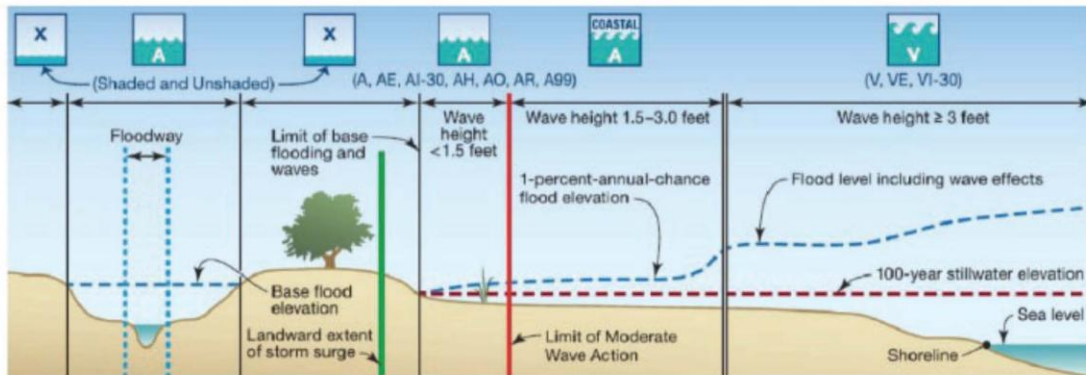
- ASCE 7 – Provides loading requirements
  - Defines flood depths/wave sizes/ect.
- ASCE 24 – Provides design requirements
  - Elevation requirements, floodproofing, ect.
- IBC - Provides charging language
  - Charges AHJ to define flood hazard area (minimum based on Flood insurance study)
  - Charging language for ASCE 24
  - Breakaway walls

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# Flood Zone Definitions

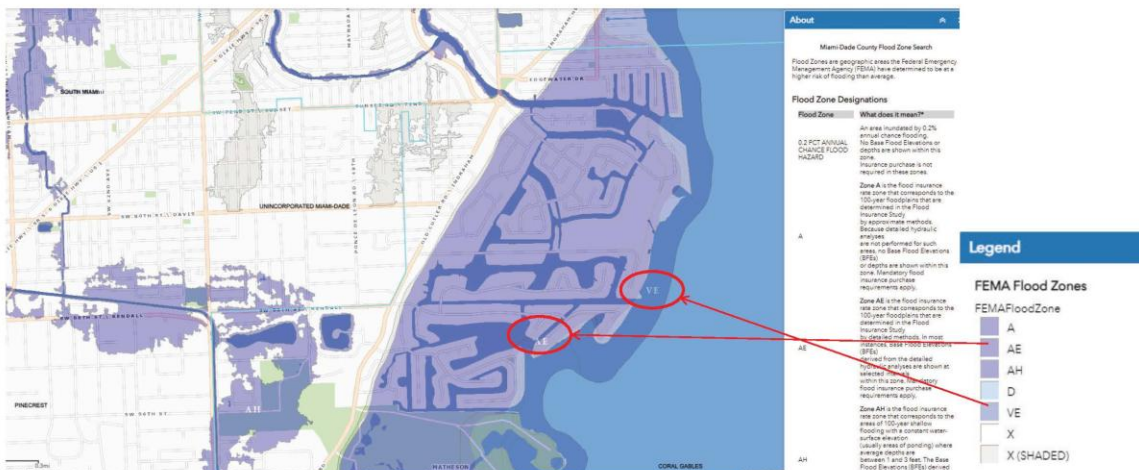


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# Flood Zone Definitions



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## Past/Current Design Requirements

- ASCE 7 Chapter 5
  - Basically unchanged for nearly 20years (7-05, 7-10, 7-16, 7-22)
  - Uses 100yr flood zone (plan area)
  - Uses 100 yr MRI flood load (+1ft for hydrostatic loads)
  - Wave loads assume full breaking waves for V-Zones and A-zones
  - Conservative (outdated) wave loading equations
  - Impact loads provide no guidance in provisions (all commentary)
  - No direct requirement for global buoyancy/sliding

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## Past/Current Design Requirements

- ASCE 24
  - Last published in 2014 (Coordinated with ASCE 7-10, IBC 2015)
  - Sets minimum elevation of occupied floor by design Flood Class (similar to risk categories)

See next page for description of Flood Design Classes →

		Flood Design Class 1	Flood Design Class 2	Flood Design Class 3	Flood Design Class 4
Minimum Elevation* of Lowest Floor (Zone A: ASCE 24-14 Table 2-1)	Zone A not identified as Coastal A Zone	DFE	BFE +1 ft or DFE, whichever is higher	BFE +1 ft or DFE, whichever is higher	BFE +2 ft or DFE, or 500-year flood elevation, whichever is higher
Minimum Elevation of Bottom of Lowest Horizontal Structural Member (Zone V: ASCE 24-14 Table 4-1)	Coastal High Hazard Areas (Zone V) and Coastal A Zone	DFE	BFE +1 ft or DFE, whichever is higher	BFE +2 ft or DFE, whichever is higher	BFE +2 ft or DFE, or 500-year flood elevation, whichever is higher

- Dry floodproofing requirements
- Foundation type requirements
- Break-away walls
- Flood resistant materials

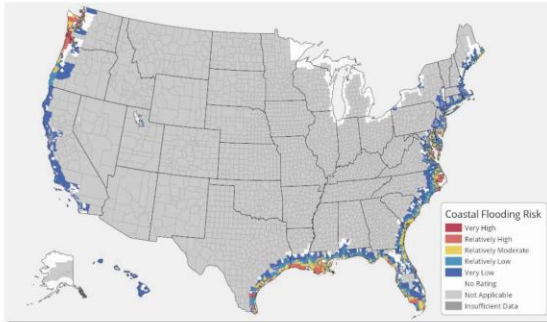
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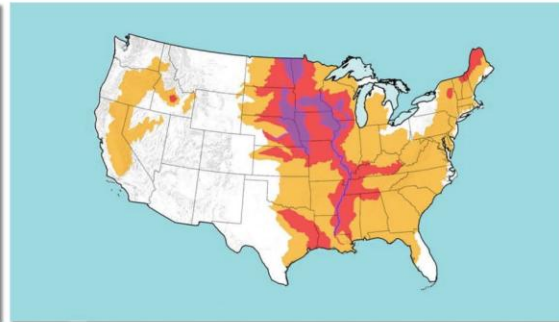


## Historical Code Design Issues

- Over 50% of population has at least moderate flood hazard



**Coastal Flooding Hazard**  
Approximately 40% of US population



**Riverine Flooding Hazard**  
Approximately 12% of US population

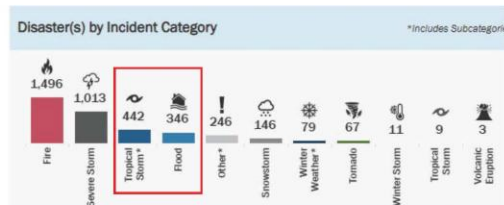
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## Historical Code Design Issues

- Large exposure of US population to Flood Hazard
  - 99% of US counties had flooding event (1996-2019)
  - 788 flood/tropical storm disaster declarations since 1990



<https://www.fema.gov/data-visualization/disaster-declarations-states-and-counties>

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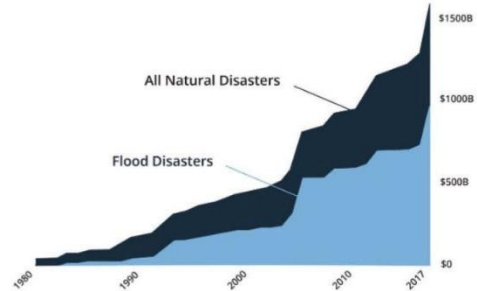
# Historical Code Design Issues

- 100yr base flood hazard leads to common exceedance
  - 30 yr. average flood damage ~ 2 Billion/yr
  - Since 1978-2012 NFIP has paid out 48.1 Billion

Number of properties at substantial flood risk\* by county in 2020<sup>7</sup>



<https://community.fema.gov/ProtectiveActions/s/article/Flood-Impact>  
<https://www.fema.gov/data-visualization/historical-flood-risk-and-costs>  
<https://www.flooddefenders.org/problem>



\$1 trillion since 1980 / \$850 billion since 2000<sup>1</sup>

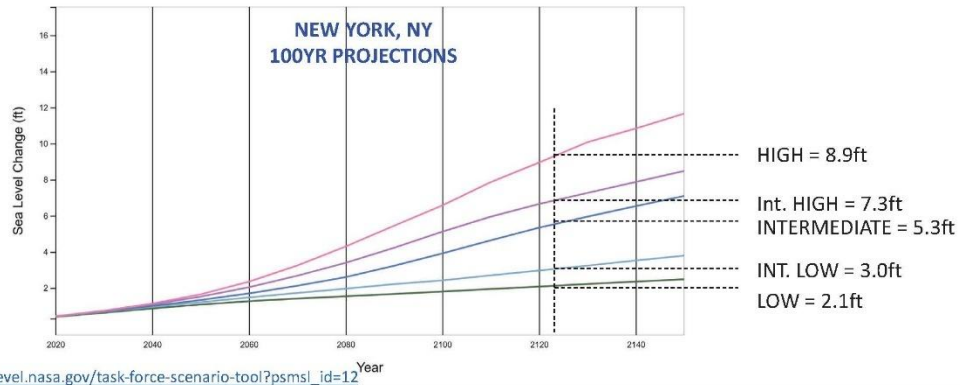
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# Historical Code Design Issues

- And its all getting worse with climate change



[https://sealevel.nasa.gov/task-force-scenario-tool?psmsl\\_id=12](https://sealevel.nasa.gov/task-force-scenario-tool?psmsl_id=12)

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## Historical Code Design Issues

- Historical Code Design Issue summary
  - Flood hazard impacts large portion of population
  - Code uses 100yr hazard plan area
    - 1% annual exceedance at site
  - Code uses 100yr flood depth
    - Sometimes minimal freeboard used
  - No national codified accounting for climate change
    - Sea level rise
    - Increase in storm intensity

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## Current Practice

- Recognizing the gap in design standards some owners are doing something different
  - Increase in freeboard requirements (up to 5ft or using 500yr MRI)
  - Accounting for sea level rise (Typically built in freeboard)
  - Specifying maximum leakage rates for dry floodproofing
- Typically the owners doing proactive flood design are not developers but institutional/agency/government

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## Current Practice

- Recognizing the gap in design standards some AHJ's are doing something different. Some examples:
  - Miami Beach, FL: 1' to 5' freeboard over BFE based on zone
  - Houston, TX: 500yr flood + 2ft freeboard
  - Norfolk, VA: BFE + 3ft and include 500yr flood plain
  - King County, WA: BFE + 3ft
  - South Kingston, RI: 100yr MRI + 5ft SLR
  - South San Francisco, CA: BFE + 3ft

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## The Present & Near Future

- Updated codes are (almost) here!
  - ASCE 7-22 Supplement #2 (published 5/2023)
  - ASCE 24-24 (fall 2024)
  - IBC 2027
- Significant changes to flood design methodology

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# The Present & Near Future: ASCE 7-22 Sup.

## 2 Existing (ASCE 7-16)

- 5.1 General
- 5.2 Definitions
- 5.3 Design Requirements
  - 5.3.1 Design Loads
  - 5.3.2 Erosion and Scour
  - 5.3.3 Loads on Breakaway Walls
- 5.4 Loads During Flooding
  - 5.4.1 Load Basis
  - 5.4.2 Hydrostatic Loads
  - 5.4.3 Hydrodynamic Loads
  - 5.4.4 Wave Loads
    - 5.4.4.1 Breaking Wave Loads on Vertical Piles or Columns
    - 5.4.4.2 Breaking Wave Loads on Vertical Walls
    - 5.4.4.3 Breaking Wave Loads on Non-Vertical Walls
    - 5.4.4.4 Breaking Wave Loads from Obliquely Incident Waves
    - 5.4.4.5 Impact Loads
- 5.5 Consensus Standards and Other Affiliated Criteria

## Update (ASCE 7-22)

- 5.1 General
- 5.2 Definitions and Symbols
  - 5.2.1 Definitions
  - 5.2.2 Symbols
- 5.3 Design Requirements
  - 5.3.1 Flood Hazard Area
  - 5.3.2 Design Loads
  - 5.3.3 Design Stillwater Flood Depth
    - 5.3.3.1 Stillwater Elevation Determination When Data Not Available Beyond the 100-year Flood
  - 5.3.4 Effects of Relative Sea Level Change
  - 5.3.5 Erosion
  - 5.3.6 Flood Velocity
    - 5.3.6.1 Flood Velocity in Coastal Areas
    - 5.3.6.2 Flood Velocity in Riverine Areas
  - 5.3.7 Wave Effects
    - 5.3.7.1 Wave Height
    - 5.3.7.2 Wave Period and Wavelength
  - 5.3.8 Scour
    - 5.3.8.1 Scour at Walls
      - 5.3.8.1.1 Scour at Walls Due to Nonbreaking Waves
      - 5.3.8.1.2 Scour at Walls Due to Breaking Waves
    - 5.3.8.2 Scour at Vertical Piles and Columns
  - 5.3.9 Debris
    - 5.3.9.1 Debris Impact
      - 5.3.9.1.1 Debris Impact Objects
      - 5.3.9.1.2 Site Hazard Assessment for Localized Marine Debris, Shipping Containers, Ships, Small Vessels, and Barges
      - 5.3.9.1.3 Extraordinary Debris Impact Loading
    - 5.3.9.2 Debris Damming
  - 5.3.10 Loads on Breakaway Walls
  - 5.3.11 Site-Specific Studies
  - 5.3.12 Performance Based Design

- 5.4 Loads During Flooding
  - 5.4.1 Load Basis
  - 5.4.2 Hydrostatic Loads
    - 5.4.2.1 Vertical Hydrostatic Force
    - 5.4.2.2 Lateral Hydrostatic Force
    - 5.4.2.3 Seepage
  - 5.4.3 Hydrodynamic Loads
  - 5.4.4 Wave Loads
    - 5.4.4.1 Wave Loads on Vertical Piles or Columns
      - 5.4.4.1.1 Non-breaking Wave Loads on Vertical Piles or Columns
      - 5.4.4.1.2 Breaking Wave Loads on Vertical Piles or Columns
    - 5.4.4.2 Lateral Wave Loads on Walls
      - 5.4.4.2.1 Lateral Non-breaking Wave Loads on Non-elevated Vertical Walls
      - 5.4.4.2.2 Lateral Breaking Wave Loads on Non-elevated Vertical Walls
    - 5.4.4.3 Lateral Breaking Wave Loads on Non-Vertical Walls
    - 5.4.4.4 Lateral Breaking Wave Loads from Obliquely Incident Waves
    - 5.4.4.5 Lateral Wave Loads on Walls of Elevated Walls
  - 5.4.4.3 Wave Uplift Forces on Elevated Structures and Non-Elevated Structures with Overhangs
  - 5.4.5 Debris Impact Loads
    - 5.4.5.1 Debris Impact Load Determination
      - 5.4.5.1.1 Simplified Debris Impact Load for Passenger Vehicles or Small Vessels
      - 5.4.5.1.2 Elastic Debris Impact Loads
      - 5.4.5.1.3 Alternate Methods of Debris Impact Analysis
    - 5.4.5.2 Debris Types and Properties
    - 5.4.5.3 Extraordinary Debris Impact
    - 5.4.5.4 Debris Impact Load Redistribution
- 5.5 Flood Load Cases
  - 5.5.1 Stability for Global Uplift
  - 5.5.2 Stability for Global Sliding
- 5.6 Consensus Standards and Other Affiliated Criteria

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# The Present & Near Future: ASCE 7-22 Sup.

## 2

### Scope Comparison: Flood Hazard Area & Design Depths

### Existing (ASCE 7-22)

- 100-yr floodplain for flood area for all structures
- 100-yr flood as basis for flood hazard
  - Design Flood Elevation
  - Addition of wave height
  - Addition of 1 ft freeboard

### Updated (ASCE 7-22 Supplement 2)

- 500-yr floodplain for flood area for RC II, III, and IV
  - ✓ 100-yr floodplain for RC I (no change)
- MRI based flood hazard
  - ✓ consistent with other chapters (Seismic, Wind)

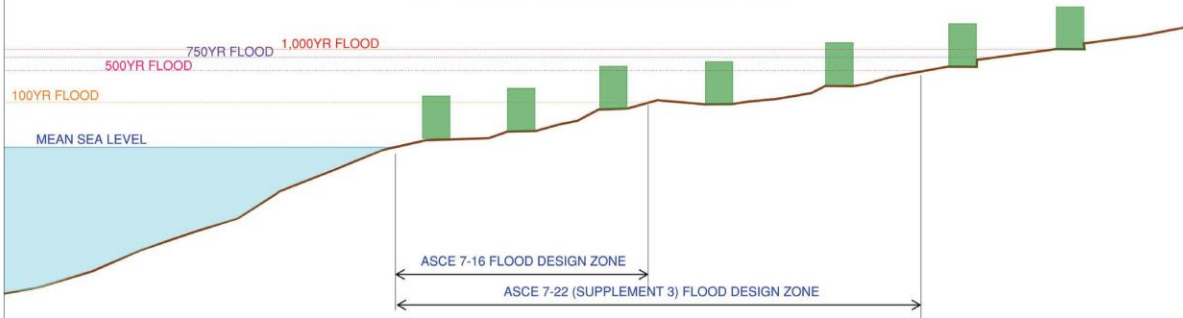
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# The Present & Near Future: ASCE 7-22 Sup. 2

Scope Comparison: Flood Hazard Area



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# The Present & Near Future: ASCE 7-22 Sup. 2

Scope Comparison: Flood Hazard Area



100yr vs. 500y flood zone example

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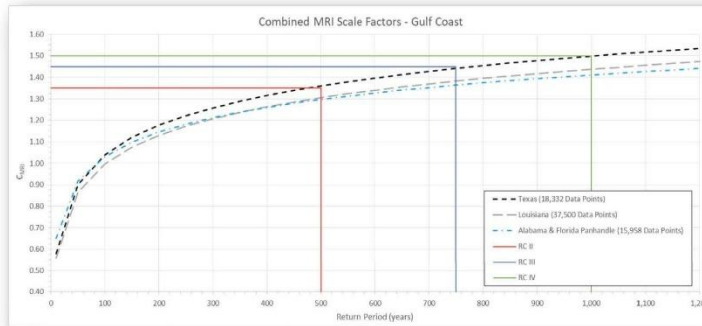
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# The Present & Near Future: ASCE 7-22 Sup. 2

## Scope Comparison: Flood Design Depths

- Risk Category Based MRI's
  - RC I – 100yr
  - RC II – 500yr
  - RC III – 750yr
  - RC IV – 1,000yr



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# The Present & Near Future: ASCE 7-22 Sup. 2

- Updated guidance on velocity and wave determination
- Loading Equations:
  - Expanded guidance for loading equations
  - Significant updates to loading equations and expanded guidance
- Expansion of requirements for Debris impacts/damming
- Requirement for inclusion of historical SLR in design
- Alignment of load combinations with updated hazard/equations

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## The Present & Near Future: ASCE 24-24

- Alignment of provisions with ASCE 7-22 supplement #2
  - Changing horizontal extent to 500 yr flood plain
  - Changing elevation, not exactly the same as ASCE 7, but similar
  - Include climate change provisions
- Make changes that weren't done in the last cycle
- Get these changes done in time for adoption IBC 2027 (by 6/1/24)

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## Summary/Next Steps

- ASCE 7-22/ASCE 24-24 take large step forward in improving performance of structures in floods.
- Need to ensure local adoption and enforcement of improved flood provisions
  - Residential is next large scope that needs addressed
- Still a lot of improvement to be made.
  - ASCE 7-28 proposal list is long but includes research needs
  - Improved mapping
  - Future Conditions (7-28 chapter 36)

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## B.6 Tomiczek

### Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience



May 16-17, 2024  
Princeton University

#### State of the Practice: Damage Classification, and Fragility Quantification for Structural Design for Coastal Flood Hazard Resilience

Lessons Learned from Case Studies  
and Post-Event Reconnaissance

*Tori Tomiczek, US Naval Academy*  
*vjohnson@usna.edu*



Hurricane Sandy, Toms River, NJ

### Outline

- Introduction
- What can we learn from case studies (focusing on residential infrastructure)?
  - Understanding hazard conditions, performance, and structural fragility
  - Standardizing damage assessment
  - Leveraging technology to capture ephemeral data
- The future of case studies
  - Longitudinal studies - functionality and recovery
  - Opportunities for AI-training
- Summary and conclusions



## Introduction

September 9, 2008



3

## Introduction

September 15, 2008



4

## Introduction

- Coastal flood hazards are getting worse
- How to mitigate damage from hazard events?

### NOAA Billion Dollar Weather and Climate Disasters

Event	Year	Cost (2024 USD)
Hurricane Katrina	2005	\$198.8 billion
Hurricane Harvey	2017	\$158.8 billion
Hurricane Ian	2022	\$117.4 billion
Hurricane Maria	2017	\$114.3 billion
Hurricane Sandy	2012	\$87.8 billion
Hurricane Ida	2021	\$83.9 billion
Hurricane Irma	2017	\$63.5 billion
Hurricane Andrew	1992	\$59.9 billion
US Drought/Heat Wave	1988	\$54.0 billion
Midwest Flooding	1993	\$45.9 billion



Hurricane Ian death toll now more than 100 after storm slams into Florida, North Carolina

The Washington Post

Puerto Rico entirely without power as Hurricane Maria hammers island with devastating force

SANDY STRIKES

Frankenstorm's trail of ruin

The New York Times

Hurricane Irma, One of the Most Powerful in History, Roars Across Caribbean

Hurricane Ida: One million people in Louisiana without power

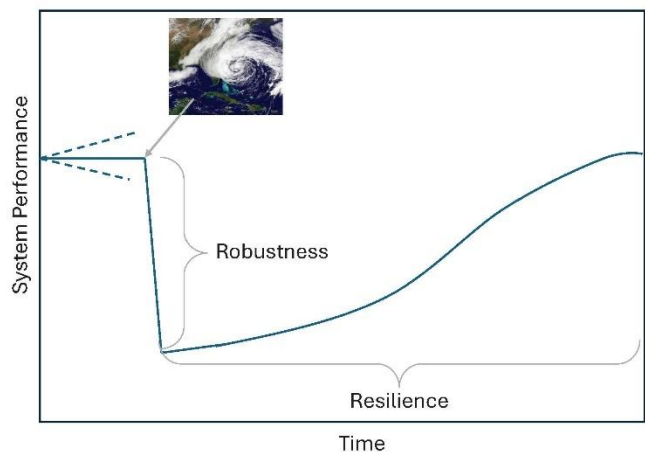
BBC

The ferocity of Hurricane Otis stunned hurricane experts and defied forecast models. © CBS NEWS

5

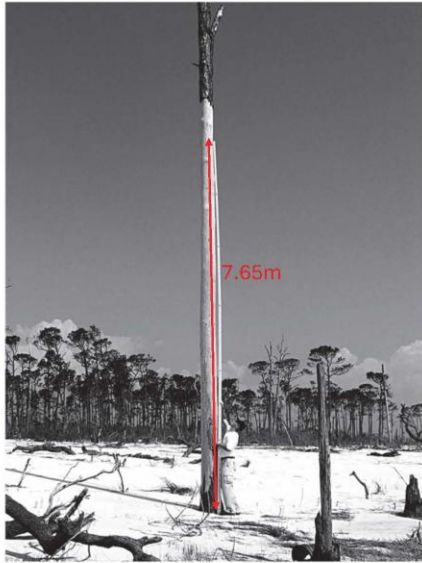
## Case Studies – What Can We Learn?

- Opportunity to capture ephemeral data on structural performance during storms
- Determine damage levels to inform recovery efforts, design & construction practices
- Monitor recovery timelines and assess resilience



6

## Assessing the Hazard

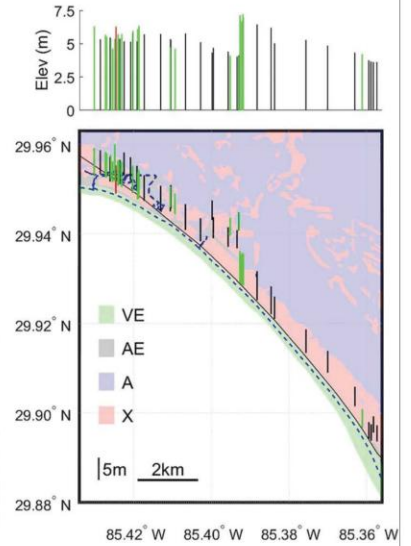


### High Water Mark measurement after Hurricane Katrina (2005)

Fritz, H.M., Blount, C., Sokoloski, R., Singleton, J., Fuggle, A., McAdoo, B.G., Moore, A., Grass, C., and Tate, B. (2008). "Hurricane Katrina Storm Surge Reconnaissance." *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 134 (5). [https://doi.org/10.1061/\(ASCE\)1090-0241\(2008\)134:5\(644\)](https://doi.org/10.1061/(ASCE)1090-0241(2008)134:5(644))

### High Water Mark measurement after Hurricane Michael (2018)

Kennedy, A.B., Copp, A., Florence, M., Gradel, A., Gurley, K., Janssen, M., Kaihatu, J., Krafft, D., Lynett, P., Owensby, M., Pinelli, J.P., Prevatt, D.O., Rogers, S., Roueche, D., and Silver, Z. (2008). "Hurricane Michael in the Area of Mexico Beach, Florida." *ASCE J. Waterway, Port, Coastal, Ocean Eng.*, 2020, 146(5): 05020004. [https://doi.org/10.1061/\(ASCE\)WW.1943-5460.0000590](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000590).



## Assessing Hazard Impacts

- Hurricane Ike (2008)
  - Understand relationship between environmental conditions, forces, and structural damage
  - Field + remote sensing data to evaluate damage to 1922 residential wood-framed structures
  - Generally, binary damage states (survive/fail) observed

Classification	Surviving	Destroyed	Wave Damaged
Total	1126	779	17

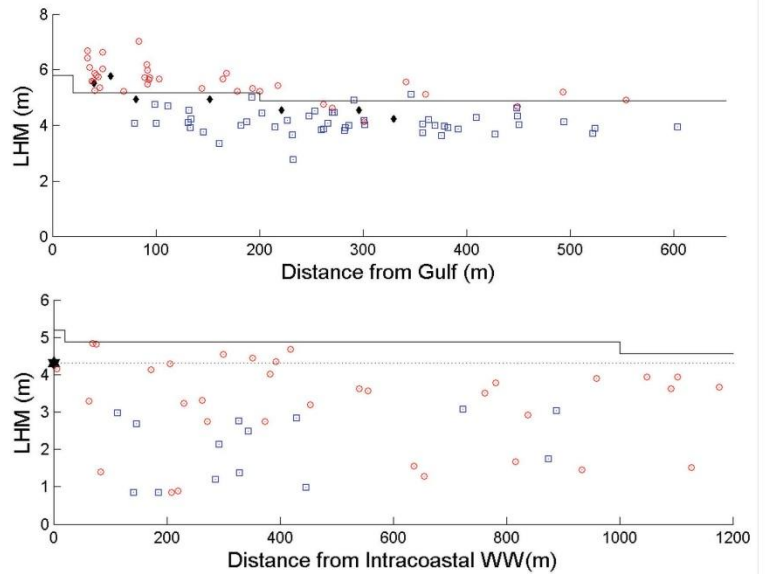


## Identifying Parameters Associated With Failure

- Near Gulf (large waves) – small elevation threshold between survival and failure
- Back Bay (smaller waves) – elevation is less important

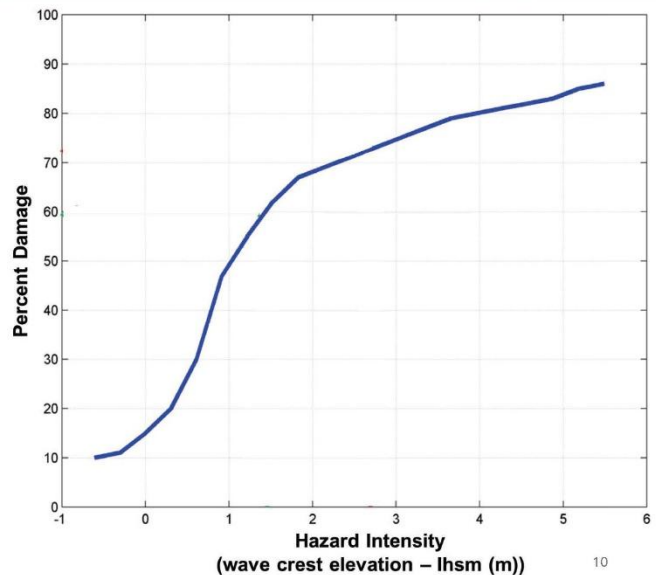
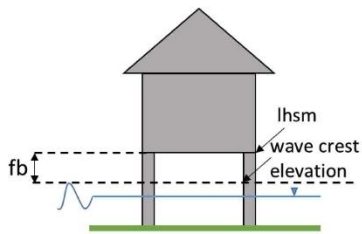
Kennedy, A.B., Dosa, M., Zarama, F., Gravois, U., Roger S., Sallenger, A. (2011). "Inundation and destruction of the Bolivar Peninsula during Hurricane Ike." Coastal Engineering Proceedings, 32 (2010). <https://doi.org/10.9753/icce.v32.management.15>

Kennedy, A.B., Rogers, S., Sallenger, A., Gravois, U., Zachry, B., Dosa, M., and Zarama, F. (2010). "Building Destruction from Waves and Surge on the Bolivar Peninsula during Hurricane Ike," J. Waterway, Port, Coastal and Ocean Eng.-ASCE, in press, doi:10.1061/(ASCE)WW.1943-5460.0000061.



## Assessing Damage Prediction

- Depth-Damage Curves
- FEMA: CCM/Hazus damage predictions
- Similar curves from USACE, others

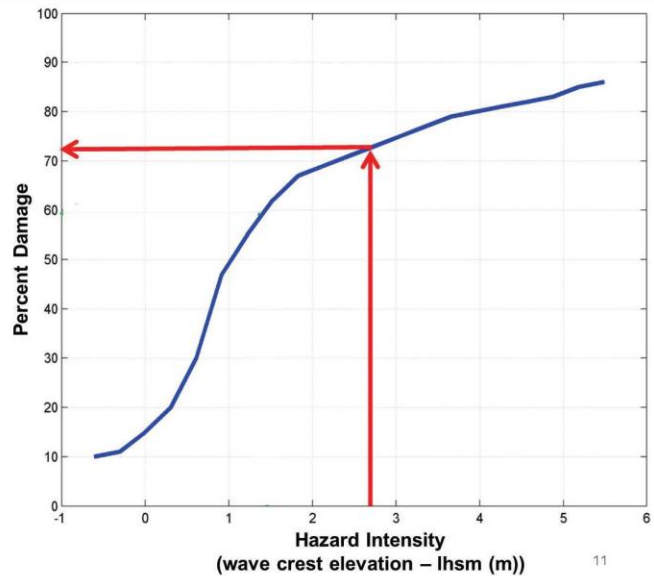


## Assessing Damage Prediction

- FEMA Depth – Damage Curves
  - Predicted damage during Hurricane Ike

**Case 1:**

- Wave crest – lism: 2.7 m
- Predicted Damage: 72%



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## Assessing Damage Prediction

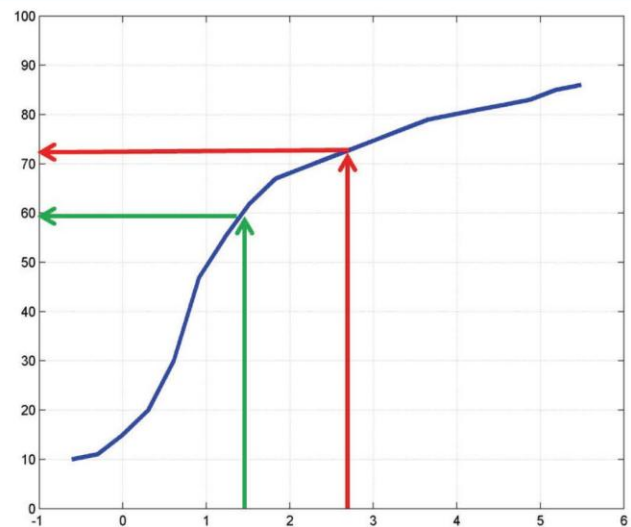
- FEMA Depth – Damage Curves
  - Predicted damage during Hurricane Ike

**Case 1:**

- Wave crest – lism: 2.7 m
- Predicted Damage: 72%

**Case 2:**

- Wave crest – lism: 1.5 m
- Predicted Damage: 60%



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## Assessing Damage Prediction

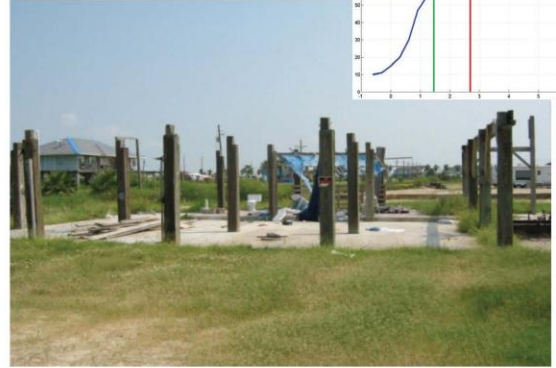
- Observed damage after Hurricane Ike

**Case 1: Predicted Damage: 72%**



- Wave crest – l<sub>hsm</sub> = 2.7 m
- Interior water damage, minimal structural damage
- Significant Wave Height: 0.99 m

**Case 2: Predicted Damage 60%**



- Wave crest – l<sub>hsm</sub> = 1.5 m
- Completely destroyed (100% Damage)
- Significant Wave Height: 1.37 m

Tomiczek, T., Kennedy, A. B., and Rogers, S. (2012). "Survival Analysis of Elevated Homes on the Bolivar Peninsula after Hurricane Ike." ATC/SEI Advances in Hurricane Engineering Conference. 13

## Fragility Development

- Fragility development – assume damage is normally distributed
- Backwards multiple regression to identify important variables

**Table 1.** Residual Variances for Fragility Regressions

Regression variant	$H_S$ (m)	$FB_{H_h}$ (m)	Age group	$V_{H2O}$ (m/s)	All FEMA/ASCE loads	Modified slamming load ( $H_{1/250}$ )	Relative residual variance $RY^2$
1			X		X		0.634
2			X	X			0.7612
3		X	X	X			0.5647
4	X	X	X	X			0.3618
5	X	X	X				0.3909
6			X			X	0.3921
Data range	(0.75, 2.23)	(-4.0, 1.8)	(1, 2, 3, 4)	(0.43, 1.61)			
Useful regression limits	(0.8:2)	(-3: 1)	(1, 2, 3, 4)	(0.5:1.5)			

Note: X's denote variables used in each regression variant.

- Consider multiple variables: significant wave height, freeboard, age of structure, water velocity, FEMA wave slamming load

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## Understanding Structural Performance

- Fragility development

**Table 1.** Residual Variances for Fragility Regressions

Regression variant	$H_s$ (m)	$FB_{H_s}$ (m)	Age group	$V_{H2O}$ (m/s)	All FEMA/ ASCE loads	Modified slamming load ( $H_{1/250}$ )	Relative residual variance $RY^2$
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Useful regression limits	(0.8:2)	(-3: 1)	(1, 2, 3, 4)	(0.5:1.5)			

Note: X's denote variables used in each regression variant.

1. Age + ASCE/FEMA equations show some skill, but fairly large residual
2. Age +  $V_{H2O}$  gives worse agreement (wave height is important)
3. Age +  $V_{H2O}$  + FB improves skill somewhat
4. Age +  $V_{H2O}$  + FB +  $H_s$  shows best overall skill
5. Age + FB +  $H_s$  shows good skill ( $V_{H2O}$  does not add as much as  $H_s$ )
6. Mod. Slamming Force shows good skill

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## Understanding Structural Performance

- Fragility development

**Table 1.** Residual Variances for Fragility Regressions

Regression variant	$H_s$ (m)	$FB_{H_s}$ (m)	Age group	$V_{H2O}$ (m/s)	All FEMA/ ASCE loads	Modified slamming load ( $H_{1/250}$ )	Relative residual variance $RY^2$
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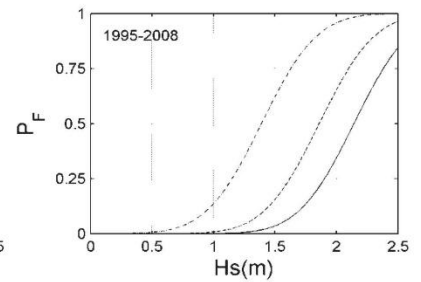
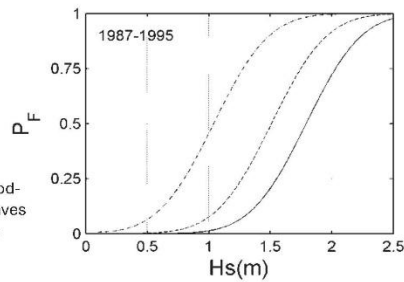
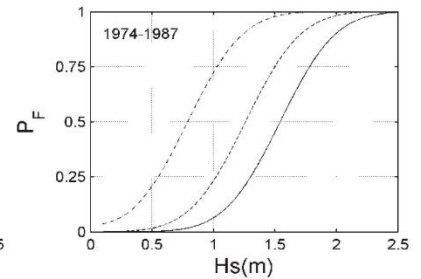
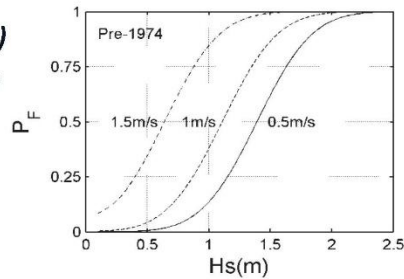
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6. Mod. Slamming Force shows good skill

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## Empirical (Data-Driven) Fragilities

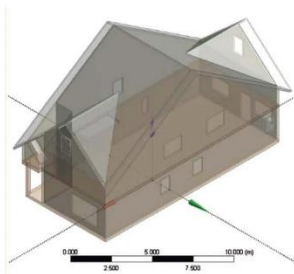
$$P_F = \Phi(\text{Age}, V_{H2O}, H_s, fb_{Hs})$$

$$r^2 = 0.638$$



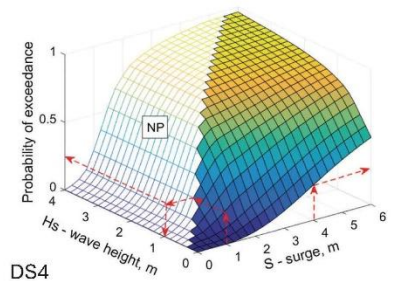
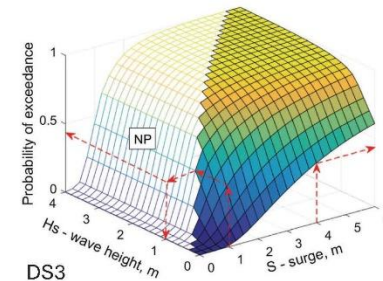
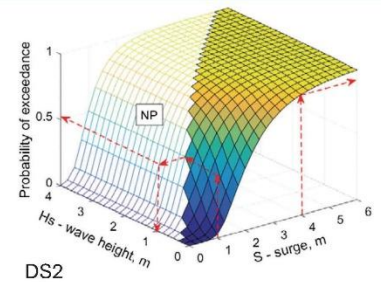
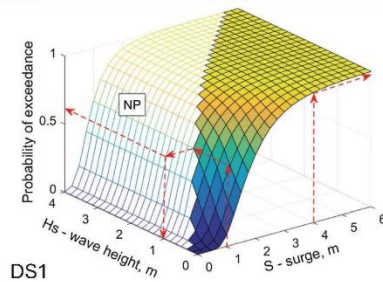
Tomiczek, T., Kennedy, A.B., and Rogers, S. (2012). "Collapse Limit State Fragilities of Wood-Framed Residences from Storm Surge and Waves during Hurricane Ike." ASCE J. Waterway, Port, Coastal, and Ocean Eng., 140 (1), 10.1061/(ASCE)WW.1943-5460.0000212.

## Physics-Based Fragilities



- Combine CFD with structural analysis to estimate fragility for 4 damage states.

Do, T.Q., van de Lindt, J.W., Cox, D.T. (2019). Hurricane Surge-Wave Building Fragility Methodology for Use in Damage, Loss, and Resilience Analysis. J Struct Eng 146(1): [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0002472](https://doi.org/10.1061/(ASCE)ST.1943-541X.0002472).

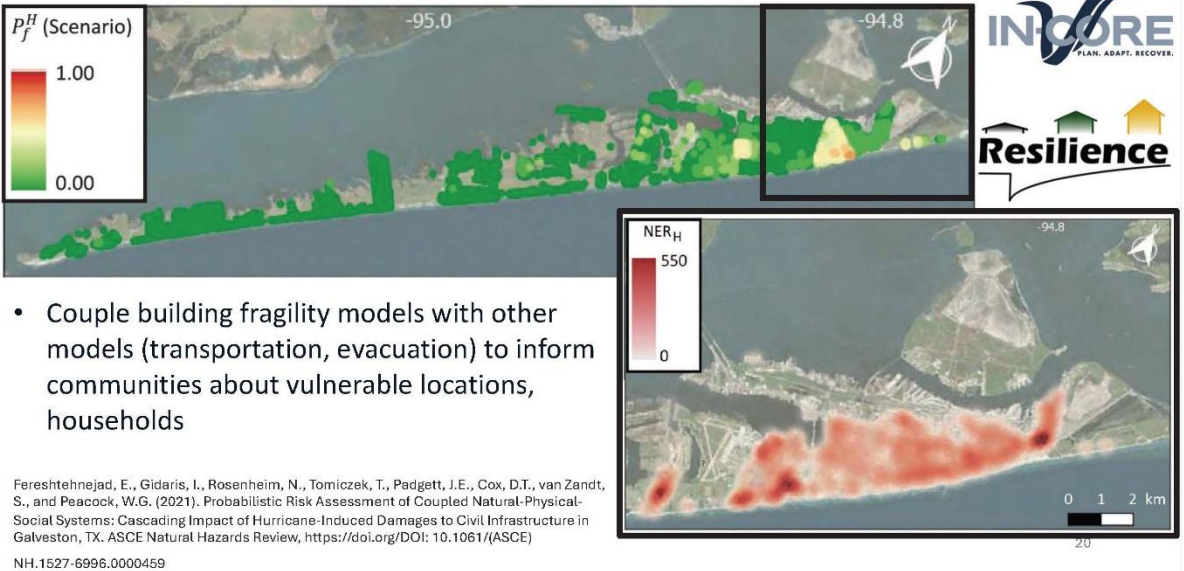


## A Suite of Building Fragility Functions

Source	Flood Type		Hazard Intensity				Structure features								Fragility Development				Overall Status			
	Coastal	Riverine	Surge depth, S	Significant wave height, Hs	Overland flow speed, U	Flood duration, T	3-s gust wind speed, U <sub>max</sub>	Distance shore	Archetype	Occupancy	Material	Elevation	Age	Basement	Foundation type	Number of story	Footprint area/shape	Type	Event/Source	Regression model	Damage state	Single-variable
Tomiczek et al. (2014)	✓	✓	✓	✓	✓	✓	✓		R	W	LHSM	✓	✓	✓	✓	✓	Emp.	Ike (2008), N=2,000	Normal	Binary	✓	✓
FEMA HAZUS (2009)	✓	✓	✓	✓	✓	✓	✓		R, C, P, I <sup>a</sup>	W, C, S, M <sup>b</sup>	FFE	✓	✓	✓	✓	✓	Emp.	FIMA claims data <sup>c</sup>	-	N/A	✓	✓
USACE NACSS (2006, 2015)	✓	✓	✓	✓	✓	✓	✓		R, C <sup>d</sup>	W, C, S, M <sup>b</sup>	FFE	✓	✓	✓	✓	✓	Emp.	Sandy (2012), w/ interviews <sup>d</sup>	-	N/A	✓	✓
Hatzikyriakou et al. (2016)	✓	✓	✓	✓	✓	✓	✓		R	W, M	LHSM	✓	✓	✓	✓	✓	Emp.	Sandy (2012), N=638	Logistic	DS1-DS5	✓	✓
Massarra et al. (2019)	✓	✓	✓	✓	✓	✓	✓		R	W	W	✓	✓	✓	✓	✓	Emp.	Katrina (2005), N=866	Logistic	DS1-DS3 <sup>e</sup>	✓	✓
Massarra et al. (2020)	✓	✓	✓	✓	✓	✓	✓		R	W	FFE	✓	✓	✓	✓	✓	Emp.	Katrina (2005), N=866	Logistic	DS1-DS3 <sup>e</sup>	✓	✓
Amini et al. (2024)	✓	✓	✓	✓	✓	✓	✓		R, C	W, C	LHSM	✓	✓	✓	✓	✓	Emp.	Iran (2022); N=3,118	Logistic/Lognormal	DS1-DS5	✓	✓
Amadio et al. (2019)	✓	✓	✓	✓	✓	✓	✓		R	M, C	-	✓	✓	✓	✓	✓	Emp.	North Italy <sup>f</sup> ; N=1158	Square root/ML	N/A	✓	✓
Nofal and van de Lindt (2020a,b)	✓	✓	✓	✓	✓	✓	✓		R, C, P, I <sup>a</sup>	W, C, S, M <sup>b</sup>	-	✓	✓	✓	✓	✓	Num.	N/A	Lognormal	DS1-DS5	✓	✓
van de Lindt and Taggart (2009)	✓	✓	✓	✓	✓	✓	✓		R	W	-	✓	✓	✓	✓	✓	Num.	N/A	-	N/A	✓	✓
Do et al. (2020, 2024)	✓	✓	✓	✓	✓	✓	✓		R <sup>g</sup>	W <sup>h</sup>	FFE	✓	✓	✓	✓	✓	Num.	ANSYS Fluent	General model	DS1-DS4	✓	✓
Pita et al. (2021)	✓	✓	✓	✓	✓	✓	✓		R <sup>g</sup>	M <sup>g</sup>	-	✓	✓	✓	✓	✓	Exp.	Expert interview <sup>g</sup>	Exponential	DS1-DS4 <sup>h</sup>	✓	✓
Godfrey et al. (2015)	✓	✓	✓	✓	✓	✓	✓		R	W	-	✓	✓	✓	✓	✓	Exp.	Vulnerability index <sup>h</sup>	-	-	✓	✓
Gomariz et al. (2021)	✓	✓	✓	✓	✓	✓	✓		R	W	-	✓	✓	✓	✓	✓	Exp.	Vulnerability index <sup>h</sup>	-	-	✓	✓

Amini, M., Figueira, S.A., Cox, D.T., Barbosa, A.R., Luettich, R.A., Bilskie, M.V., and Cobell, Z. (in preparation). Model-Data Validation of the IN-CORE Damage Model for Buildings Impacted by Hurricane Surge and Waves. International Journal of Disaster Risk Reduction. ELSEVIER.

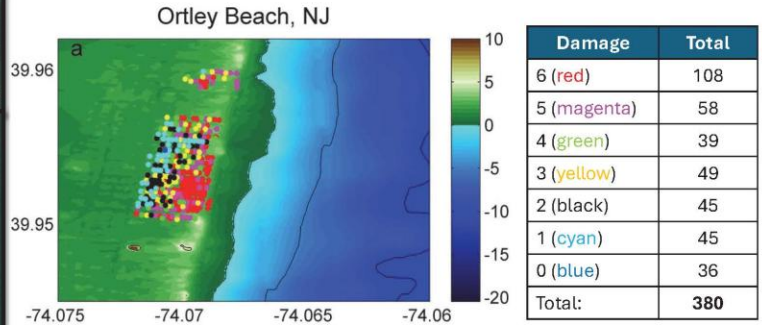
## Use of Fragilities to Inform Communities about Vulnerability



## Unexpected Observations – Sheltering by Structures

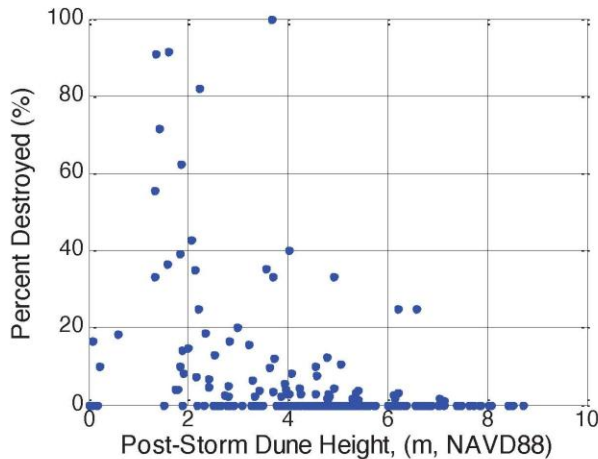


- Structures sheltered by dunes and other structures experienced less damage than unsheltered structures during Hurricane Sandy.



Tomiczek, T., Kennedy, A., Zhang, Y., Owensby, M., Hope, M.E., Lin N. (2017). Hurricane Damage Classification Methodology and Fragility Functions Derived from Hurricane Sandy's Effects in Coastal New Jersey. ASCE J. Waterway, Port, Coastal, and Ocean Eng., 10.1061/(ASCE)WW.1943-5460.0000409.

## Unexpected Observations – Sheltering by Dunes, Seawalls



- Regional-scale analysis of New Jersey, Long Island, Staten Island coastlines
- All houses one block from shore
- Post-storm dune height below 3m → large destruction rates



Coastal Engineering  
Volume 80, October 2013, Pages 79-82



Short communication

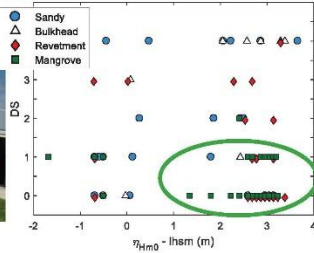
### Buried relic seawall mitigates Hurricane Sandy's impacts

Jennifer L. Irish<sup>a</sup>, Patrick J. Lynett<sup>b</sup>, Robert Weiss<sup>c</sup>,  
Stephanie M. Smallegan<sup>a</sup>, Wei Cheng<sup>c</sup>

Tomiczek, T., Kennedy, A., Zhang, Y., Owensby, M., Hope, M.E., Lin N. (2017). Hurricane Damage Classification Methodology and Fragility Functions Derived from Hurricane Sandy's Effects in Coastal New Jersey. ASCE J. Waterway, Port, Coastal, and Ocean Eng., 10.1061/(ASCE)WW.1943-5460.0000409.

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## Unexpected Observations – Sheltering by Vegetation



Tomiczek, T., O'Donnell, K., Furman, K., Webbmartin, B., and Scyphers, S. (2020). Rapid Damage Assessments of Shorelines and Structures in the Florida Keys after Hurricane Irma. ASCE Natural Hazards Review. 21 (1). [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000349](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000349)

- Structures sheltered by emergent vegetation experienced less damage than unsheltered structures in recent extreme events.

Figure Credit: Andrew Kennedy, Kwasi Perry



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## Need Consistent, Objective Damage Assessments

- Important to ensure consistency among assessment teams
- Allow for robust fragility development, comparison across regions, hazards, geographies



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# Objective Methods for Damage Assessment



Damage State	Qualitative Wind Damage Description	Qualitative Surge/Flood Damage Description	Roof Cover Damage	Window/Door Damage	Roof Deck Failure	Foundation Damage	Apparent Structure Damage	Wall Cladding Damage	Wall Structure Failure	Roof Structure Failure	Structural Damage	'Softest' Floor Layer
WF-0	No Damage or Very Minor Damage Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.	No Damage or Very Minor Damage No floodwater impacts the building.	<2%	No	No	No	No	No	No	No	No	None
WF-1	Minor Damage Maintenance of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching (or repair).	Minor Damage Breakaway walls in apartment structures, (staircases, corridors, etc.) damaged or removed without physical damage to remaining structure. No floodwater impacts the building.	>1% and <15%	One window, door or garage door failure.	No	Shaly pile scour with no apparent building damage	Yes, without damage to building	Minor cladding damage with building wrap intact	No	No	No	None
WF-2	Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some missing damage to interior of building from water.	Moderate Damage Some wall cladding damage from floodwater debris or high velocity floodwater. Breakaway walls or apartment structures (staircases, corridors, etc.) damaged or removed (i.e.) physical damage to remaining structure.	>15% and <50%	> one and < the larger of 20% & 3	1 to 3 panels	Yes	Yes, with damage to building	Moderate cladding damage that does not expose structure interior, building wrap not intact	No	No	No	> 0 ft and < 2 ft from story or < 2 ft (three stories)
WF-3	Severe Damage Major window damage or roof sheathing loss. Major roof cover loss. Parasitic damage to interior from water.	Severe Damage Removal of cladding from "wash through" of surge without wall structural damage.	>50%	> the larger of 20% & 3 and <30%	>3 and <25%	Yes	Yes	"Wash through" damage	No	No	No	> 2 ft from story or > 4 ft (three stories)
WF-4	Very Severe Damage Complete roof failure and/or failure of wall frame. Loss of more than 25% of roof sheathing.	Very Severe Damage Failure of wall frame, irreparable structural damage to any portion of the building or loss of irreparable structural damage, not to exceed 25% of the building plan area.	Typically >50%	>50%	>55%	Cracked slab with visible deformation	Yes	Yes	Yes	Yes	Yes	Any irreparable structural damage or >25% unreparable damage
WF-5	Partial Collapse House without foundation, overall structure sinking, irreparable structural damage (structure still partly intact).	Partial Collapse House without foundation, overall structure sinking, irreparable structural damage to >25% of the building plan area. Structure is still partly intact.	Typically >50%	>50%	>55%	Stacking of skewed structure	Yes	Yes	Yes	Yes	Yes	Irreparable structural damage (>25%)
WF-6	Total structural failure (no intact structure).	Collapse Total structural failure (no intact structure).	Typically >50%	>50%	>55%	Yes	Yes	Yes	Yes	Yes	Yes	Total structural failure

C. J. Friedland. 2009. Residential building damage from hurricane storm surge: proposed methodologies to describe, assess and model building damage, PhD Thesis, Louisiana State University, 2009.

Friedland, C.J., and Levitan, M. (2009). Loss-Consistent Categorization of Hurricane Wind and Storm Surge Damage for Residential Structures. Proceedings of the 11th Americas Conference on Wind Engineering, San Juan, Puerto Rico

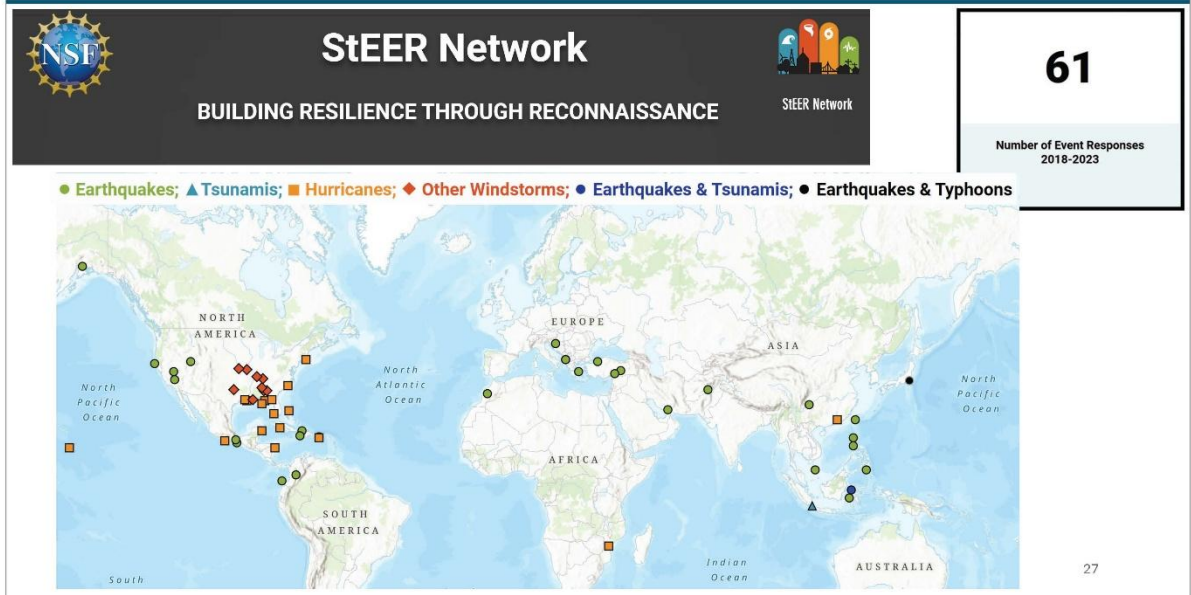
# Standardizing Damage Assessment

Component	No Damage		Minor		Moderate		Major		Destroyed	
	0	1	2	3	4	5	6			
Roof	No visible damage	Very few shingles missing (<15% of roof area) Damage to gutters	Significant amount of shingles missing 15-50% of roof area Interior of roof is not exposed	Many shingles missing >50% of roof area Damage to roof frame	Holes in roof due to debris or wind; sheathing is exposed but not house interior	Large parts of roof are missing or collapsed; house is still intact	—			
Walls	No visible damage	Minor cladding removal (<10% of one wall) Small scratches causing aesthetic damage	Cladding has been removed from >10% of one wall or from multiple walls Interior sheathing exposed on <10% of house	Cladding has been removed from >25% of walls Greater than 10% of sheathing is exposed but insulation and house interiors are not	Minor structural wall damage, including debris caused holes or repairable damage	Walls have collapsed, bent, or are out of plumb; structural damage Large holes in walls Major structural damage	—			
Foundation	No visible damage	Scour <0.15 m (<0.5 ft) deep around foundation Water marks around foundation Structurally sound	Scour 0.15-0.3 m (0.5-1 ft) Structurally sound foundation Evidence of weathering on piles	Scour 0.3-0.6 m (1-2 ft) Structurally sound foundation Minor damage to piles	One pile out of plumb, or damaged Scour >0.6 m (>2 ft) Minor damage to foundation	Major but repairable foundation damage House has differentially settled Greater than one pile is damaged	House is missing Irreparable foundation damage			
Attachments and detached structures: stairways, breakaway walls, air conditioning, sheds, etc.	No visible damage	Less than two exterior air conditioning, pipes, etc., have been damaged or removed Damage to stair, porches, detached garage, or walkways; most structures remain intact	Two or more exterior amenities (stairways, electrical wiring, etc.) are gone or destroyed Severe damage to decks, detached garages, etc.	Detached structures destroyed/missing	—	—	—			
Openings: windows, doors, attached garages	No visible damage	One window or door is broken (glass only) Screens may be damaged or missing	Greater than one window is broken but damage is all on lower story of 2+ story houses Less than four total openings are damaged Damage to frames of doors and windows	Four or more windows and doors are broken One or more doors was removed Damage to windows/doors on upper levels Attached garage door damaged or gone (bent or otherwise broken)	—	—	—			

Interior Damage Characteristics Not Shown

Torniczek, T., Kennedy, A., Zhang, Y., Owensby, M., Hope, M.E., Lin N. (2017). Hurricane Damage Classification Methodology and Fragility Functions Derived from Hurricane Sandy's Effects in Coastal New Jersey. ASCE J. Waterway, Port, Coastal, and Ocean Eng., 10.1061/(ASCE)WW.1943-5460.0000409. 26

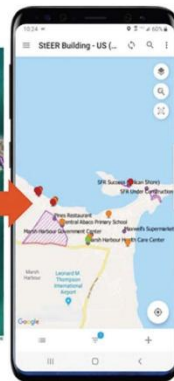
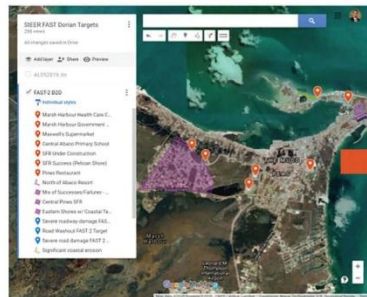
## Opportunities – Coordination, Collaboration & Data Reuse



## Opportunities - Leveraging Technology

### StEER: Structural Extreme Event Reconnaissance Network

HURRICANE MICHAEL:  
FIELD ASSESSMENT TEAM 1 (FAT-1)  
EARLY ACCESS RECONNAISSANCE REPORT (EARR)



Kijewski-Correa T, Roueche DB, Mosalam KM, Prevatt DO and Robertson I (2021) StEER: A Community-Centered Approach to Assessing the Performance of the Built Environment after Natural Hazard Events. *Front. Built Environ.* 7:636197. doi: 10.3389/fbuil.2021.636197

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# Opportunities - Virtual Damage Assessment

**VDA Results**

**Legend**

**Assessment Status:**

- Full (3118)
- Partial (290)

**Damage State:**

- No Damage (DS0)
- Minor (DS1)
- Moderate (DS2 & DS3)
- Major (DS4)
- Complete (DS5 & DS6)

**Damage Scale:**  
Tomiczek et al. (2017)

**An example of VDA details**

Source: SEER

NIS Id. Id: 697089214  
 NIS Occupancy: RES1 1SMB  
 NIS Building Type: Wood (W)  
 Act Year Built: 1951  
 Elevated: No

**Damage States:** DSS

- Roof: D55
- Walls: D55
- Foundation: D50
- Attachments: DS1
- Openings: DS3

**Damage Description:** Roof has large holes and suffered heavy damage; Walls have been destroyed on front of house.

**Confidence Level:** High  
**Source of Data:** SEER Aerial Imagery and Streetview

Figueira, S.A., Amini, M., D. T. Cox, & A. R. Barbosa. (in preparation) Virtual Structural Damage Assessment of Buildings in Fort Myers Beach, FL Subject to Impact from Hurricane Ian (2022)". Natural Hazards Review, ASCE.

# Opportunities - Longitudinal Studies of Damage and Recovery

NIST SP 1230-2

Community Resilience-Focused Technical Investigation of the 2016 LUMBERTON, NORTH CAROLINA FLOOD  
COMMUNITY RECOVERY ONE YEAR LATER

Sutley, E.J., Dillard, M.K., and van de Lindt, J.W. (Eds.). (2021). Community Resilience-Focused Technical Investigation of the 2016 Lumberton, NC Flood: Community Recovery One Year Later. NIST Special Publication 1230-2.

Damage State	Oct 2017	March 2018
DS=0	~80	~80
DS=1	~40	~20
DS=2	~10	~10
DS=3	~10	~10
DS=4	~0	~50

Tomiczek, T., O'Donnell, K., Furman, K., Webbmartin, B., and Scyphers, S. (2020). Rapid Damage Assessments of Shorelines and Structures in the Florida Keys after Hurricane Irma. ASCE Natural Hazards Review. 21 (1). [https://doi.org/10.1061/\(ASCE\)NH.1527-6996.0000349](https://doi.org/10.1061/(ASCE)NH.1527-6996.0000349)

Recon

- Sep 28, 2022: Hurricane Ian landfall (Cat 4)
- Oct 2022: FEMA pre-MAT
- Oct 2022: NSF SEER - San Carlos
- Oct 2022: NSF SEER - FMB
- Nov 2022: ASCE Recon - SI + FMB
- Jan 2023: FEMA MAT
- Mar 6-8, 2023: OSU Recon - FMB
- Jun 3-4, 2023: OSU Recon - FMB
- Jan 13-14, 2024: OSU/URI Recon - FMB
- May 4-5, 2024: OSU/URI Recon - FMB
- Aug/Sept 2024

Figueira, S.A., Amini, M., D. T. Cox, & A. R. Barbosa. (in preparation) Virtual Structural Damage Assessment of Buildings in Fort Myers Beach, FL Subject to Impact from Hurricane Ian (2022)". Natural Hazards Review, ASCE.

## Focus has been on (Residential) Buildings



Galveston, TX  
Photo by Tori Tomiczek



May 21, 2009  
Seaside Heights, NJ  
Photo by USGS

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## Other Building Typologies



Fawcett Hospital, Port Charlotte FL, Hurricane Ian  
Photo Credit: Layton Construction



Grand Bahama Airport, Hurricane Dorian  
Photo Credit: Ramon Espinosa/AP

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## Other Community Lifelines

Transportation: roadways, bridges



Electric and power

Drinking water, stormwater, wastewater



Telecommunications

## Remaining Questions

### Knowledge Gaps

- Temporarily evolving fragilities – when does damage occur during storms?
- Debris propagation and hazard assessment
- Effects of sheltering and channeling in building arrays on building fragility
- Potential for remote sensing, machine learning, artificial intelligence in damage assessment, fragility estimation



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## Summary and Conclusions

### Lessons Learned from Case Studies

- Post-event case studies allow for forensic identification of hazard conditions, infrastructure performance, and system fragility
  - “Unexpected observations” may lead to important new knowledge about building exposure, fragility
  - Fragilities can inform community planning to identify vulnerable residents, areas
- Standardization of damage assessment methods important if comparing across neighborhoods, geographies, events
- Emerging technology can increase geographical reach, impact of case studies

### Opportunities for Ongoing and Future Case Studies

- Longitudinal studies of damage and recovery, dataset expansion, cross-event and cross-geography comparisons of performance
- Virtual damage assessment
- Coordination, collaboration, and data reuse (StEER)
- Additional work is necessary to address knowledge gaps, improve fragility estimation and community resilience in the face of climate change and coastal hazards

**Prepare now for future case studies: field observations, physical & numerical modeling**

- “When,” not “if” next extreme event

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## Thank you!

Tori Tomiczek  
vtjohnson@usna.edu



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## B.7 Wisemiller

# NEW YORK-NEW JERSEY HARBOR AND TRIBUTARIES COASTAL STORM RISK MANAGEMENT STUDY

Climate Adaptation Workshop: Structural  
Design for Coastal Flood Resilience  
Princeton University, New Jersey


May 16, 2024

New York District















## NY NJ HARBOR & TRIBUTARIES STUDY SUMMARY

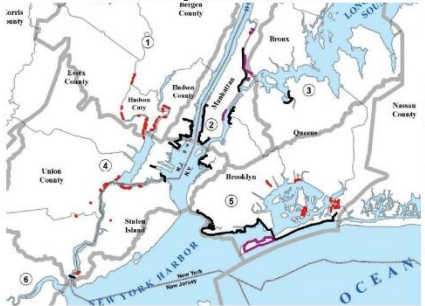
2



### STUDY AREA

- The largest and most densely populated of the 9 NACCS Focus Areas
- Area covers 2,150+ square miles and 900+ miles of affected shoreline
- 25 counties in New York & New Jersey
- Affected population of roughly 16 million people, including New York City and the six most populated cities in New Jersey

### Tentatively Selected Plan



**Black lines** – Primary structural features approximately 15-25 ft. NAVD88  
**Purple lines** – Structural induced flooding mitigation features also approx. 15-25 ft. NAVD 88  
**Red lines** – High Frequency Flood Risk Reduction Features approximately 10 ft. NAVD88

### COASTAL STORM RISKS & DAMAGES

- Significant Life/Safety Risk and over 275,000 Structures in Potential Impact Area
- Incorporates Dozens of Other Ongoing and Planned CSRMM Projects
- Present Value Damages for 100-Year Storm Range from \$100+B for Intermediate sea level rise (SLR) to over \$350B for High SLR Projection

### STUDY SCOPE

- **Study Cost:** \$19.4M, cost-shared 50/50 with NYSDEC and NJDEP thru July 2022, and 100% federal thereafter.
- **Study Schedule:** Additional Time Requested. Current approved study completion is June 2024
- **Funding:** Additional funding requested. Study cost-shared to June 2022, then 100% federal funded via Disaster Relief Suppl. Appros. Act funds.
- **Study Scope:** WRDA 2020/2022 allows for possible scope expansions now under consideration.

### STUDY SCHEDULE

- Draft Feasibility Report and integrated Tier 1 Environmental Impact Statement Released for 6 month extended public day review in September 2022 with meetings held throughout area. Comment closing date was March 31, 2023. Approximately 2,800 comments received.
- See [WWW.NAN.USACE.ARMY.MIL/NYNJHATS](http://WWW.NAN.USACE.ARMY.MIL/NYNJHATS) for Draft Report and all appendices.
- **Dual pathway plan for advancing and completing the study with early actionable elements followed by a revised and refined comprehensive plan\***
- **Draft Integrated Interim Response Report tentatively scheduled for April 2025\***
- **Revised Draft Integrated Comprehensive Plan Report tentatively scheduled for April 2026\***
- **Final Chief of Engineers Report tentatively scheduled for June 2028\***

**\* - Subject to higher authority endorsement/approval and funding.**



# DRAFT REPORT, TIER 1 ENVIRONMENTAL IMPACT STATEMENT AND ALL APPENDICES



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Found at <https://www.nan.usace.army.mil/NYNJHATS>

U.S. Army Corps of Engineers, New York District Website

Missions / Civil Works / Projects in New York / NY & NJ HATS

**Draft Report September 2022**

Comments received regarding the Draft Integrated FRI/ES will assist in the agency's evaluation of the proposed action and will be reflected in the project record. All written comments, including contact information, will be made a part of the administrative record, available to the public under the Freedom of Information Act (FOIA). The Administrative Record, or portions thereof, may also be posted on a Corps of Engineers' website.

**Start Here** →

The **DRAFT Study StoryMap** is an interactive platform with interactive web-based content, including interactive maps, animations, renderings, and summaries.

**Readers Guide**

**Draft Integrated Feasibility Report and Tier 1 Environmental Impact Statement**

**Appendix A: Environmental**

- Sub-appendix A1: Endangered Species Act (ESA)
- Sub-appendix A2: Endangered Species Act (ESA)
- Sub-appendix A3: Essential Fish Habitat
- Sub-appendix A4: Coastal Zone Management Act
- Sub-appendix A5: Clean Water Act
- Sub-appendix A6: Flood Risk and Flood Insurance

**Public Meeting Documents**

- Alternative 2: Future With Project Reduced Risk and Residual Risk
- Alternative 3A: Future With Project Reduced Risk and Residual Risk
- Alternative 3B: Future With Project Reduced Risk and Residual Risk
- Alternative 4: Future With Project Reduced Risk and Residual Risk
- Alternative 5: Future With Project Reduced Risk and Residual Risk
- Coastal Storm Risk Management Features/Measures By Storm Frequency
- New York Bight Ecological Model
- Environmental Justice
- Tier 1 Environmental Impact Statement
- 100th Street (Manhattan) Elevated Promenade Concept
- 145th Street (Manhattan) Elevated Promenade Concept
- Coney Island Elevated Promenade Concept
- Exchange Place (Jersey City) Elevated Promenade Concept

**January 2024 Update**

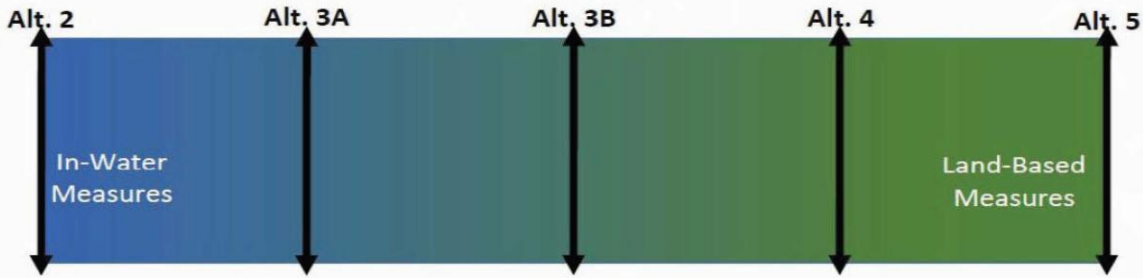
The formal public comment period for the New York State Harbor and Tributaries Study Draft



# ALTERNATIVE PLANS – PROS & CONS WITH EACH



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- Alternative 1: No action
  - Alternative 2: Harbor-wide storm surge barrier + shore-based measures
  - Alternative 3A: Multi-basin storm surge barriers + shore-based measures
  - Alternative 3B: Multi-basin storm surge barriers + shore-based measures**
  - Alternative 4: Single-basin storm surge barriers + shore-based measures
  - Alternative 5: Shore-based measures only
- Alternatives span spectrum from large in-water storm surge gates to numerous shoreline-based structures. Alternatives also have (or will have) complementary non-structural and natural and nature-based features (where feasible).
  - Best Solution Appears to Involve Multiple, Layered Features
  - Possible Phased Implementation:
    - 1) Short-term: Construct Actionable Features,
    - 2) Mid-Term: Further Evaluate, Design and possibly Construct More Complex Features,
    - 3) Long-Term: Adapt and expand features, as feasible and environmentally acceptable, due to further sea level rise and climate change

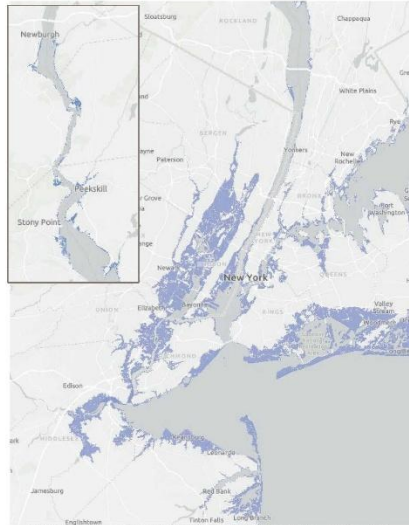


## ALTERNATIVE 1 – NO ACTION (FUTURE WITHOUT PROJECT CONDITION)

5



All alternatives are currently focused on evaluating possible actions to lessen impacts from severe, infrequent coastal storms with intermediate sea level rise

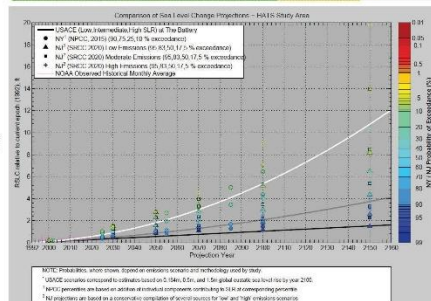


1% flood extent (with intermediate RSLC)

Alternative 1 Includes Other Existing and Ongoing Coastal Storm Risk Management Projects



Study is evaluating wide range of possible sea level rise



NOTE: Panel B10c shows storm-topped or wetland-topped and technology used by study. USACE estimates correspond to values based on 5, 10, 25, 50, and 100 global coastal sea level rise by year 2050. Panel C10c presents sea level rise estimates of intermediate conditions corresponding to the designating scenario. All estimates are based on a constant rate of sea level rise of 0.10 m per century (1.0 mm per year) constant.



## COMPOSITE: ALTERNATIVE PLANS SHOWING STORM SURGE BARRIER LOCATIONS CONSIDERED

6

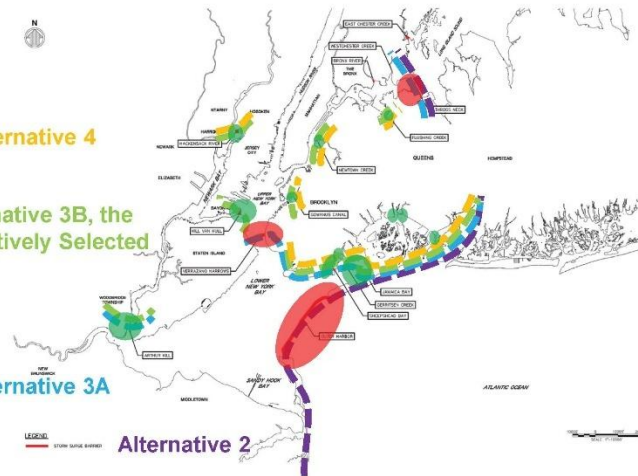


Alternative 4

Alternative 3B, the Tentatively Selected Plan

Alternative 3A

Alternative 2



- All alternative plans will include nonstructural measures, as feasible, for areas with unaddressed coastal storm risk
- All alternative plans will include natural and nature-based features where applicable and feasible

Alternative 5 (shore-based measures only) not shown in figure

- Storm Surge Gate location included in TSP
- Storm Surge Gate location NOT included in TSP



## KEY METRIC COMPARISON OF ALTERNATIVES

Alternative	Percentage of Area at Reduced Risk	Years to fully Construct	First Cost (\$B)	Average Annual Cost	Average Annual Benefits*	Net Benefits	Benefit to Cost Ratio
2	96%	32	\$112.3	\$5.0B	\$4.6B	-\$0.5B	0.91
3A	87.1%	24	\$76.9	\$3.2B	\$6.4B	\$3.2B	1.99
<b>3B</b>	<b>63%</b>	<b>14</b>	<b>\$52.7</b>	<b>\$2.6B</b>	<b>\$6.3B</b>	<b>\$3.7B</b>	<b>2.45</b>
4	45.9%	14	\$43.0	\$2.1B	\$5.0B	\$2.9B	2.39
5	3.3%	5	\$16.0	\$0.9B	\$1.9B	\$1.0B	2.21

\* Benefits currently based on estimated damages avoided to structures in study area. Critical infrastructure and other possible benefits under refinement and have not been included in the net benefit calculations at this time.

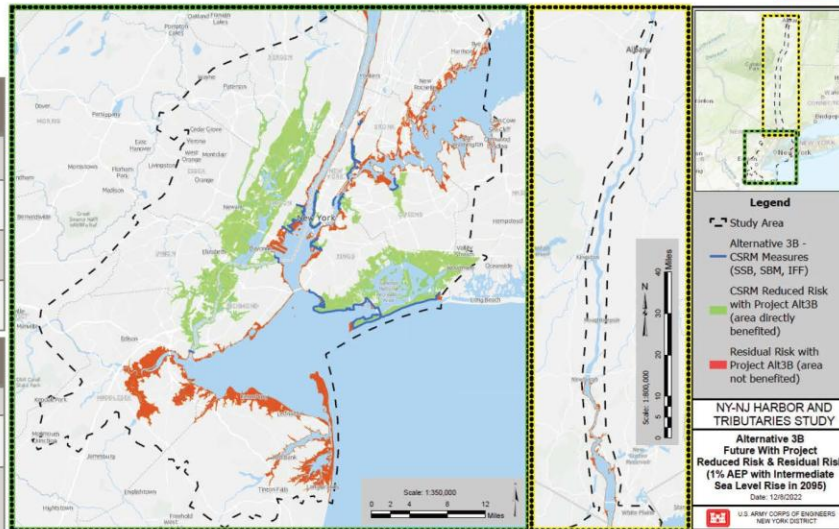


## ALTERNATIVE 3B – THE TENTATIVELY SELECTED PLAN

63.0% Study Area at Direct Risk Benefited

Feature Type	Approx. Miles
Storm Surge Barriers	2.2
Shoreline Based Measures	50.6
Induced Flooding-Mitigation Features	11.8
Risk Reduction Features (not shown)	18.7

Alternative	
First Cost (\$B):	\$ 52.7
Total Present Value Cost (\$B):	\$ 76.2
Estimated Construction Duration (years):	14







# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL



11



### Kill Van Kull Storm Surge Barrier:

- Navigable Passage: Floating Sector Gate
- 800 foot opening
- 19 foot crest elevation (NAVD88) for currently selected design storm event
- 5 Auxiliary Lift Gates
- Total Length in Water: 3,300 feet (approximately)
- Shorebased Tie-Ins: 4,800+ feet comprised of floodwalls, railroad and vehicular gates



### Arthur Kill Storm Surge Barrier:

- Navigable Passage: Floating Sector Gate
- 600 foot opening
- 19 foot crest elevation (NAVD88) for currently selected design storm event
- 2 Auxiliary Lift Gates
- Total Length in Water: 2,300 feet (approximately)
- Shorebased Tie-Ins: 700+ feet comprised of floodwalls

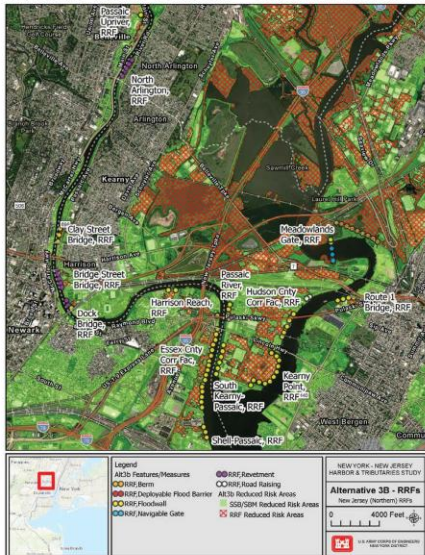


# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL

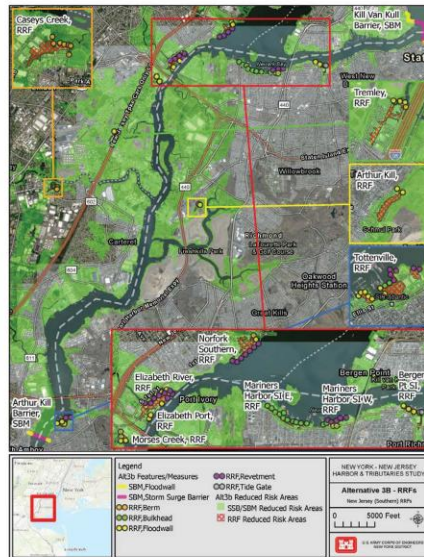


12

## Residual Risk Features – Northern New Jersey



## Residual Risk Features – NJ & SI

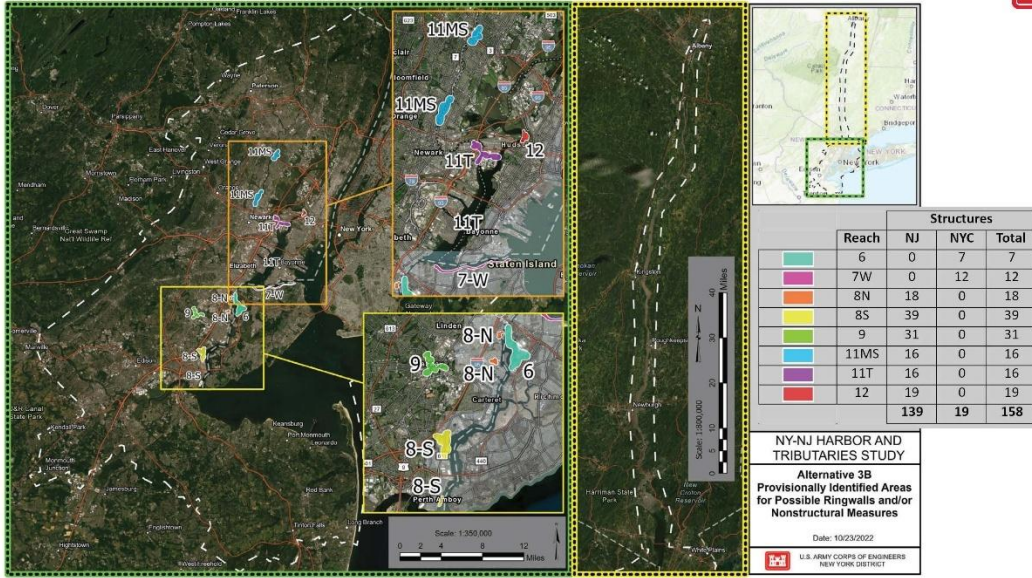




# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL



13



# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL



14

## Coney Island Boardwalk

### Existing Conditions



### Rendering of Initial Proposal



## South Brooklyn and Jamaica Bay Area



## Risk Reduction Feature Details







# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL

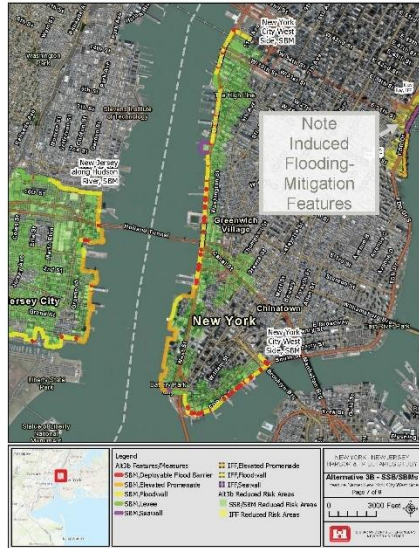
17



## Lower Manhattan Area

### Shoreline based features only

- Total length: 31,000+ feet
- Measures include: Floodwalls, levees, flip up barriers, pedestrian and vehicle gates, elevated promenades, floodwalls with park, and seawalls
- Other considerations:
  - May need additional stormwater and wastewater pump station improvements
  - Need to reconcile NYNJHAT study plan for area with other non-federal plans for portions of area



## Christopher Street

### Existing Conditions



### Rendering of Initial Proposal



### Proposed During Storm Conditions



# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL

18



## Jersey City Area

### Shoreline based features only

- Total length: 43,000+ feet
- Measures include: Floodwalls, levees, pedestrian, railroad and vehicle gates, elevated promenades, and seawalls

## York Street

### Existing Conditions



### Rendering of Initial Proposal



## Liberty State Park

### Existing Conditions



### Rendering of Initial Proposal



### Proposed During Storm Conditions







# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL



21

## Storm surge barrier with shoreline-based tie-ins

### Gowanus Creek Storm Surge Barrier

- 100 foot wide Sector Gate
  - 16 foot crest elevation (NAVD88) for currently selected design storm event
  - Total Length in Water: 130 feet
- Shore-based Tie-ins
- Total Length: 18,000+ feet
  - Measures include: Floodwalls, levees, vehicle gates, and seawalls

### Other considerations:

- Known contamination issues

## Red Hook and Gowanus Creek Area



## Coffey Street, Red Hook, Brooklyn

### Existing Conditions



### Rendering of Initial Proposal



# TENTATIVELY SELECTED PLAN FEATURES IN DETAIL



22

## Storm surge barrier with shoreline-based tie-ins

### Flushing Creek Storm Surge Barrier

- 135 foot wide Vertical Lift Gate Storm Surge Barrier
- 18 foot crest elevation (NAVD88) for currently selected design storm event
- 2 Auxiliary Lift Gates
- Total Length in Water: 500 feet

### Shoreline-based Tie-ins

- Total Length: 11,000+ feet
- Measures include: Floodwalls, vehicle gates, elevated promenades, floodwalls with park, and seawalls

## Flushing Bay Area



## Flushing Bay Promenade, Queens

### Existing Conditions



### Rendering of Initial Proposal







## PUBLIC ENGAGEMENT

25

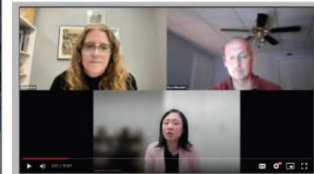


### Who do we engage?

- Elected officials
- Local government
- Non-governmental organizations
- Academic institutions
- Private entities

### Over 80 meetings.. and counting

- 23 public meetings
  - 12 hybrid, 4 in-person, 7 virtual
  - Held throughout study area
- 63 Stakeholder Engagements
  - 1 hybrid, 12 in-person, 50 virtual
  - Hosted by elected officials, local government, non-governmental organizations



Engagements 24 SEP 22 – 27 NOV 23

Brochures, meeting advertisements, and other public information materials are made available in six languages: English, Spanish, Chinese (Simplified), Chinese (Traditional), Arabic, and Russian.

Top: Media interview along the Manhattan waterfront, 15 DEC 23. Middle: Rebuild by Design NYNJHATS Teach-In (25JAN 23). Bottom: Congresswoman Velazquez NYNJHATS Town Hall (23 FEB 23).



## PUBLIC COMMENTS

26

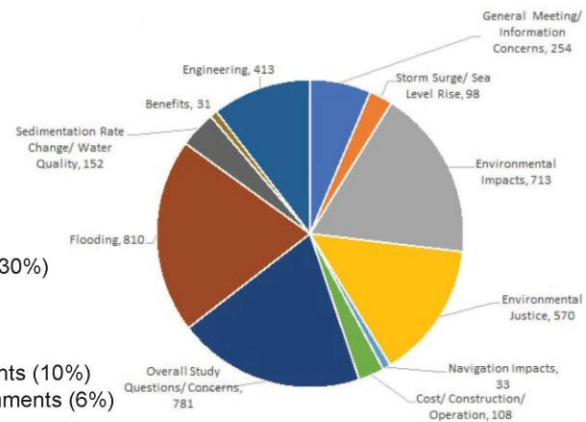


### 2,767 comments received

- Elected officials
- Local government
- Non-governmental organizations
- Academic institutions
- Private entities
- Individuals

### Breakdown by Theme

- Flooding: 810 comments (31%)
- Overall Study Questions/Concerns: 781 comments (30%)
- Environmental Impacts: 713 comments (27%)
- Environmental Justice: 570 comments (22%)
- Engineering: 413 comments (16%)
- General Meeting/Information Concerns: 254 comments (10%)
- Sedimentation Rate Change/Water Quality: 152 comments (6%)
- Cost/Construction/Operation: 108 comments (4%)
- Storm Surge/Sea Level Rise: 98 comments (4%)
- Navigation Impacts: 33 comments (1%)
- Benefits: 31 comments (1%)



Note: Some comments included more than one theme, so total percentage adds up to >100%. Number of comments in this breakdown = 2,625





## STEPS FORWARD

- Confirm Plan Selection
- Refine and Optimize Plan
  - Review remaining areas of unaddressed coastal storm risk
    - Consider other storm event levels
    - Identifying areas of feasible natural and nature-based features (independent or complementing other features)
    - Identifying areas of further non-structural measures
  - Refine Features for Optimal Design Storm
  - Optimize Risk Reduction Features (in combination with various storm surge gate closure criteria)
  - Release an Integrated Interim Response Report in April 2025 leading to an Interim Chief of Engineer's Report in May 2026
  - Release a Revised Integrated Comprehensive Plan Report in April 2026, leading to Final Chief of Engineer's Report in June 2028

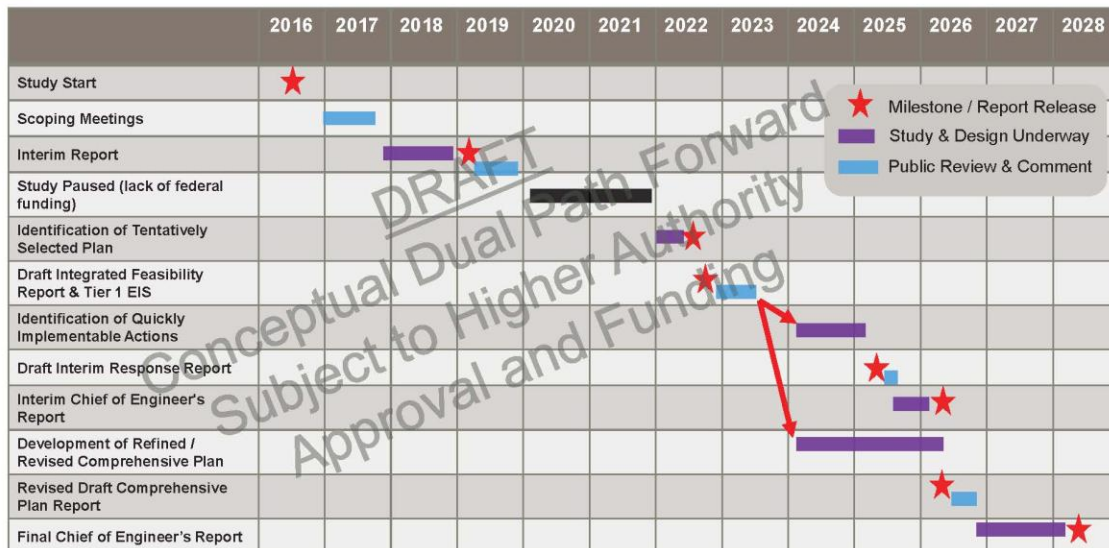


1% flood extent (with intermediate RSLC)

29



## DRAFT OVERALL STUDY SCHEDULE (AS CURRENTLY PROPOSED, AND SUBJECT TO HIGHER AUTHORITY REVIEW/APPROVAL AND FUNDING)



30





31

THANK YOU

STUDY WEBSITE

[HTTPS://WWW.NAN.USACE.ARMY.MIL/NYNJHATS](https://www.nan.usace.army.mil/nynjhats)

STORYMAP PORTAL

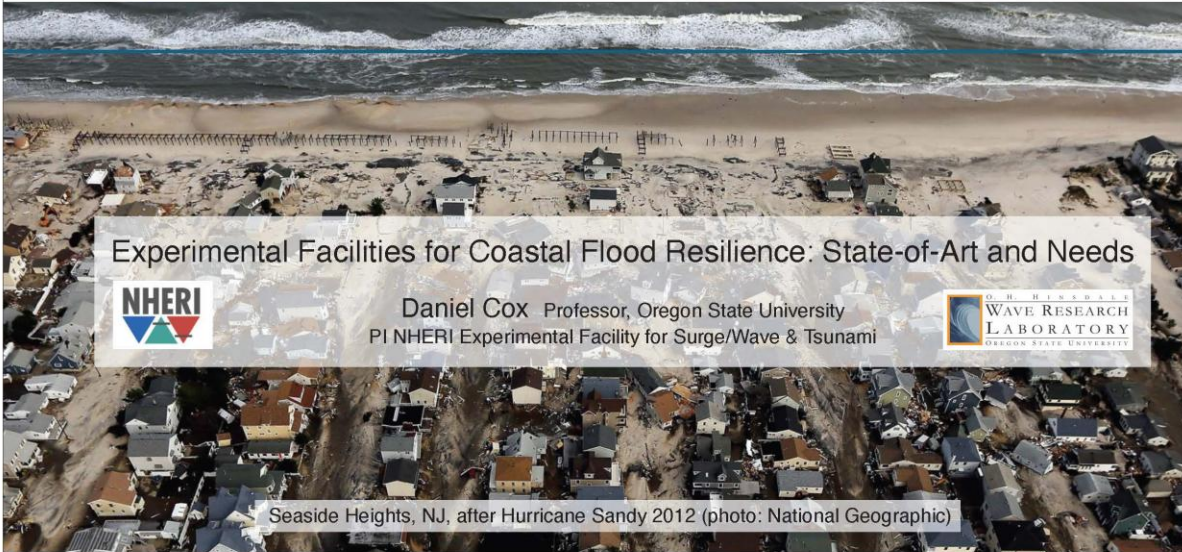
[HTTPS://HATS-CENAN.HUB.ARCGIS.COM/](https://hats-cenan.hub.arcgis.com/)

**B.8 Cox**

**Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience**



May 16-17, 2024, Princeton University

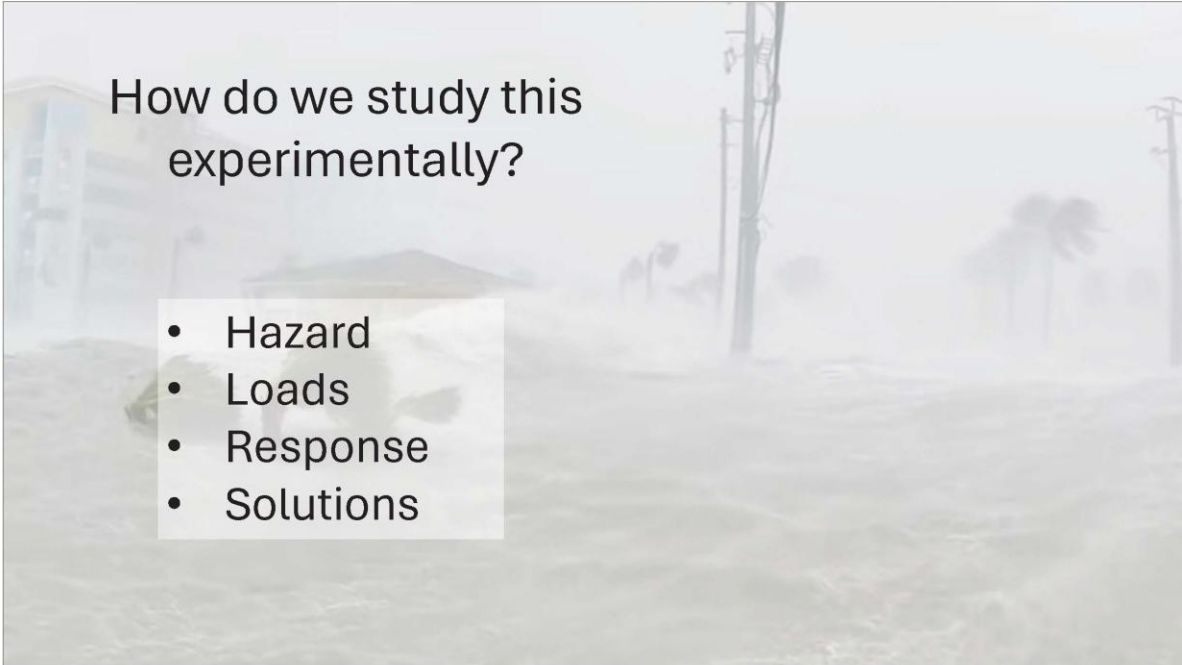
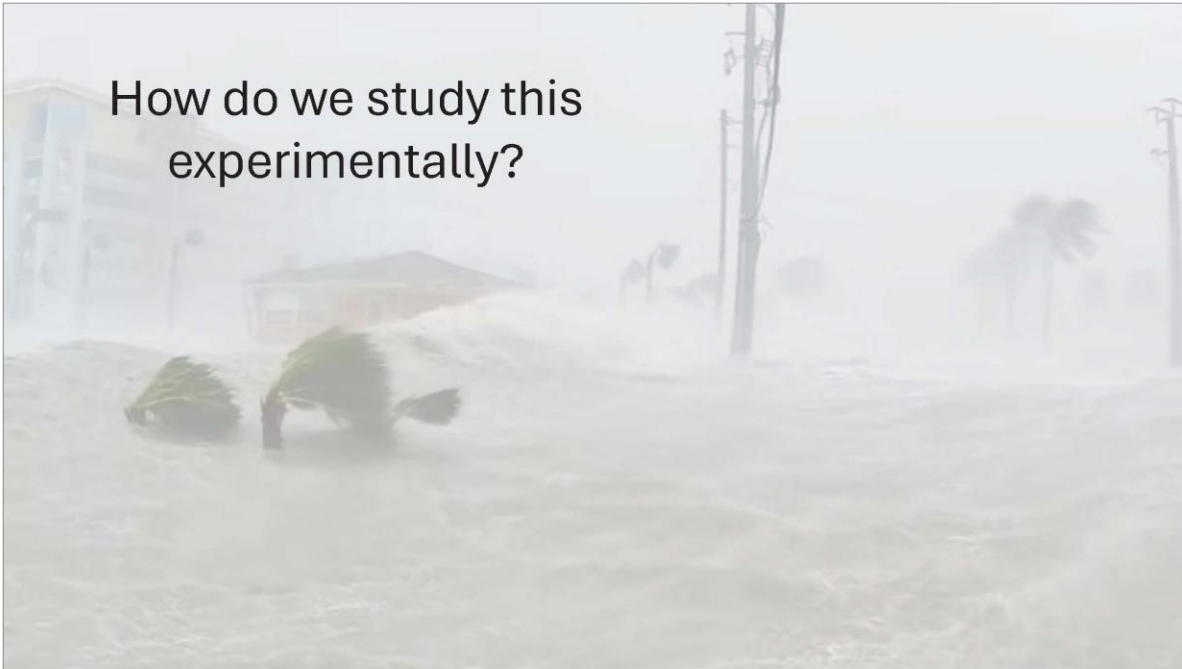
















How do we study this experimentally?

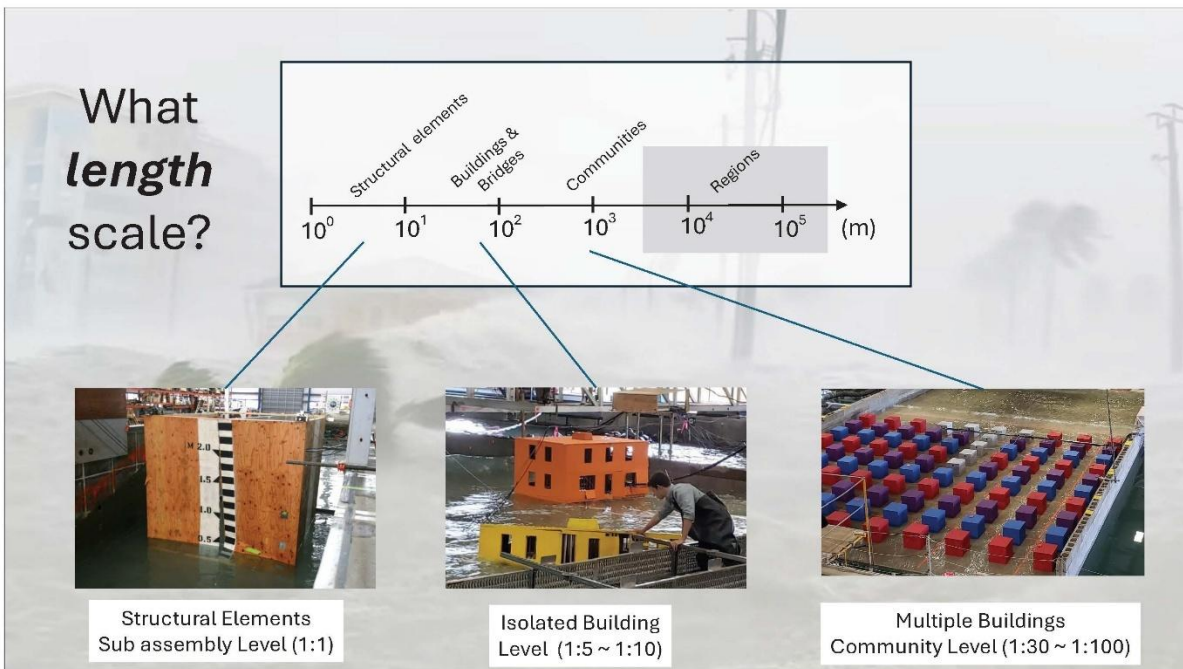
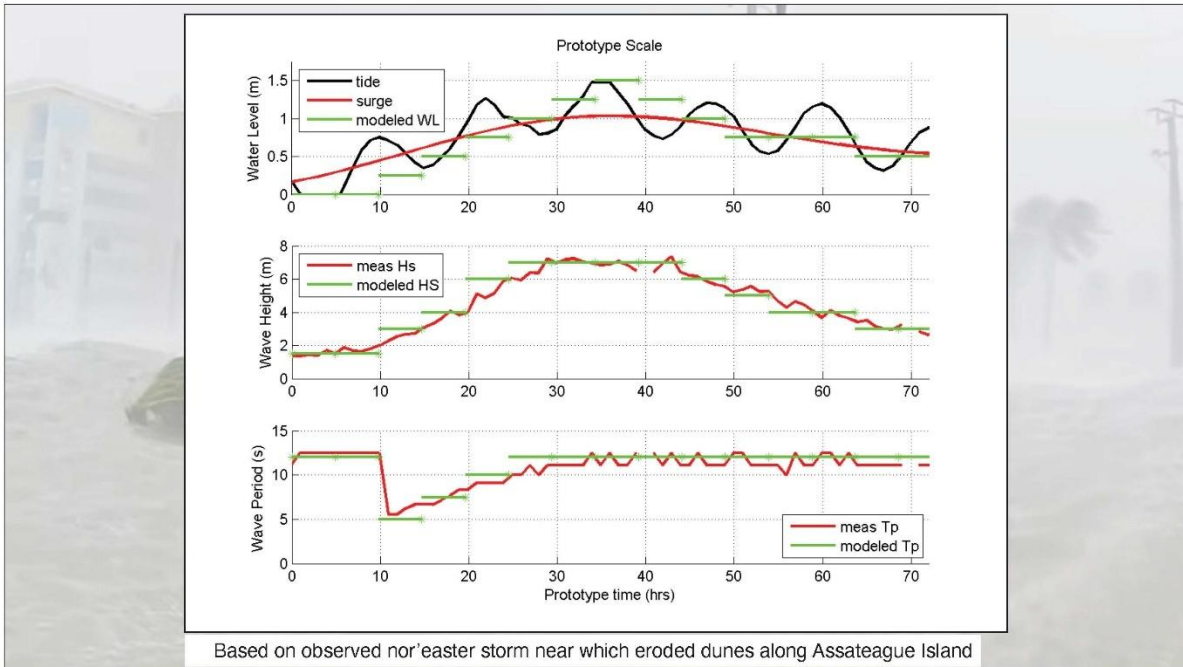
- Hazard
- Loads
- Response
- Solutions

Over what **time** scale?

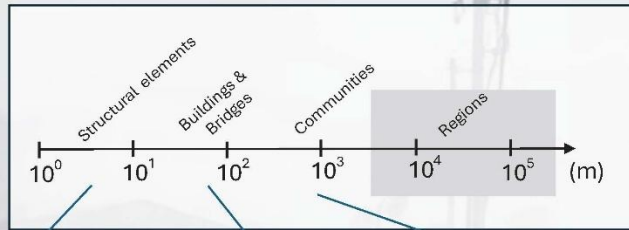


Over what **time** scale?

Wave Impulse	$10^{-3} \sim 10^{-1}$ s	
Single Wave	1 ~ 10 s	
Random Sea	$10^3$ s	(~20 min)
Peak Storm	$10^4$ s	(~3 hr)
Storm cycle	$10^5$ s	(~1 day)



What **length** scale?



Structural Elements  
Sub assembly Level (1:1)

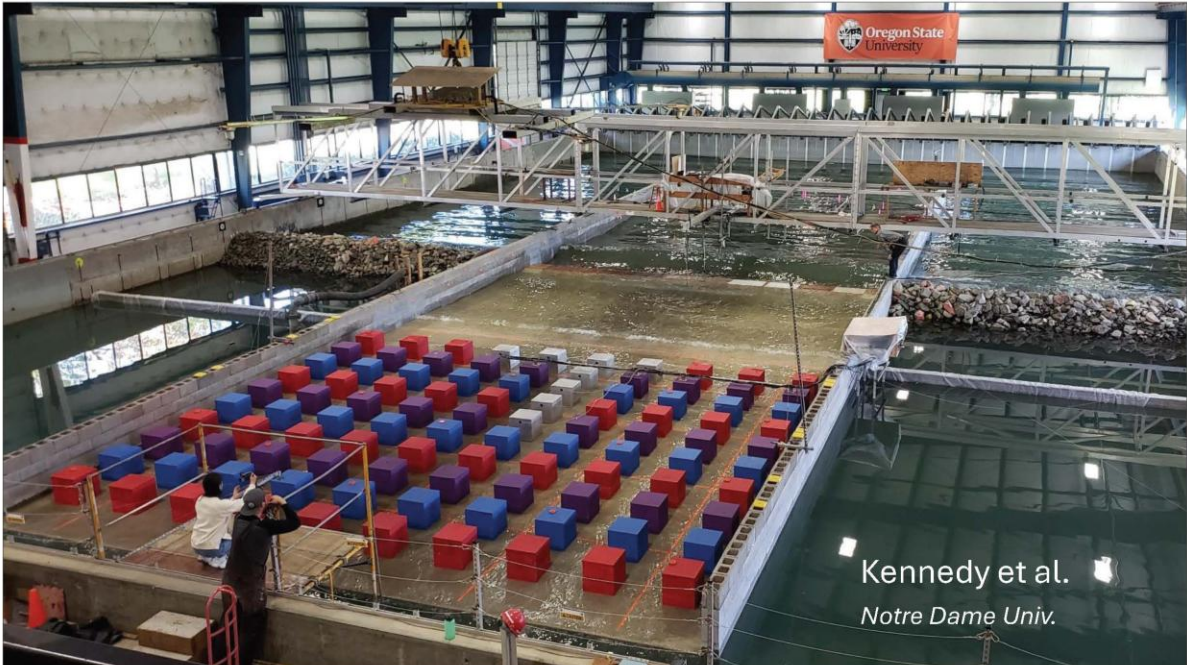


Isolated Building  
Level (1:5 ~ 1:10)



Multiple Buildings  
Community Level (1:30 ~ 1:100)



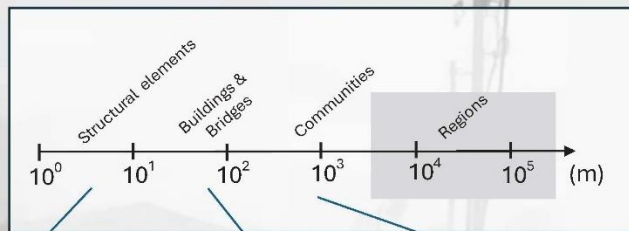




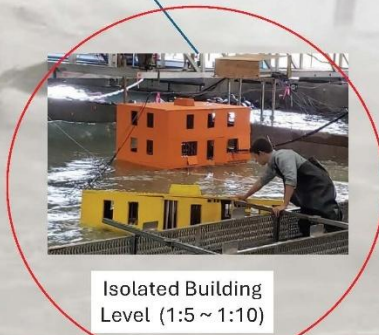
What can and can't we do well at **community** scale?

Flood hazards	A
Shielding	A
Sediment erosion	C+
Sediment scour	C
Pressure/force	B
Structure response	C-
Destructive testing	D
Debris transport	A
Debris damming	C-
Debris impact	D

What **length** scale?



Structural Elements  
Sub assembly Level (1:1)



Isolated Building  
Level (1:5 ~ 1:10)

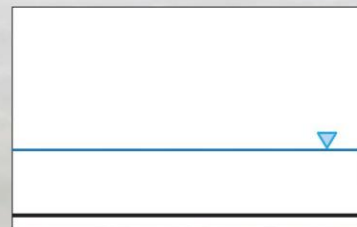
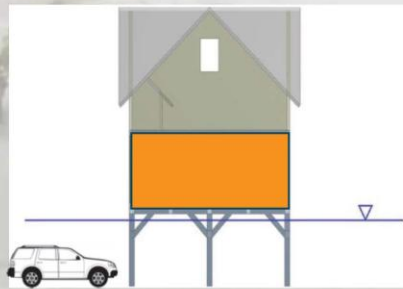


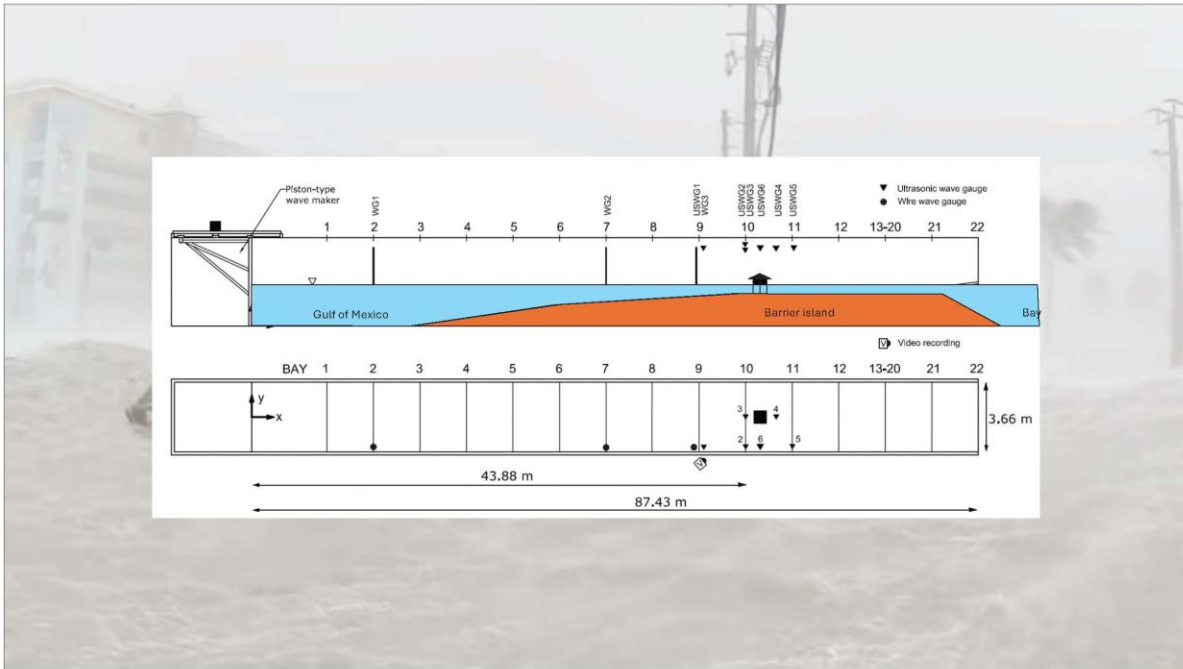
Multiple Buildings  
Community Level (1:30 ~ 1:100)



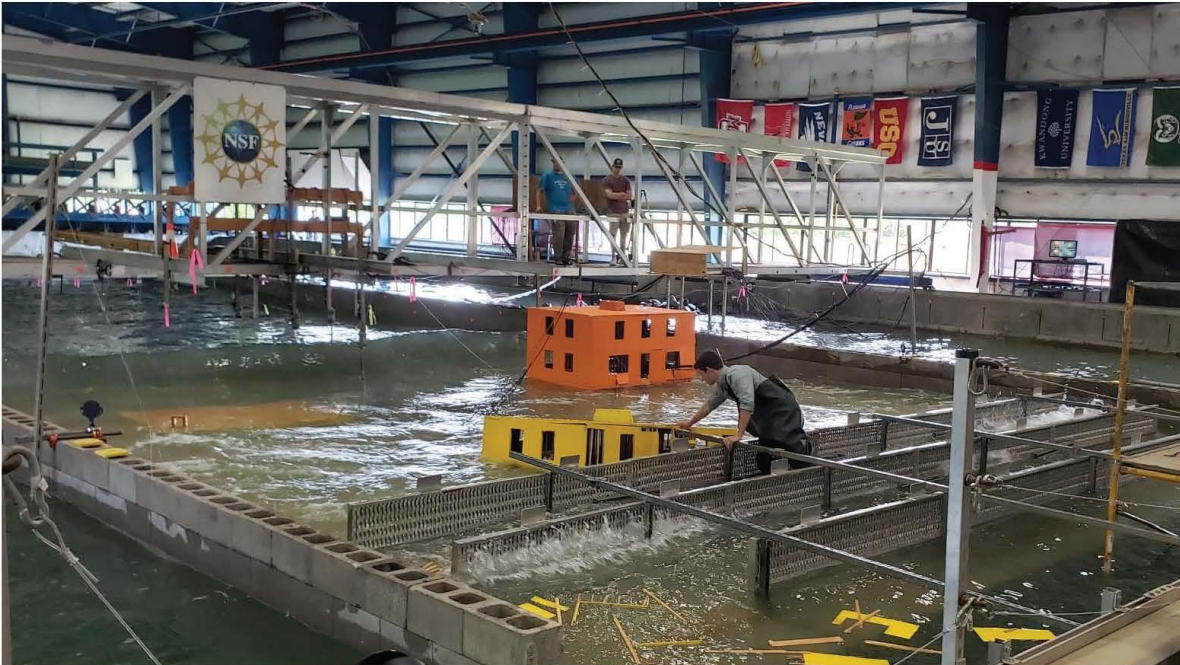
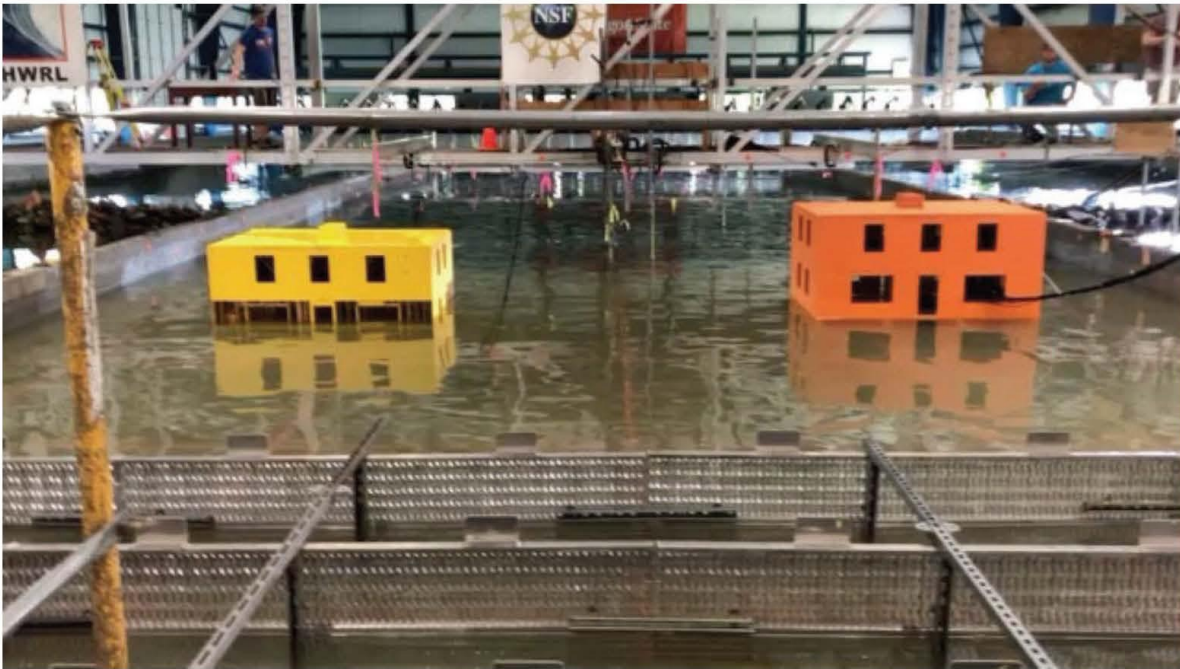
### Simplifying Assumptions

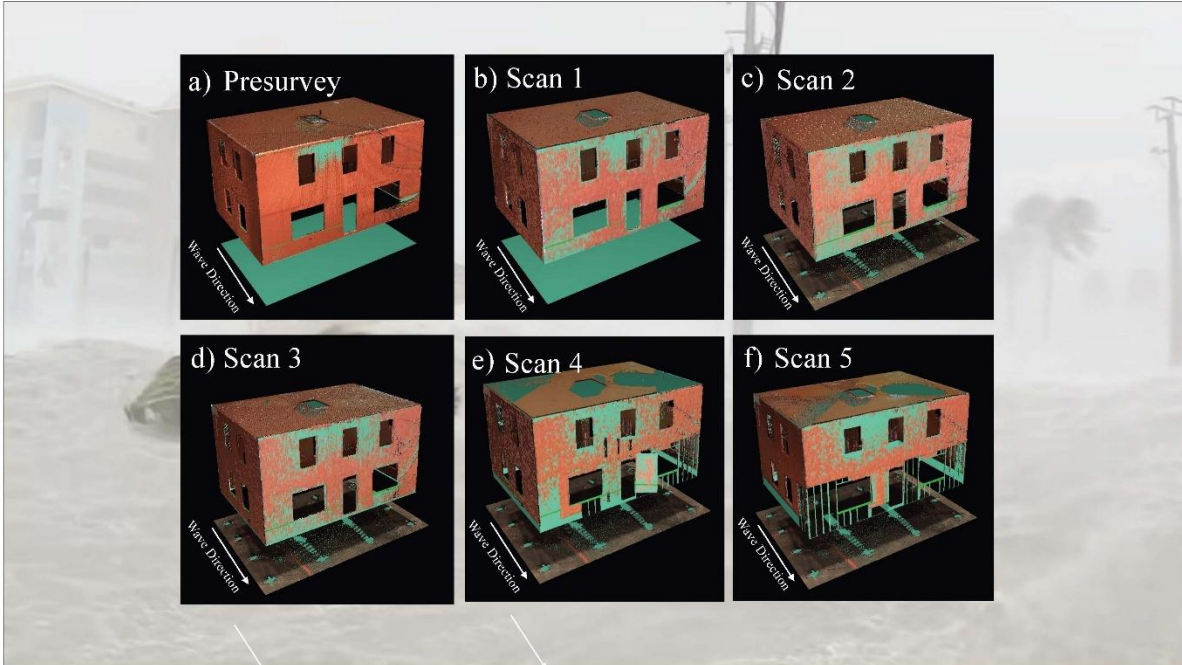
- No substructure
- No erosion or scour
- No debris
- No currents









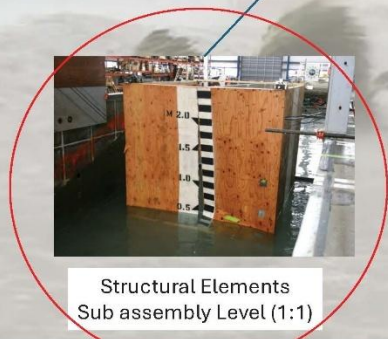
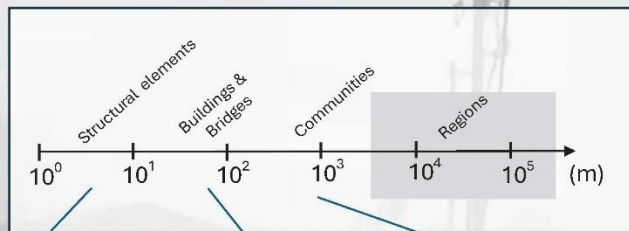


What can and can't  
we do well at  
**building** scale?

Flood hazards	A
Shielding	B+
Sediment erosion	B+
Sediment scour	B+
Pressure/force	A
Structure response	B
Destructive testing	B-
Debris transport	B
Debris damming	A
Debris impact	B

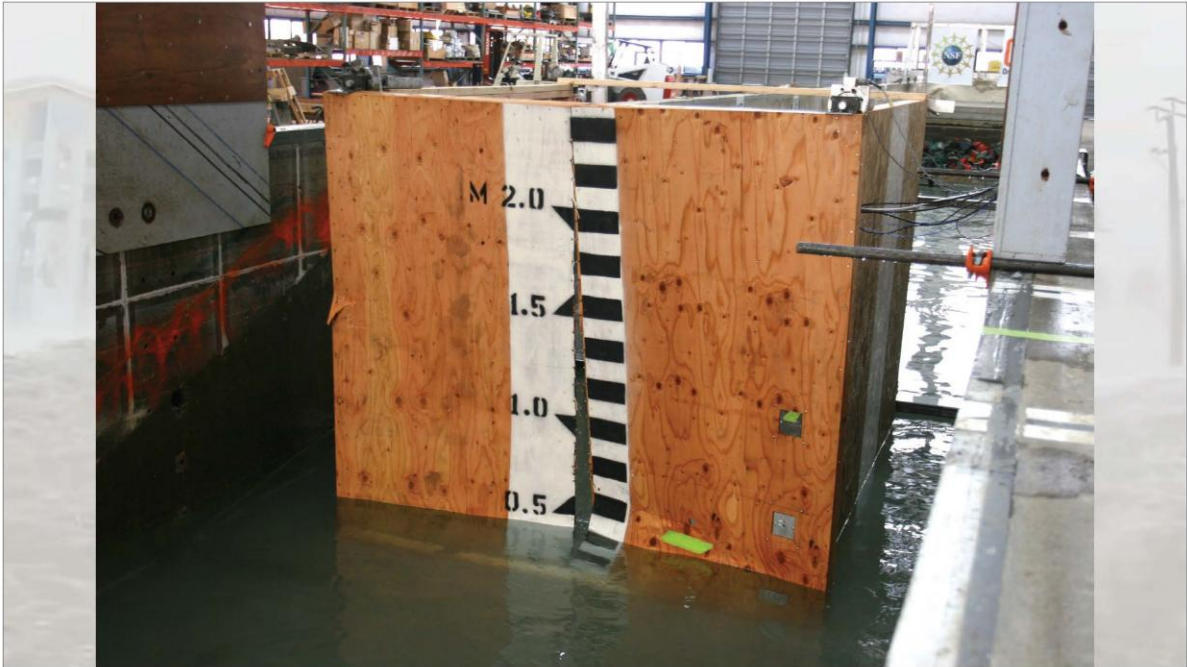


What  
**length**  
scale?



## Ridged Wall (1:1)



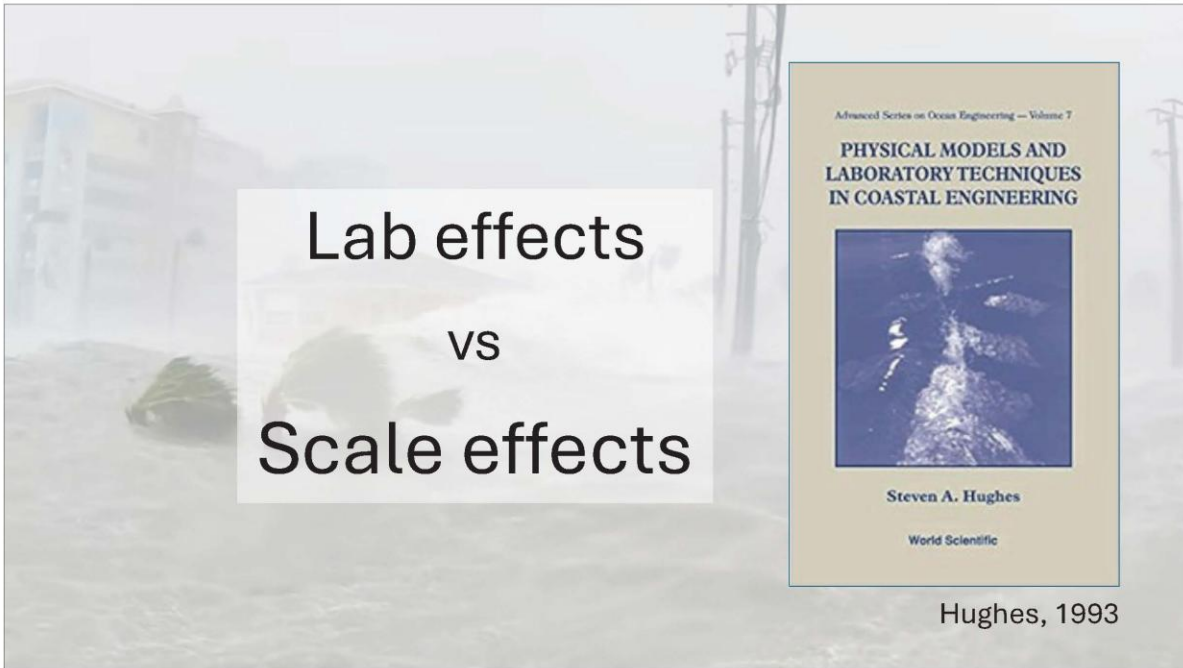




Element scale  
(1:1)

What can and can't  
we do well at this  
scale?


Flood hazards	A
Shielding	C
Sediment erosion	C
Sediment scour	A
Pressure/force	A
Structure response	A
Destructive testing	A
Debris transport	C
Debris damming	A
Debris impact	A



**Lab effects**  
vs  
**Scale effects**

Advanced Series on Ocean Engineering — Volume 7

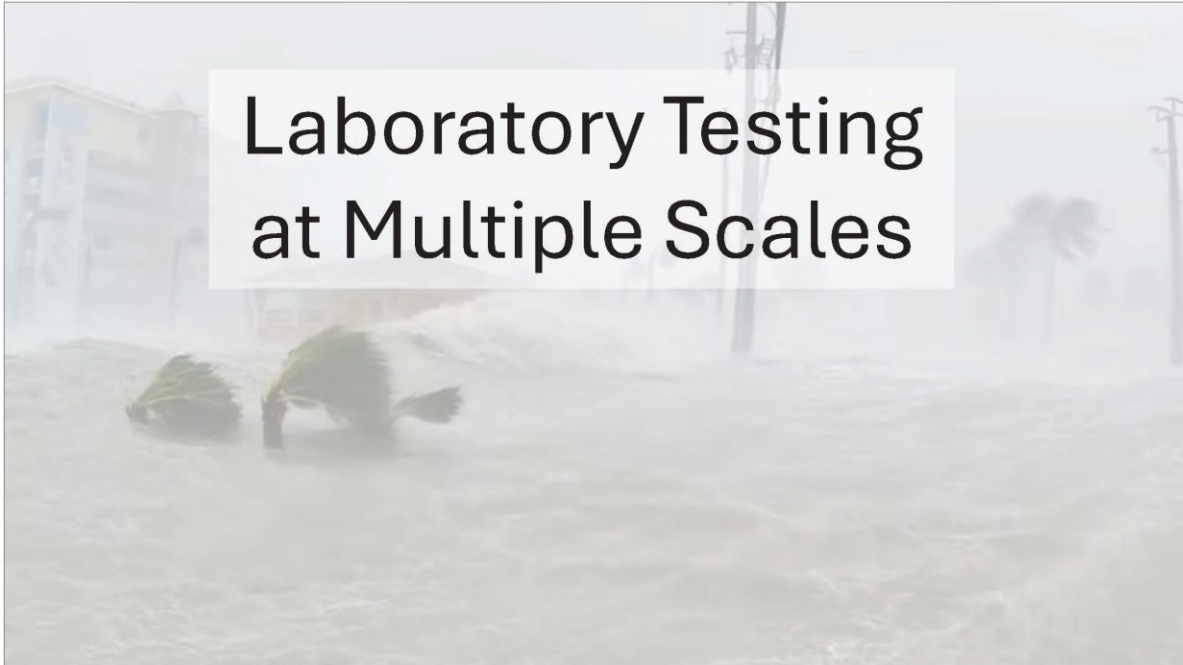
**PHYSICAL MODELS AND  
LABORATORY TECHNIQUES  
IN COASTAL ENGINEERING**



Steven A. Hughes

World Scientific

Hughes, 1993



**Laboratory Testing  
at Multiple Scales**

## Example of hydraulic/structural modeling at multiple scales

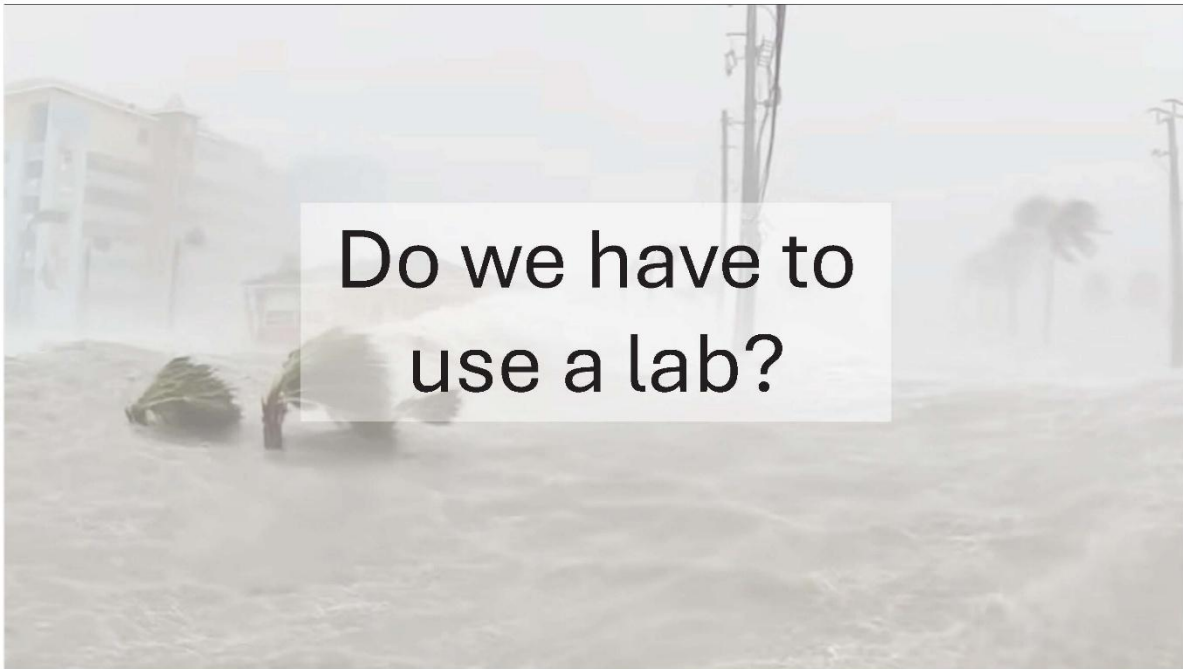


Hydraulic model study of a 1:5 scale bridge deck section subject to storm surge and waves.

Structural model study of a 1:1 scale of a bridge element subject to loads from 1:5 tests.


## Modeling at scale

	Community (1:50)	Building (1:6)	Elements (1:1)
Flood hazards	A	A	A
Shielding	A	B+	C
Sediment erosion	C+	B+	C
Sediment scour	C	B+	A
Pressure/force	B	A	A
Structure response	C-	B	A
Destructive testing	D	B-	A
Debris transport	A	B	C
Debris damming	C-	A	A
Debris impact	D	B	A

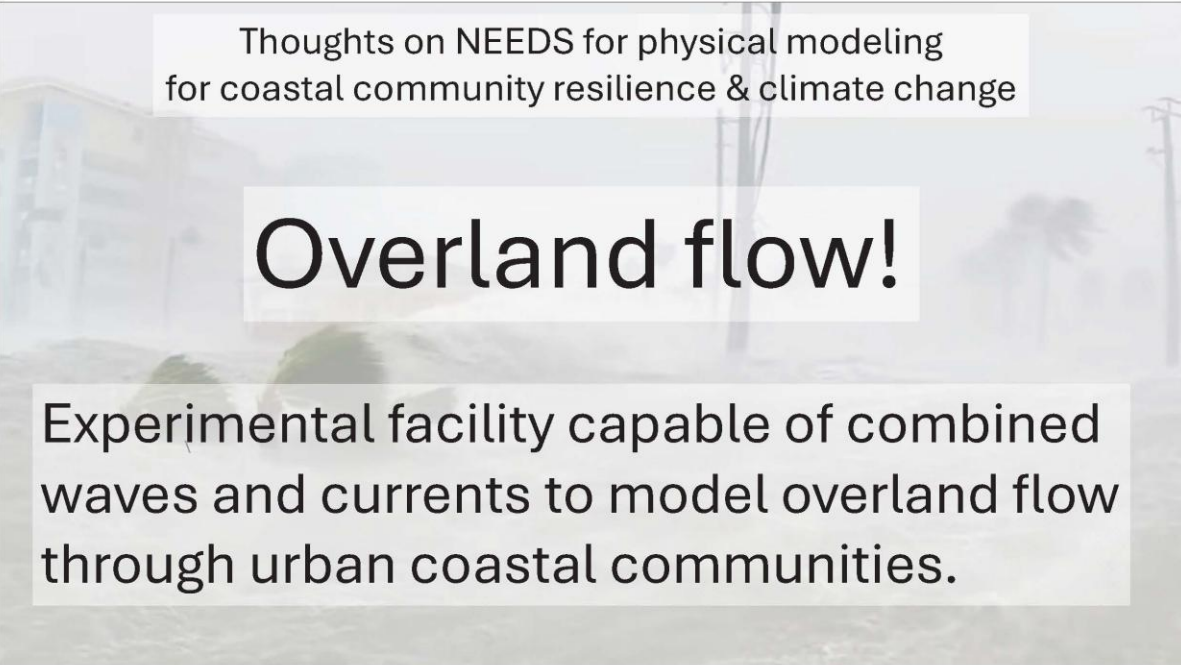


Idea from Bill Dally, Univ. North Florida  
Construct & instrument offsite  
Airlifted to FRF for testing





Thoughts on NEEDS for physical modeling  
for coastal community resilience & climate change



Thoughts on NEEDS for physical modeling  
for coastal community resilience & climate change

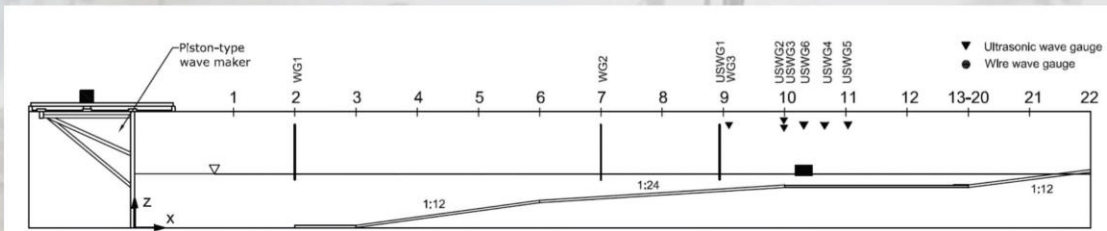
## Overland flow!

Experimental facility capable of combined  
waves and currents to model overland flow  
through urban coastal communities.

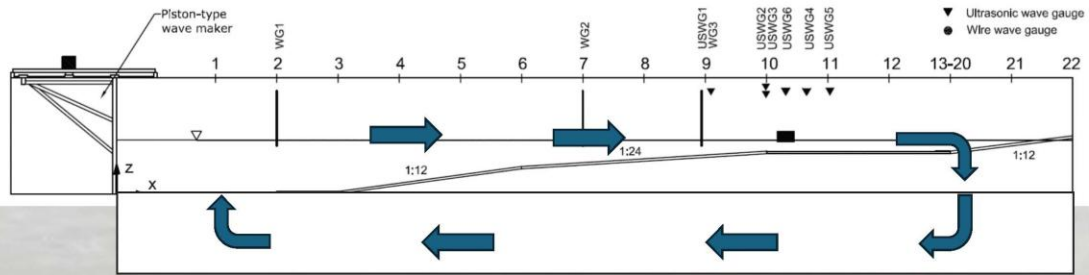
## Thoughts on NEEDS for physical modeling for coastal community resilience & climate change



## Thoughts on NEEDS for physical modeling for coastal community resilience & climate change



Thoughts on NEEDS for physical modeling  
for coastal community resilience & climate change

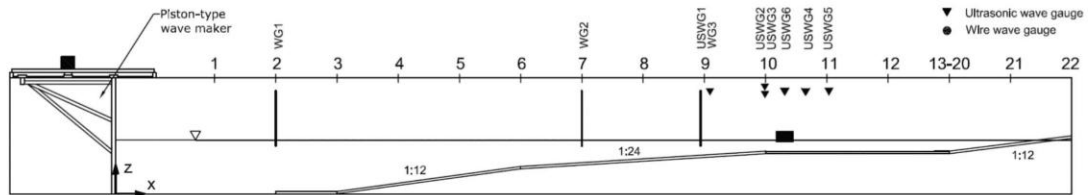


Thoughts on NEEDS for physical modeling  
for coastal community resilience & climate change

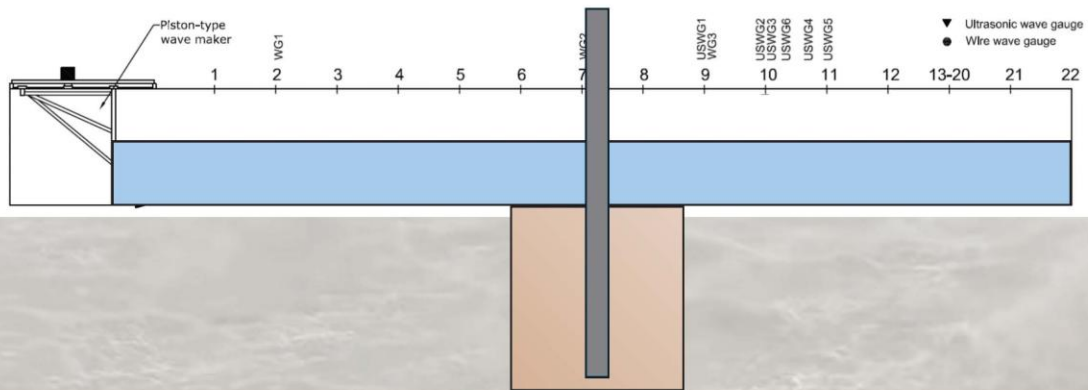
# Erosion and Scour!

Experimental facility capable of combined waves and currents induced erosion and scour in the presence of structures.

# Thoughts on NEEDS for physical modeling for coastal community resilience & climate change



# Thoughts on NEEDS for physical modeling for coastal community resilience & climate change



Thoughts on NEEDS for physical modeling  
for coastal community resilience & climate change

## Partnerships with Unique Coastal Laboratories Globally

US: ERDC, FRF (USACE)

Europe: GWK (Germany), . . .

Asia: DPRI (Japan), PARI (Japan)



GWK, \$38M upgrade in 2023

Thoughts on NEEDS for physical modeling  
for coastal community resilience & climate change

## Funding Mechanisms to Enable Multi- institutional Research Campaigns

- Complex bathymetry is prohibitively expensive for single-investigator proposals
- Several examples exist for nearshore processes (SUPERTANK 1991; Crosstex 2005; Dune3 2019)

## Experimental Facilities for Coastal Flood Resilience: State-of-Art and Needs



Daniel Cox Professor, Oregon State University  
PI NHERI Experimental Facility for Surge/Wave & Tsunami




# Thank you!

([dtc@oregonstate.edu](mailto:dtc@oregonstate.edu))

# Coastal Process Numerical Modeling: Existing Tools, Present Challenges, Future Directions

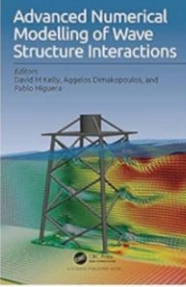
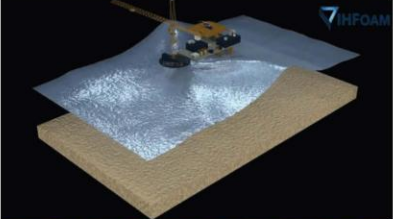
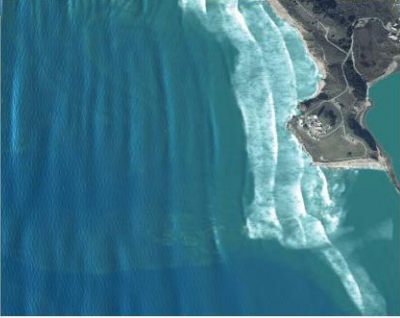
Patrick Lynett

Climate Adaptation Workshop:  
Structural Design for Coastal Flood Resilience  
Princeton University  
May 16-17, 2024



## Outline

- *Overview of Coastal Modeling (theories, approximations, numerical approaches)*
- *Computational expense, practicality of usage; application vs research*
- *Machine-Learning and other numerical modeling shortcuts; Faster-than-realtime computing and visualization*
- *Gaps in our modeling abilities*

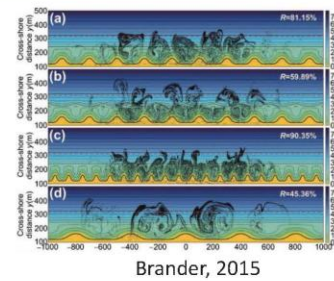


USC Immersive Computing for Coastal Engineering

2

## Overview of Coastal Modeling

- Consider hydro to be:
  - Weakly dispersive (wavelength > depth)
  - Highly nonlinear (wave height ~ depth)
  - Highly sheared (bottom, internal, surface shear)
    - Multi-phase (air, water, sediment)
    - Multi-material (fluid, sediment, debris, etc)
- Interactions across a wide range of spatial and temporal scales
- Wave Equation models vs Fluid Dynamics Models



## Overview of Coastal Modeling

- Wave Equation models (MSE, Nonlinear Shallow Water, KdV, Boussinesq, Multi-Layer)
- Used for coastal wave transformation over relatively large (10's to 100's of wavelengths) spatial extents
- Make some assumption about nonlinearity and/or dispersion. Implies an assumption of the vertical shape of the velocity and pressure distributions
- Shear and turbulence tend to be handled with an "engineering" approach; transport modeling follows



## **Overview of Coastal Modeling**

- *Wave Equation models for hydro – structure interaction*
- *Ideally suited for mildly sloping structures (sloped breakwaters, dunes, reefs)*
- *Vertical structures can be approximated in various ways*
- *Bottom roughness handled with a friction parameter*
- *1<sup>st</sup>-order approximation of hydrodynamic loads*
  - *Drag, added mass, etc*



Immersive Computing for Coastal Engineering

## Overview of Coastal Modeling

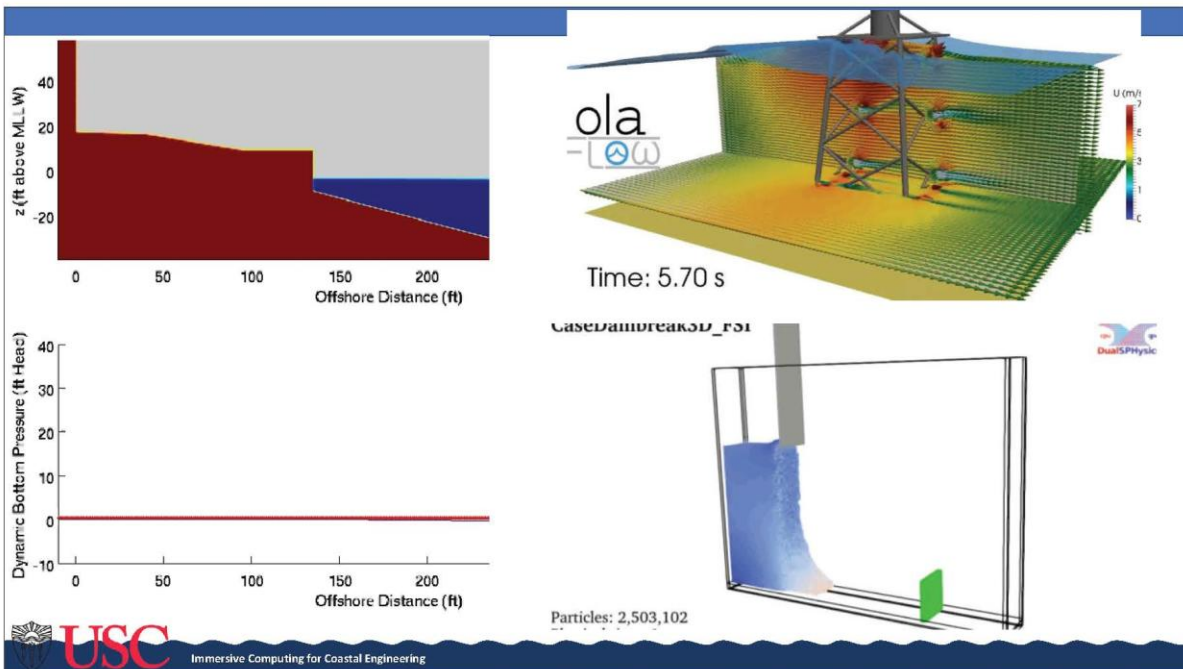
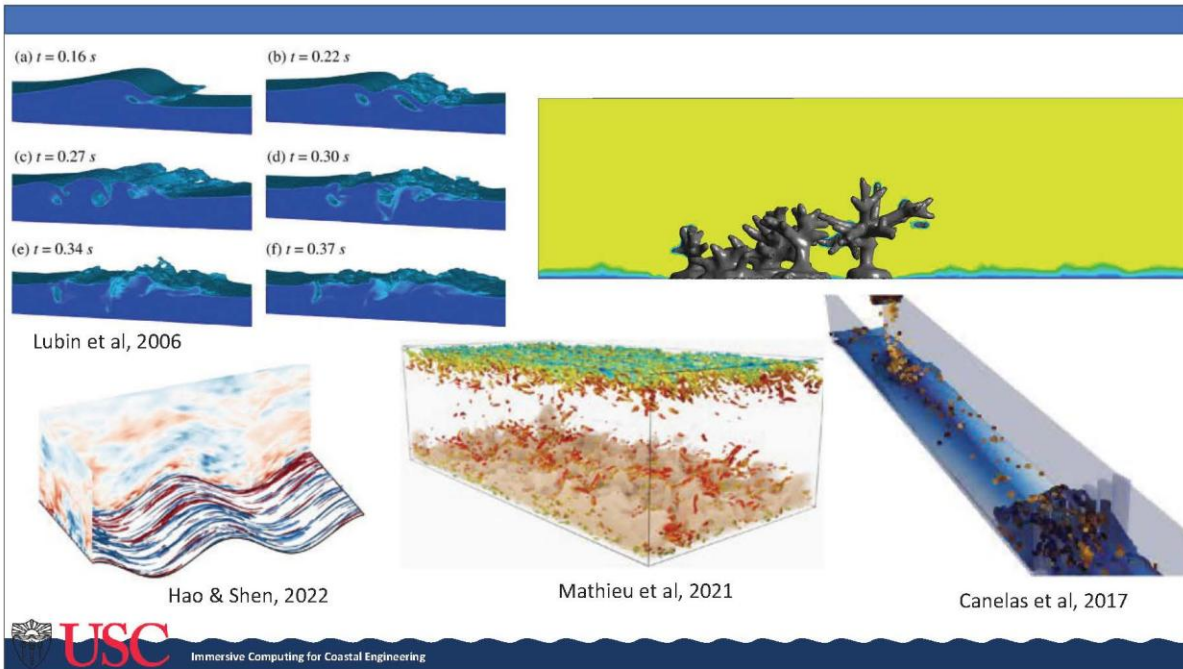
- *Wave Equation models (MSE, Nonlinear Shallow Water, KdV, Boussinesq, Multi-Layer)*
- *Best for:*
  - *Coastal process characterization for Civil Works projects*
  - *“Filling in the Gaps” for experimental (lab & field) studies*
  - *Providing boundary conditions for refined 3D simulation and experimental studies*
  - *Fast & reasonable characterization for experimental design [field scale resolutions  $O(1\text{ m})$  for wind waves]*



## Overview of Coastal Modeling

- *Fluid Dynamics Models (Euler/Potential Flow, RANS, LES, SPH, MPM, LBM, DNS)*
- *Used for coastal wave transformation over relatively small ( $\ll 1$  to  $\sim 10$  wavelengths) spatial extents*
- *Differences in these approaches lies in how they are averaged (in small time and space), how they handle the averaged-out components (turbulence models), and how they are gridded (or not gridded)*
- *Research-level simulations often require very fine grids*





## Overview of Coastal Modeling

- **Fluid Dynamics Models (Euler/Potential Flow, RANS, LES, SPH, MPM, LBM, DNS)**
- **Best for:**
  - **Understanding the 3D properties of complex flows, including multi-phase and multi-material**
  - **High fidelity transport, when coupled with proper turbulence models**
  - **Users with large computational resources and/or patience [field scale resolutions  $O(10\text{ cm})$  to  $O(1\text{ mm})$  for wind waves]**
  - **Discovery, if done with great care**

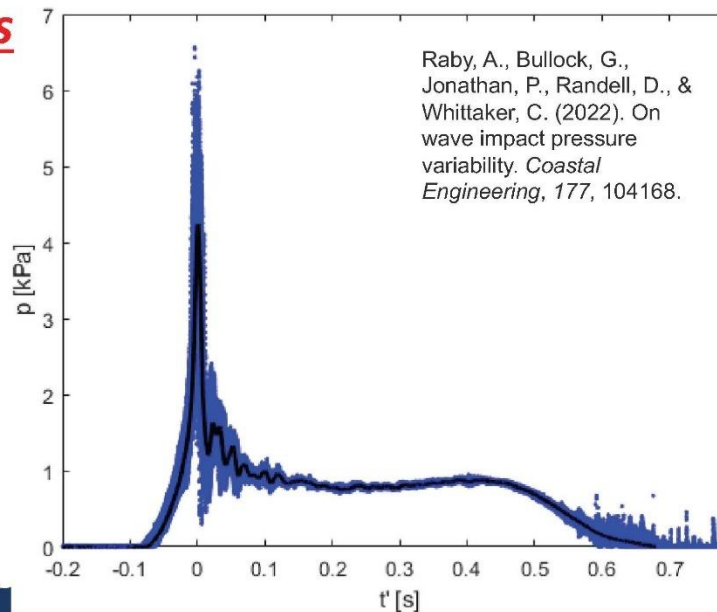
## Recent Advancements

- **For wave-equation models, robust (forgiving) solvers [double-edged sword; broadens general user base and application space, but narrows fundamental research applicability]**
- **Machine-learning [primary goal is to provide solution more quickly]**
  - **Area is currently exploding, but still difficult to apply for complex physics**
  - **Physics-informed NN [minimize error with governing equations during training]**
    - **Forward-prediction [strongly dependent on training of specific configuration, forecast a fraction of a period forward]**
    - **Sub-grid modeling [permits coarser resolution in numerical solution]**
    - **Proxy for the expensive components [e.g. Poisson Pressure Eqn in CFD, or dispersive terms in Wave Equation models]**
- **Efficient utilization of GPU's [ $>80$  TFLOPS on a single card]**
  - **Often requires a ground-up rethink of the numerical solution scheme**
  - **Enables concurrent computation, interaction, and visualization**

## Gaps & Challenges

We can model these things, but not sure how well...

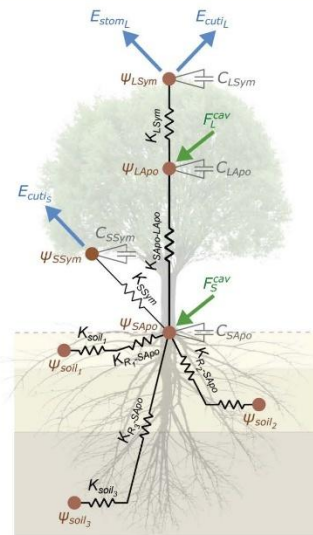
- Capturing uncertainty in detailed (3D) flow structure modeling
- Well established trial-to-trial variance in wave impact loads (in well controlled experiments)



## Gaps & Challenges

We can model these things, but not sure how well...

- Hydro-Morpho-Ecosystems modeling
  - Mortality & fragility of ecosystem components, short and long-time scales
  - Function of various stresses, both physical and environmental
  - How does strength (engineering function) change with environmental stress
  - Need to use real plants to find this information... can't scale them down



## **Gaps & Challenges**

*We can model these things, but not sure how well...*

- *Transport during extreme events in the built environment [or really anytime...]*
  - *Fundamental issues with numerical modeling of kinematics at the scales relevant for transport*
  - *Cyclone & tsunami events: floating debris in mixed wave, current, wind; Material properties of the debris*
- *Groundwater – ocean mixing; saline intrusion on various time scales*
- *Configurations with multiple materials and/or multiple phases*

## B.10 Padgett

Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience

   PRINCETON UNIVERSITY

May 16-17, 2024  
Princeton University

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# Coastal Bridges: Performance and Design for Coastal Resilience

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**Jamie E. Padgett**  
Stanley C. Moore Professor and Department Chair  
Department of Civil and Environmental Engineering  
Rice University  
Houston, Texas USA



Workshop Theme 3: Structural Engineering Design Approaches

Let's explore a few key topics... 

- Performance of bridges in past coastal storm events
- Evolution in research and practice
- Resilience quantification including structure to system to community scale analyses
- Opportunities for resilience enhancement

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## Coastal bridges are crucial pieces of infrastructure



- Typically most costly/unit length of transportation infrastructure
- May be iconic, cultural, heritage
- Vital links within roadway network
- Often cited as most vulnerable pieces of network to extreme events
- Critical for emergency response and long term recovery efforts
- Over 60,000 miles of coastal roadways are regularly susceptible to flood or surge from severe storms in the US.<sup>1</sup>



<sup>1</sup> S. L. Douglass, J. M. Richards, J. Lindstrom, and J. Shaw, "An Estimate of the Extent of U.S. Coastal Highways.," in *TRB Annual Meeting*, Washington, D.C., 2005.

## Past studies have emphasized the impact of climate change on coastal transportation infrastructure

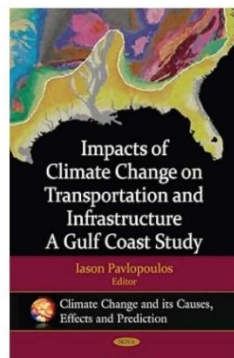


- Often focus on the threats to Gulf Coast transportation infrastructure<sup>1</sup>:
  - Increase in rainfall
    - Increase in scour potential
    - Increase in corrosion rate
  - Sea level rise
    - Increase in inundation possibility
  - Subsidence
    - Increase in inundation possibility
    - Potential damage to piers and foundations
  - Temperature rise
    - Pavement cracking
    - Increase in corrosion rate
    - Increase in maintenance costs

<sup>1</sup> CCSP 2008: Impacts of Climate Changes and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. DOT, Washington, DC.

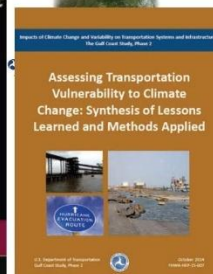
M. Meyer Presentation on Implications of Climate Change on Transportation Network/Facility Design

Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I



Gulf Coast Climate Change Adaptation Pilot Study  
Final Report

AUGUST 2010  
FTA Report No. 877  
U.S. Department of Transportation  
Federal Transit Administration  
1615 L Street, NW  
Washington, DC 20590  
www.fta.gov



Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Coast Study, Phase 2 (Mobile, Alabama)

## Typical coastal bridge failure modes during TCs: Impact damage



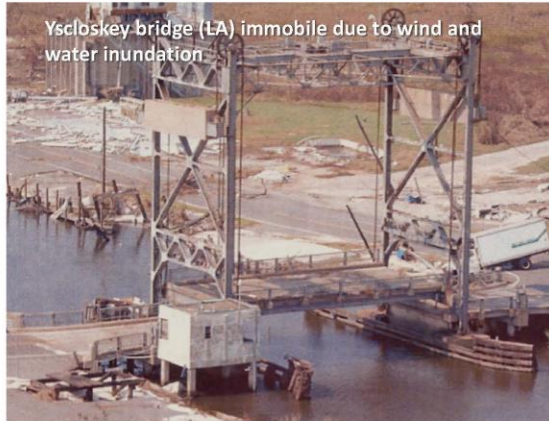
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## Typical coastal bridge failure modes during TCs: Scour damage



6

## Typical coastal bridge failure modes during TCs: Wind and water damage



Vulnerabilities of *Movable* Bridges

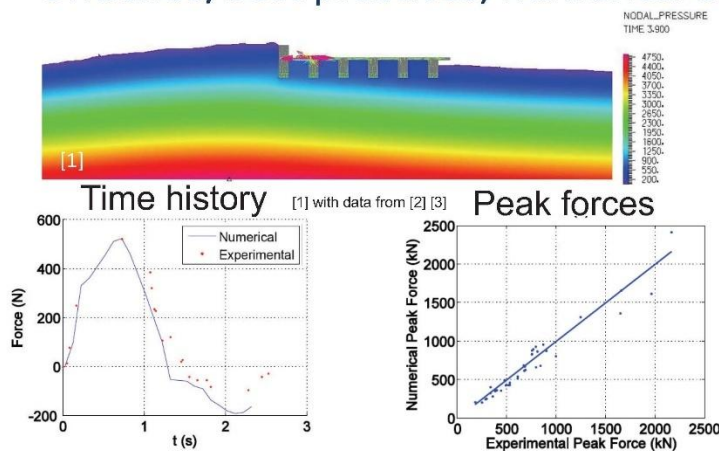
## Typical coastal bridge failure modes during TCs: Surge and wave induced damage



These experiences led to anecdotal evidence/best practices, numerical and experimental campaigns



These experiences led to anecdotal evidence/best practices, numerical and experimental campaigns

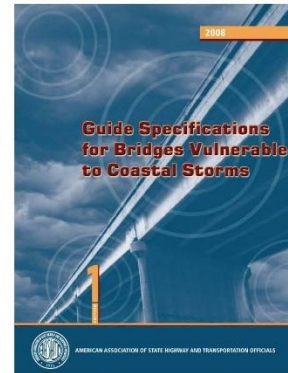


- Wave load modeling
- Influence of deck type, wave parameters
- Features like flexibility of superstructure

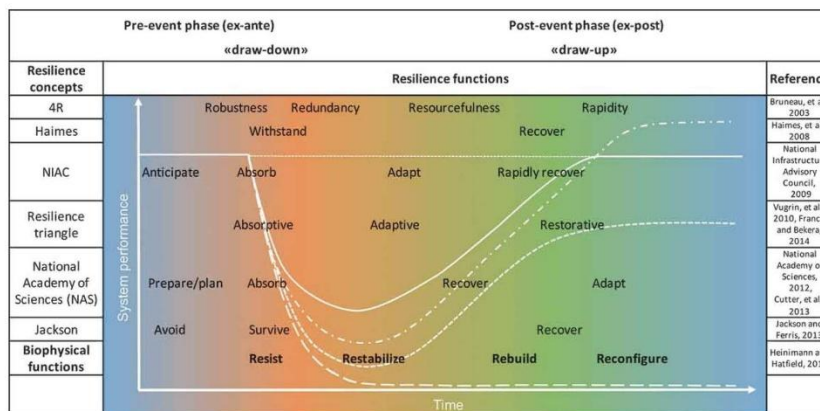
[1] Ataei and Padgett, 2010  
 [2] Bradner, 2008; OSU  
 [3] Sheppard and Marin, 2009; UF

## These experiences led to anecdotal evidence/best practices, numerical and experimental campaigns

- Subsequent work has addressed the development of models to predict the forces (primarily focused on bridge decks)
- Coastal Specs a result of pooled funds study
- Reinforced concepts
  - Elevation (e.g. 1 ft clearance over 100 yr)
  - Force accommodation
  - Force mitigation (open sacrificial parapets, holes in diaphragms to avoid entrapped air...)
- 2023 interim revisions



## Quantifying resilience requires us to evaluate potential for damage, restoration and recovery



- Structure scale
- Network / system scale

Figure 1. Example resilience characterization drawing from state-of-art review (Gasser et al. 2019)

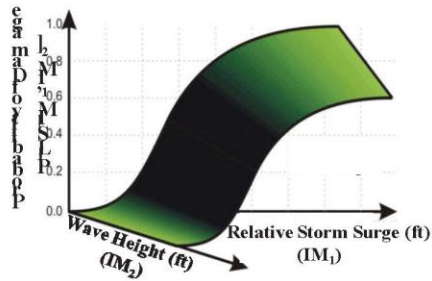
Gasser et al. (2019) "A review on resilience assessment of energy systems" *Sustainable and Resilient Infrastructure*. doi.org/10.1080/23789689.2019.1610600

# Quantifying resilience requires us to evaluate potential for damage, restoration and recovery



- Fragility analysis:
  - Empirical (e.g. Padgett and Spiller, 2008)
  - Analytical (e.g. Ataei and Padgett, 2012)
  - Simulation-based (e.g. Balomenos et al, 2020)
- Features emerging / requiring attention:
  - Multiple failure modes
  - Correlated failures and spatial variability
  - Coupled aging and deterioration
  - Alternative design details and retrofits

$$P_F = P[D > C | \mathbf{IM}]$$



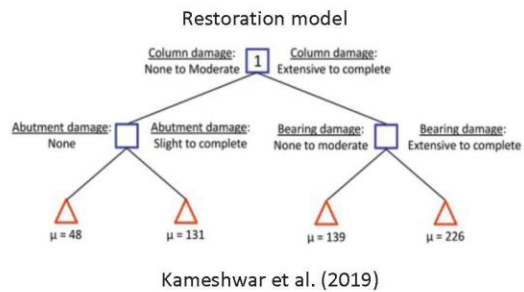
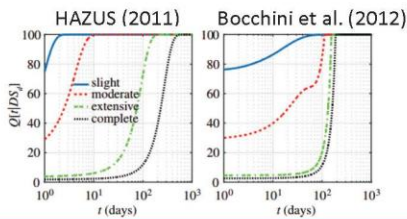
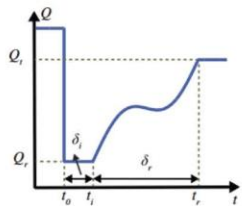
$$P(\text{Failure} | \mathbf{IM}, \mathbf{X}) = \frac{1}{1 + \exp(-l(\mathbf{IM}, \mathbf{X}))}$$

New FHWA project...

# Quantifying resilience requires us to evaluate potential for damage, restoration and recovery

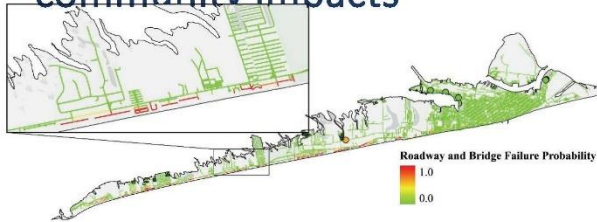


- Functionality and restoration functions:

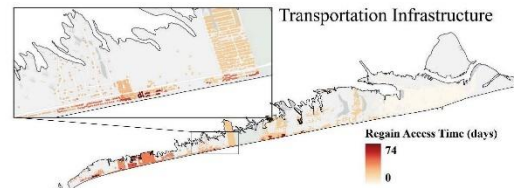
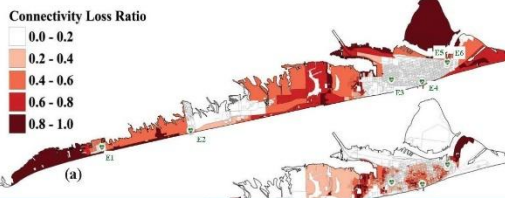


- Features emerging / requiring attention:
  - Explicit functionality ties
  - Explicit resource requirements

# Bridge resilience has direct impact on transportation network resilience and other community impacts

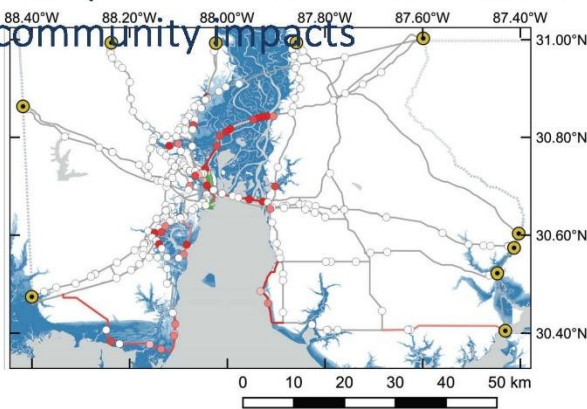


Galveston  
Jupiter Book



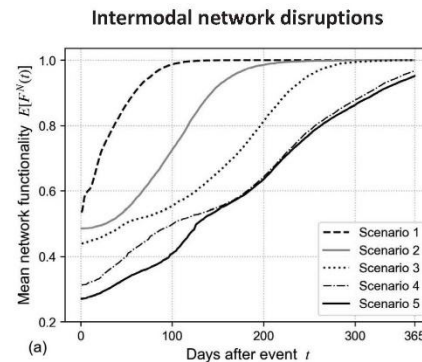
15

# Bridge resilience has direct impact on transportation network resilience and other community impacts



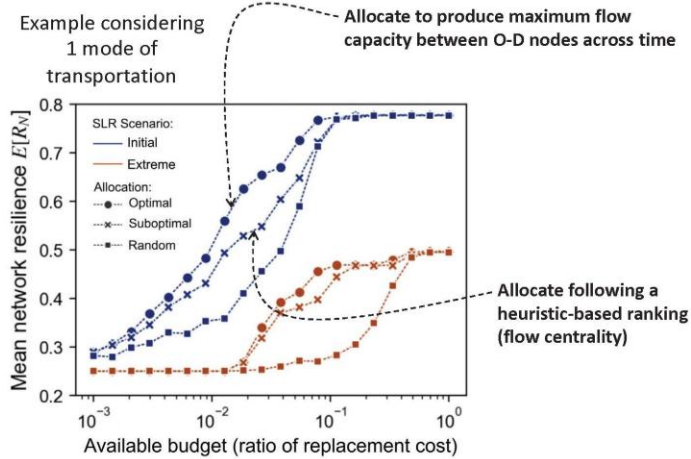
Surge height (m):  $\leq 1$  1-2 2-3 3-4 4-5  $> 5$   
 Expected bridge downtime (days):  $\circ$  0-30  $\circ$  30-60  $\circ$  60-120  $\circ$  120-240  $\circ$  240-365  
 Expected link downtime (days):  $-$  0-30  $-$  30-60  $-$  60-120  $-$  120-240  $-$  240-360

Tafur and Padgett, (in review). "Resilience modeling of diverse seaports and intermodal freight networks subjected to storm hazards"



16

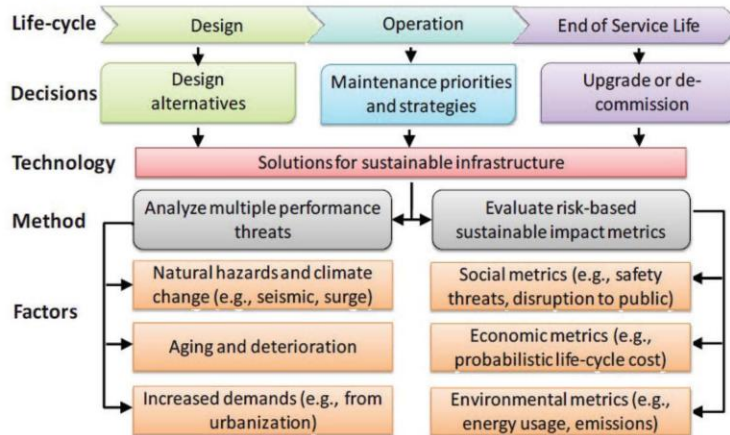
## Potential to support decisions on recovery resource allocation or preparedness



Tafur A., Argyroudis S., Mitoulis S. and Padgett J.E. (In Preparation); Tafur, Padgett and Gonzalez (2022)

17

## Consider enhanced bridge design through broader sustainability lens (including hazard resilience)



18

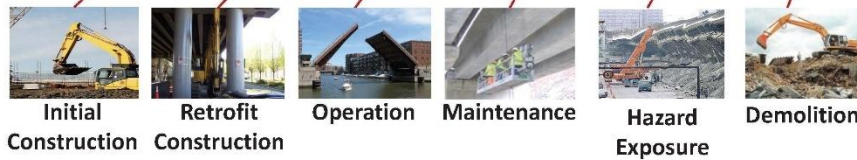
## Consider enhanced bridge design through broader sustainability lens (including hazard resilience)



- Life-cycle sustainability (LCS) indicator assessed as a sum of contributions from various life phases:

$$LCS(\mathbf{X}, T) = S_{ci}(\mathbf{X}) + S_{cr}(\mathbf{X}) + S_{op}(\mathbf{X}, T) + S_m(\mathbf{X}, T) + S_h(\mathbf{X}, T) + S_d(\mathbf{X}, T)$$

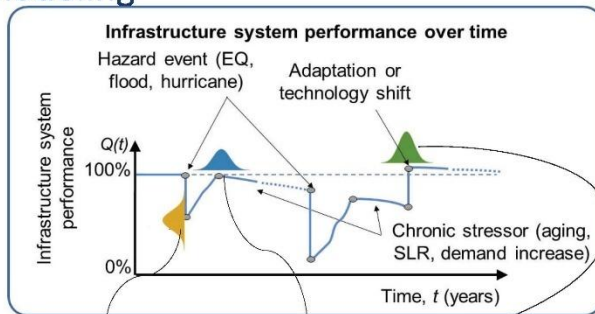
$\mathbf{X}$ =vector of continuous or categorical design parameters  
 $T$ =total service life



- Array of measures:
  - waste generation, embodied energy, emissions, monetary costs, etc

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## A pitch for "Smart and Equitable Resilience" Infuse intelligence into multi-hazard resilience modeling

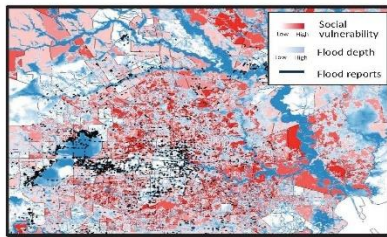


Example new information sources updating models in smart resilience platform

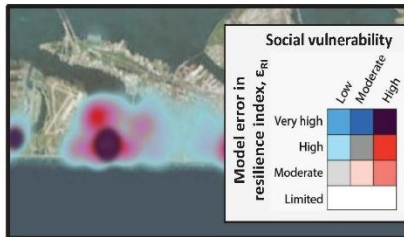
- Harness information from diverse data sources
- Leverage intelligent algorithms
  - Fuse data and learn from new information
  - Afford efficient and confident resilience estimation

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## A pitch for “Smart and Equitable Resilience” Uncover bias and promote equity in resilience quantification



Uncover and overcome data inequities and imbalances



Identify and improve equity in resilience predictions



Guide interventions that enhance equitable resilience

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## Other practical considerations when pursuing resilient bridges (systems that depend upon them)



- Design selection for heightened performance, new materials and systems
- Innovate adaptive structures
- Design decisions on sacrificial bridges or bridge elements
- Retrofit decisions on high priority bridges
- Post-event resource allocation
- Post-event budget requests
- Recovery/repair incentives
- Pre-event staging of materials and contracts



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# Acknowledgements




- Padgett Research Group
  - *Current:* Raul Rincon, Andres Calvo, Anibal Tafur, Kendall Capshaw, Jainish Patel, Kooshan Amini, Pranavesh Panakkal
  - *Former:* S. Kameshwar, Georgios Balomenos, Navid Ataei
- Collaborators
  - Colleagues from the NIST COE
- Rice University
- Funding agencies



- Workshop organizers and sponsors:





## B.11 Reis


 **Elevated Structures:  
Performance and Design for Coastal and Offshore Resilience**


**Cláudia Reis**

Department of Civil and Environmental Engineering  
Institute for Cyber Physical Infrastructure and Energy  
P.C. Rossin College of Engineering and Applied Science  
Lehigh University

 [claudia.reis@lehigh.edu](mailto:claudia.reis@lehigh.edu)

 **LEHIGH**  
UNIVERSITY

 **Content**



- Introduction
- Challenges
- Performance criteria
- Test-case

Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience, May 16-17 2024, Princeton University



## Introduction

- Data from the United Nations due to the resilience of coastal communities in the framework of climate changes
  - More than 680M people, nearly 10 percent of the global population, live in low-lying coastal zones.
  - Communities in low-lying areas are 15 times more likely to be killed by hydro-threats than less vulnerable regions
  - Need to reduce those impacts by developing strategies to enhance the resilience of coastal communities and ecosystems.
  - That includes:
    - Predict risk
    - Predict vulnerabilities
    - Develop strategic solutions towards sustainability

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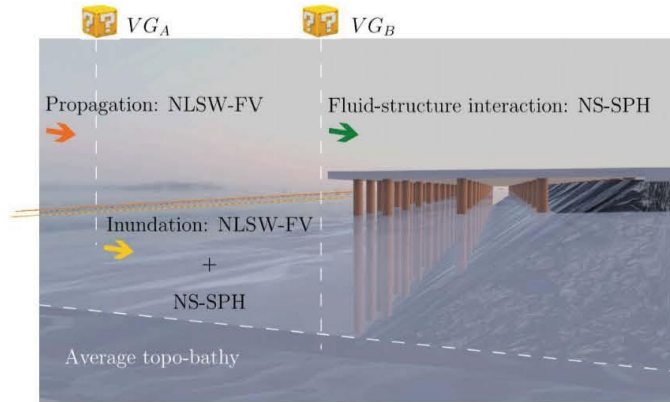
## Introduction

- United States has a goal of achieving 100% carbon pollution-free electricity by 2035.
  - The current national targets of offshore wind energy are to deploy 30GW by 2030 and 15GW of floating offshore wind energy by 2035.
  - For marine energy, the current targets are to deploy 50 MW by 2025, 500 MW by 2030, and 1 GW by 2035.
  - The US have abundant and geographically distributed resources, offshore wind and marine energy technologies that are critical in achieving this national goal.
  - To support the clean energy transition, new knowledge and technological innovations are required to overcome some barriers.

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## Challenges



Reis, Cláudia, et al. "A numerical methodology for estimating site-specific cascading earthquake and tsunami dynamic loading on critical infrastructure." *International Journal of Disaster Risk Reduction* 100 (2024): 104163.

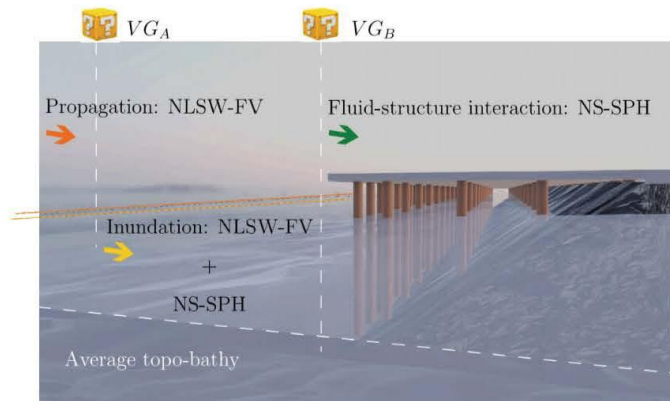
### Environmental conditions:

- frequent loads
- extreme loads
  - frequent natural hazards: usually with return periods in the order of the lifespan of the structure (50-100y return period events)
  - infrequent natural hazards: extreme events that have return periods in the orders of thousand(s) of years

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## Challenges



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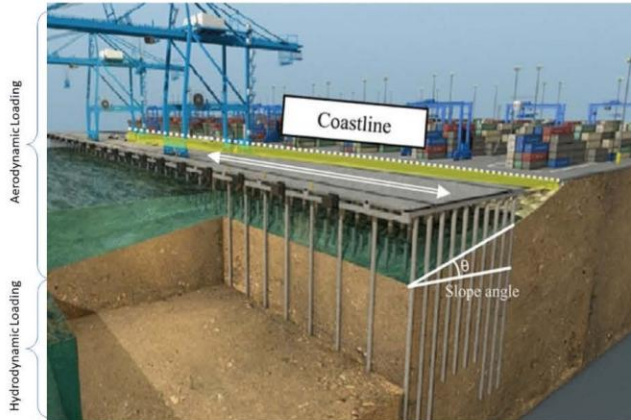
### Environmental conditions:

- often neglected:
  - time-dependent variations
  - sea level rising
  - topo-bathymetric conditions

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## Challenges

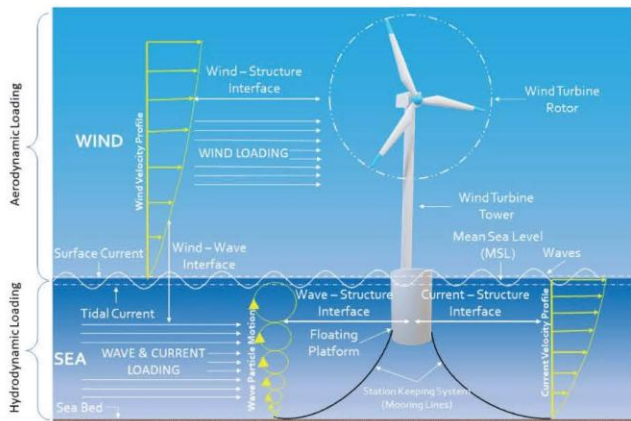


- often neglected fluid(s)-solid(s) interactions including:
  - hydrodynamic loading
  - supra-structure
  - infra-structure
  - soil
- often neglected are also the compatibilities between the performance criteria of cyber and physical components

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## Challenges



### Critical infrastructure:

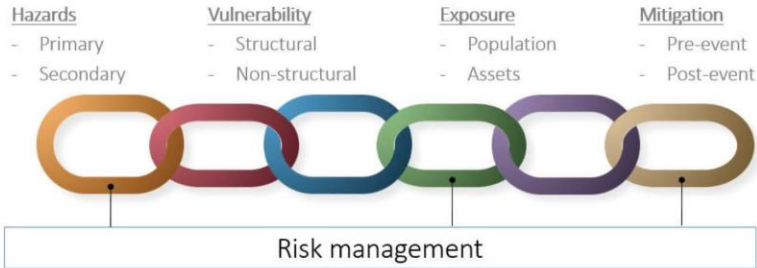
- better understanding of coupled aero-hydro-geotechnical-structural interactions
- and acknowledging the major source of uncertainty are the natural conditions in short and long time periods

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## Performance criteria

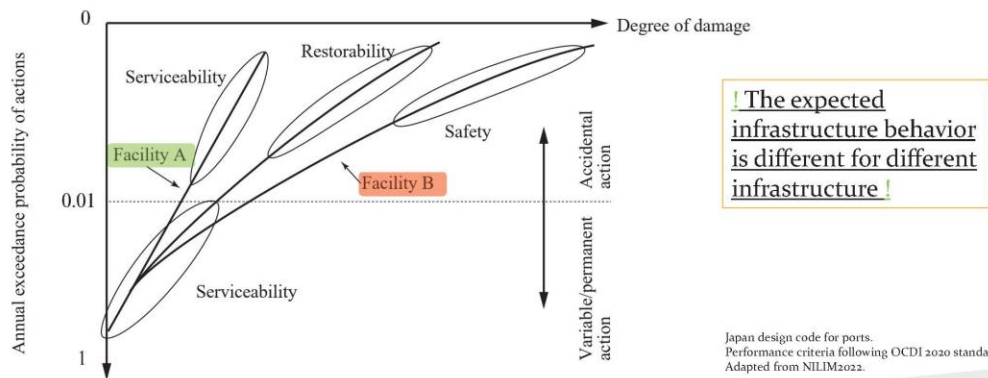
$$R_{NH} = f(NH_p | NH_s, V, E)$$



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## Performance criteria



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## Performance Criteria



### Delivering Climate Responsive Resilient Building Codes and Standards

Findings from the Global Resiliency Dialogue Survey of Building Code Stakeholders in Canada, Australia, New Zealand and the United States

November 2021



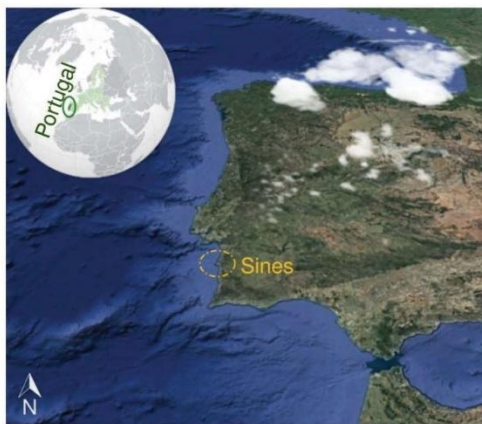
#### Important to:

- bridge the gap among recommendations from different design codes and standards for regular structures
- target hazard assessment to define loading patterns for critical infrastructure

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## Test case



### Mega-data center in Sines, Portugal

Portugal attracted 3.5 billion to handle the data of the BIG4 Facebook, Google, Amazon, Microsoft, and many others of IT with one of the largest mega data centers

#### Contractual agreement to:

- characterize design loading pattern due to cascading earthquake and tsunami multi-hazard
- provide design recommendation to successive actions

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## Test case



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## Test case

### Task 1:

- collect, organize and prepare topo-bathymetric and data-center design data,
- collect grids for the numerical simulations,

### Task 2:

- identification of potential regional/local tsunamigenic sources within Southwest Iberia region,
- characterization of the source parameters for each source, including single and composed ruptures. Each source rupture corresponds to a multi-hazard scenario,
- generation of the initial conditions for the earthquake and tsunami simulations,

### Task 3:

- topo-bathymetric conditions - nested grids using 200m discretization on open ocean and high-resolution 1m-grids on coastal site,

### Task 4:

- seismic simulation of the multiple scenarios using Ground Motion Prediction equations

### Task 5:

- tsunami simulation considering:
  - tidal influences – mean and high sea level conditions
  - climate changes influences – sea rising (only expansion configs of port)
- port configuration influences
  - current configuration
  - configuration after expansion of Terminal XXI,
  - configuration after expansion of Terminal XXI and construction of the new Vasco da Gama terminal.

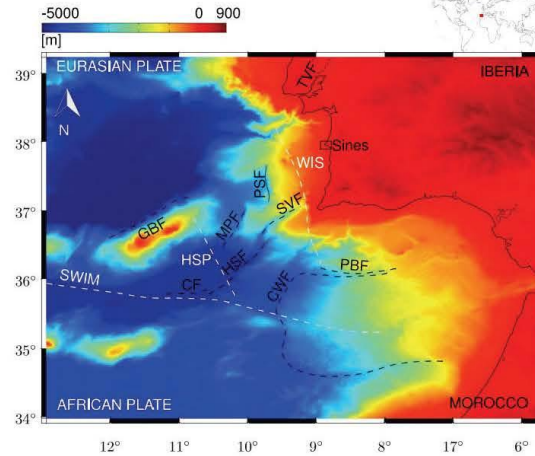
### Task 6:

- dynamic loading patterns
  - seismic acceleration
  - tsunami forces
- design recommendations for high performance criteria.

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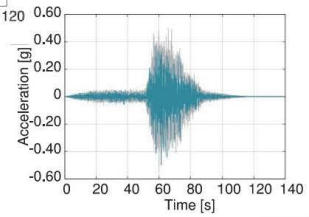
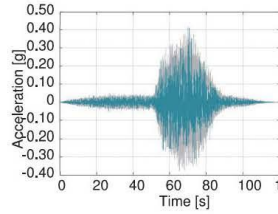
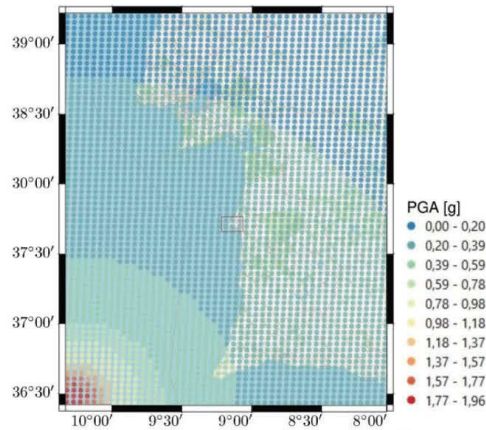
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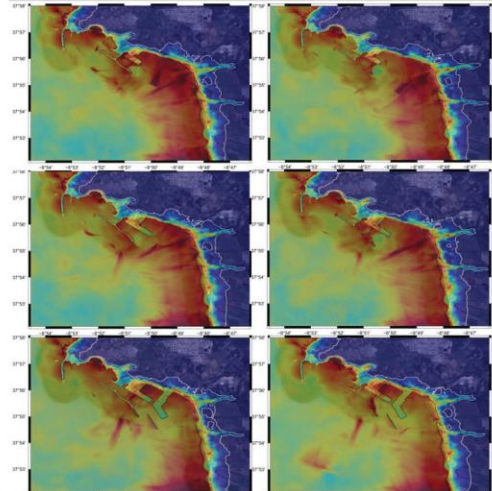
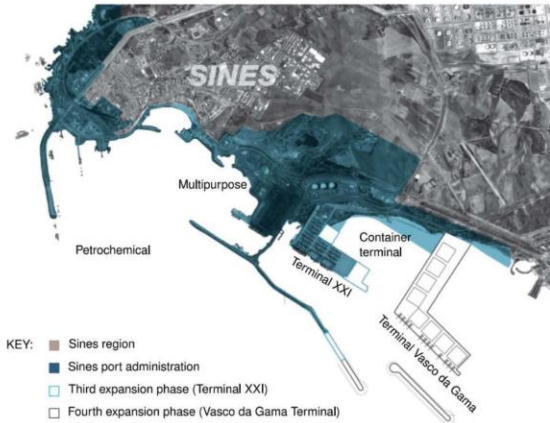
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- design recommendations for high performance criteria.

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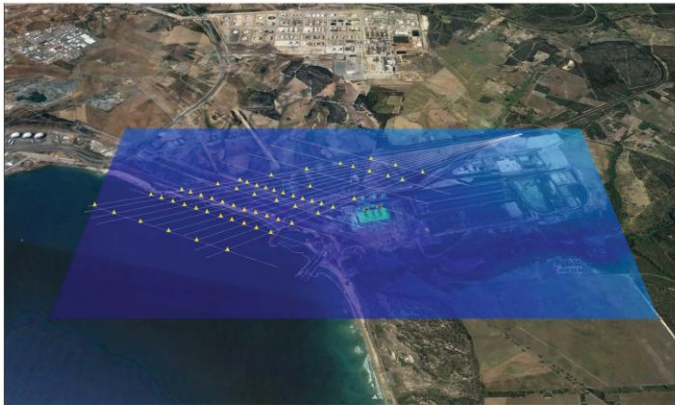
## Test case



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## Test case



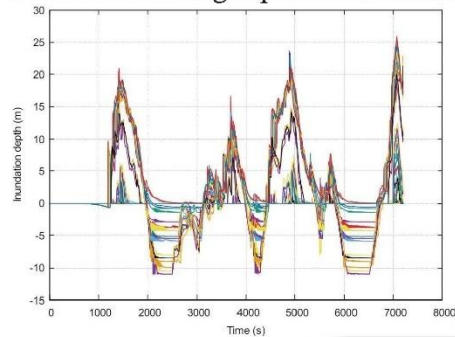
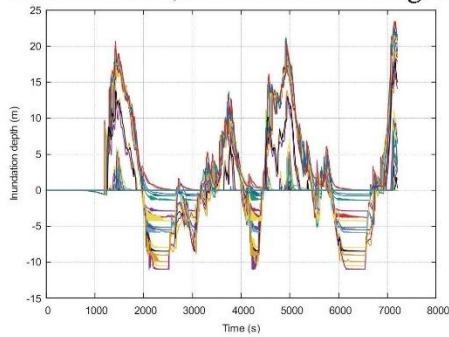
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## Conclusions

Tsunami scenarios - wave height @ shoreline:

HSL current sea, HSL and rea rising due to climate changes prediction



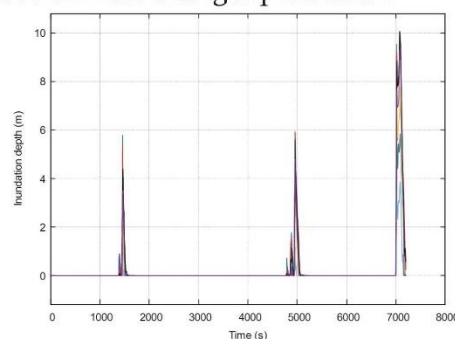
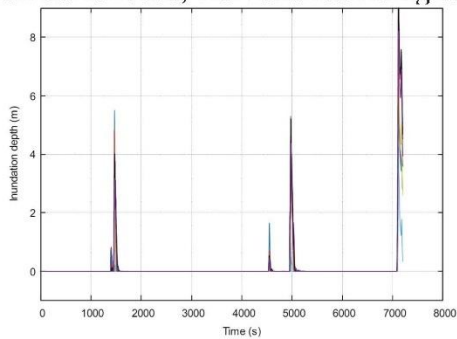
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## Conclusions

Tsunami scenarios – inundation depth @ virtual gauges:

HSL current sea, HSL and rea rising due to climate changes prediction



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## Conclusion

- Then we provided coupled loading patterns for the hazardous scenarios and design recommendations
- The main conclusions are simple:
- Loading characterization
  - importance of time-dependent variables when characterizing loading patterns for critical infrastructure and considering
- Design of infrastructure:
  - interactions, interactions, interactions!
- The implementation of the conclusions are challenging due to high uncertainty, complexity of the phenomena involved in fluid(s)-solid(s) interactions.

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## B.12 Do

**Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience**




   **PRINCETON UNIVERSITY** **May 16-17, 2024**  
**Princeton University**

**Performance Based Design Approach to  
Coastal Design of Structures**

**Trung Do, Ph.D., P.E.**  
*University of South Alabama*

 **UNIVERSITY OF SOUTH ALABAMA**  **Colorado State University**  **Oregon State University**  **COASTAL RESILIENCE CENTER**  
*A U.S. Department of Homeland Security Center of Excellence*

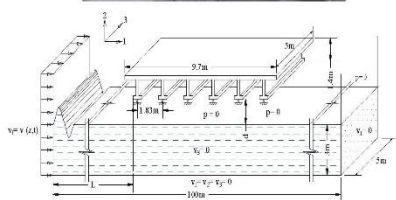
**Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience**

   **PRINCETON UNIVERSITY** **May 16-17, 2024**  
**Princeton University**

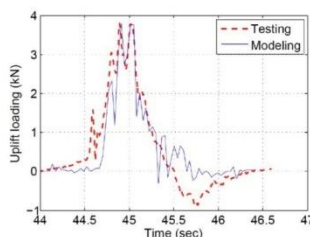
**Outlines**

1. Fluid/Structurers interaction testing and modeling
2. Physic based fragility method for wave and surge
3. Fragility Applications for Performance Based Design
4. Multi-hazard fragilities

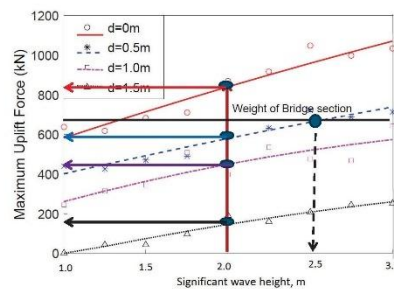
### One-sixth scale bridge superstructure test



One-sixth scale bridge model and sketch of full scale in numerical model



Compare result for total uplift on bridge between model and test

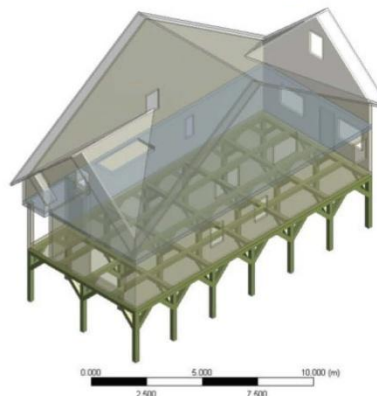


In some cases, total uplift exceed the self-weight of bridge superstructure causing failure

### Building models

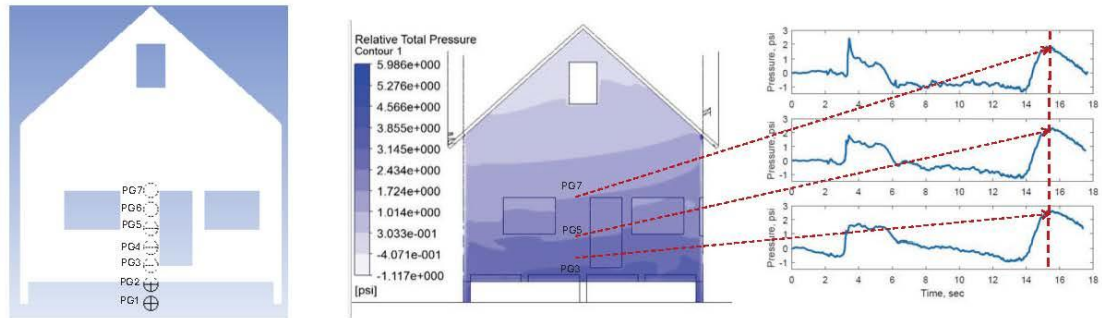


- The buildings are modeled in ANSYS Fluent
- Piles rising from 0, 1m, 2m, and 3m, from the ground
- TMA spectrum for hurricane waves with  $H_s = 1, 2, \text{ and } 3 \text{ m}$
- Wave peak period,  $T_p$ , from 8s to 14s
- Surge (SWL, food) levels  $h = 1, 2, 4 \text{ m and } 6\text{m}$

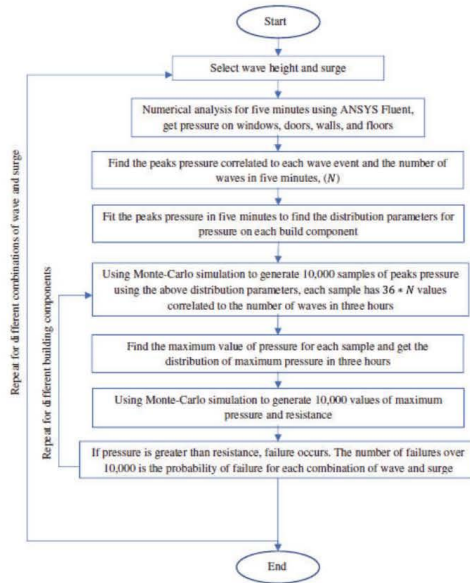


Archetype 1 With 3-m elevated pile from ground

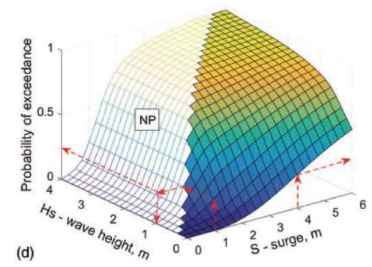
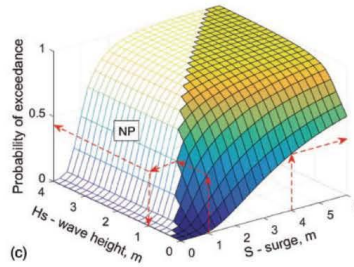
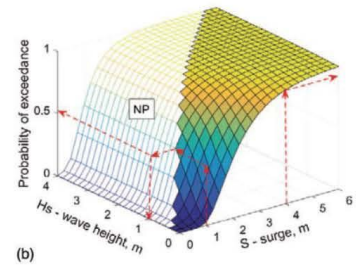
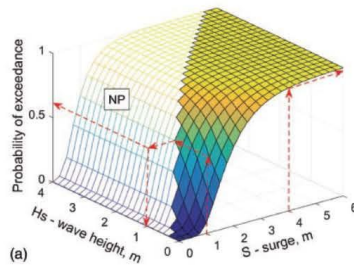
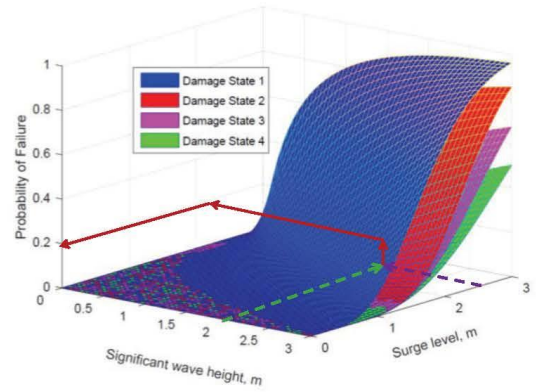
## Pressure measured location and distribution at one wave impact event



Component	Damage State				
	0	1	2	3	4
<b>Roof</b>	<ul style="list-style-type: none"> <li>No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>Few shingles missing (&lt;1% of roof area)</li> <li>Minor damage to gutters</li> </ul>	<ul style="list-style-type: none"> <li>Significant amount of shingles missing 15-30% of roof area</li> <li>minor damage to frame</li> <li>Interior of roof is not exposed</li> </ul>	<ul style="list-style-type: none"> <li>Holes in roof due to debris or wind-sheathing is exposed but not house interior</li> </ul>	<ul style="list-style-type: none"> <li>Large parts of roof are missing or collapsed, structural damage</li> <li>Roof sheathing failure</li> </ul>
<b>Walls</b>	<ul style="list-style-type: none"> <li>No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>Minor cladding removal (&lt;10% of 1 wall)</li> <li>Small scratches/ aesthetic damage</li> </ul>	<ul style="list-style-type: none"> <li>Cladding removed from &gt;25% of wall surfaces</li> <li>Interior sheathing exposed on &lt;25% of house but insulation and house interiors are not</li> </ul>	<ul style="list-style-type: none"> <li>Minor structural wall damage, including debris caused holes or repairable damage</li> <li>Wall failure with 1 bolt</li> </ul>	<ul style="list-style-type: none"> <li>Walls have collapsed, bent or are out of plumb, structural damage</li> <li>Large holes in walls</li> <li>major structural damage</li> <li>Wall failures with 2 two or more bolts</li> <li>Floor Failure</li> </ul>
<b>Openings: Windows, Doors, Attached Garages</b>	<ul style="list-style-type: none"> <li>No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>1 window or door is broken (glass only)</li> <li>Screens may be damaged or missing</li> </ul> <p>01 Window/door damage</p>	<ul style="list-style-type: none"> <li>Windows/doors broken or removed</li> <li>Damage to frames of doors and windows</li> <li>Attached garage door damaged or gone (bent or otherwise broken)</li> </ul> <p>02 Window/Door/Gara Door Failure</p>		
<b>Interior/Surge</b>	<ul style="list-style-type: none"> <li>No visible damage</li> </ul>	<ul style="list-style-type: none"> <li>No flooding</li> <li>Minimal/no evidence of rain intrusion- minor water damage in corners or around windows only</li> <li>Minor water damage to interior furnishings</li> </ul> <p>Surge not reach the floor</p>	<ul style="list-style-type: none"> <li>Slight evidence of flooding</li> <li>Water marks (0-1') above floor</li> <li>Evidence of rain intrusion-dampness/ minor water damage on &lt;10% of wall area or ceiling</li> <li>Water damage to interior furnishings</li> <li>No mold</li> </ul> <p>Surge 0-1ft above the floor</p>	<ul style="list-style-type: none"> <li>Water marks (1'-4')</li> <li>Rain/water damage to ceiling: wet spots, dripping, or sagging</li> <li>Dampness on &gt;25% of wall areas</li> <li>Evidence of dripping or cracks on walls</li> <li>Mold</li> </ul> <p>Surge 1-4ft above the floor</p>	<ul style="list-style-type: none"> <li>Water marks 4' or higher</li> <li>Structural ceiling damage from rain- wet spots and sagging</li> <li>Structural Damage to interior walls</li> </ul> <p>Surge &gt;4ft above the floor</p>

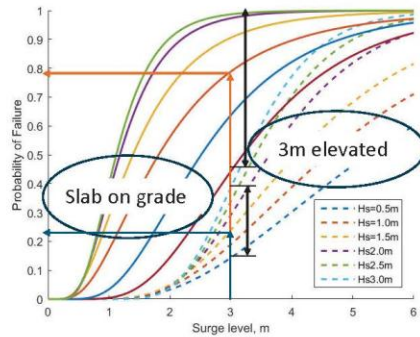


Fragilities surfaces for building subjected to wave and surge



IN-CORE (Interdependent Networked Community Resilience Modeling Environment)

Fragility curves for 1 story-building subjected to wave and surge (DM4 - Destruction)



At  $S=3\text{m}$  (surge level) and  $H_s=1.5\text{m}$  (Significant wave height)  
 - Probability of failure for slab on grade building is  $P_f=78\%$

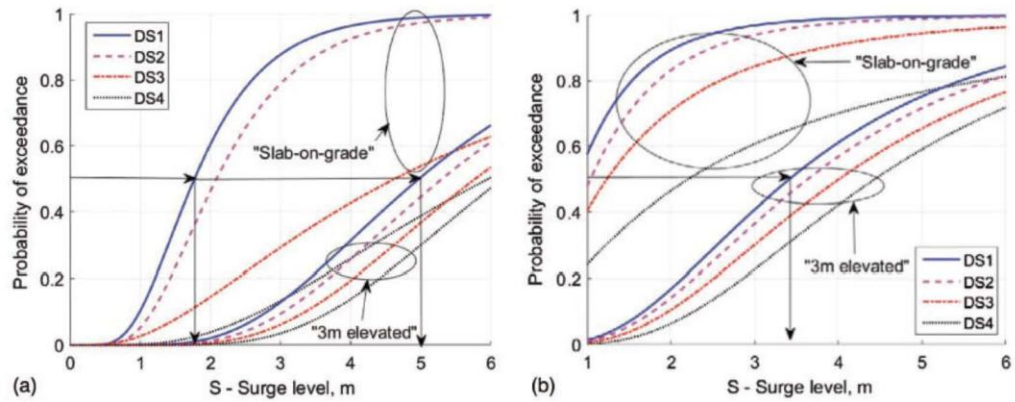
- If building was elevated to 3m,  $P_f=22\%$

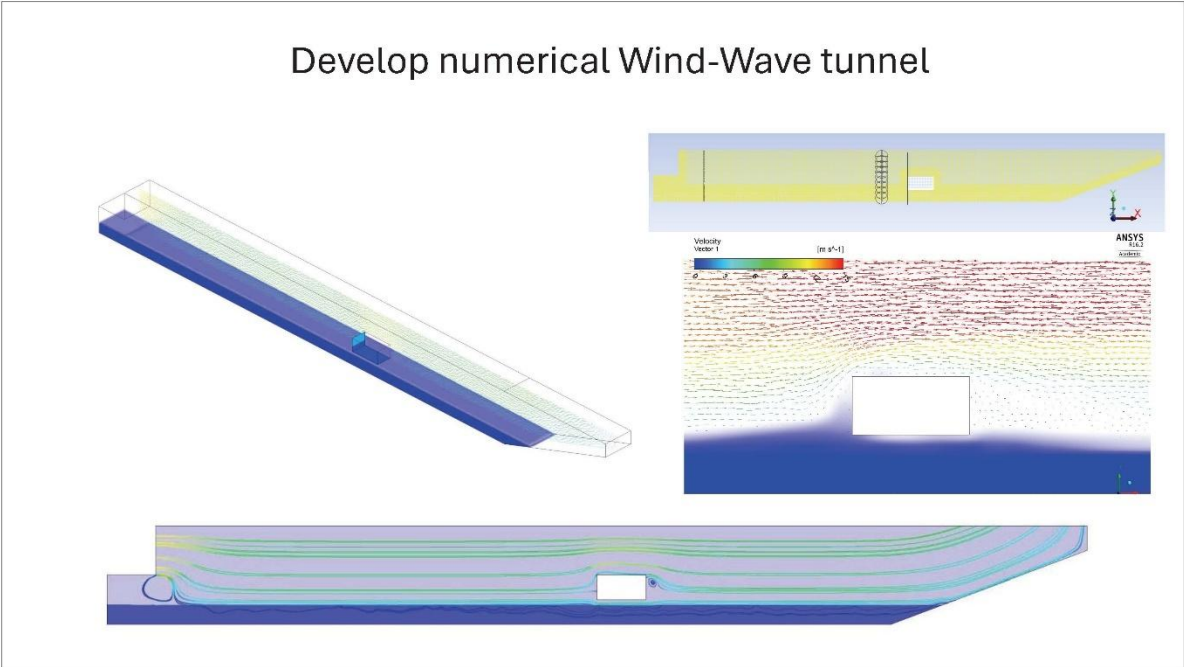
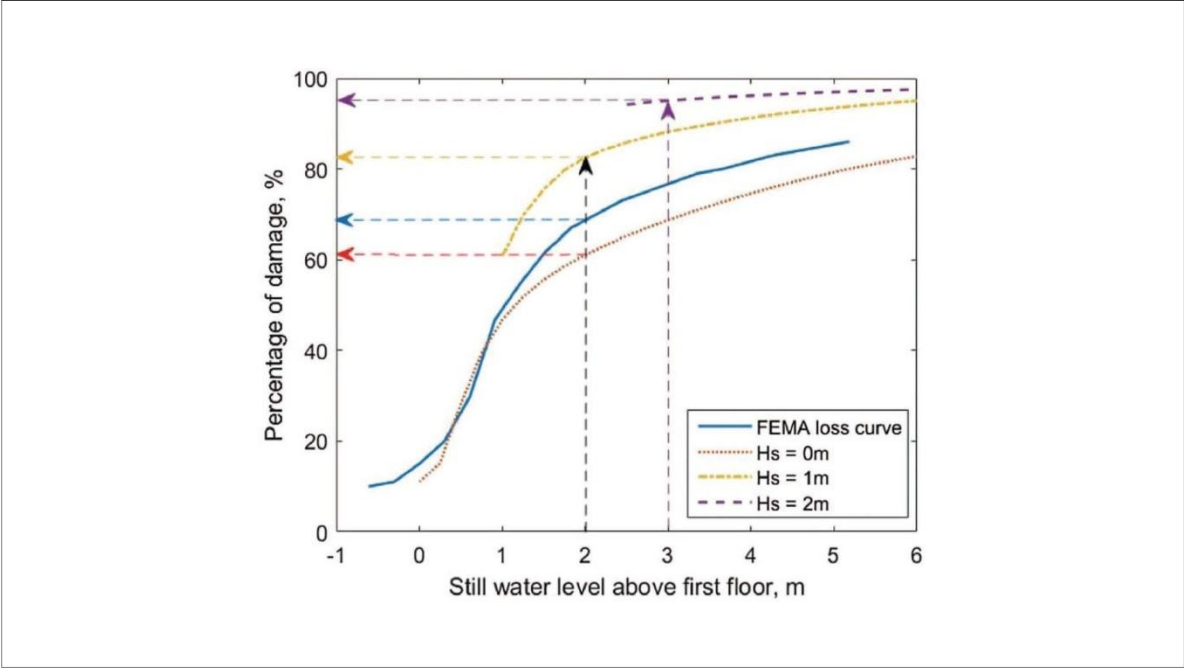
At surge level of 3m and with the effects of wave ( $H_s$  from 0.5m to 3.0m), the probability of failure for slab on grade building is 45% - 100%

For 3m elevated with the same environmental conditions, probability of failure reduces to 15%-40%

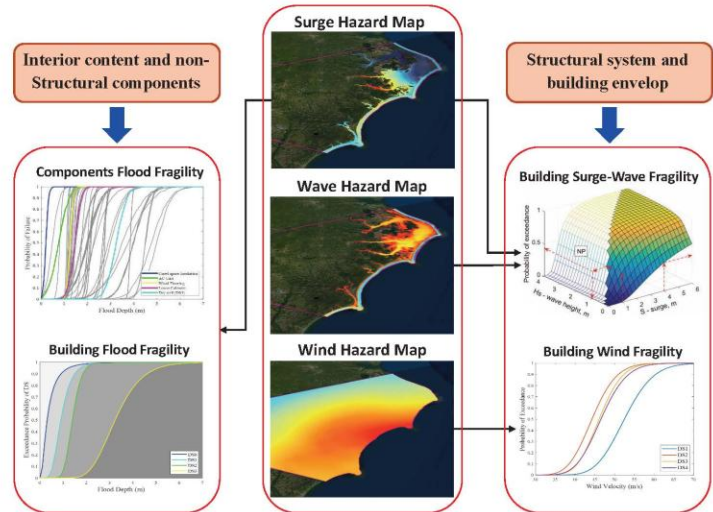
Fragility curve for some specific significant wave heights:

(a) significant wave height,  $H_s = 0\text{m}$ ; and (b) significant wave height,  $H_s = 1\text{m}$ .





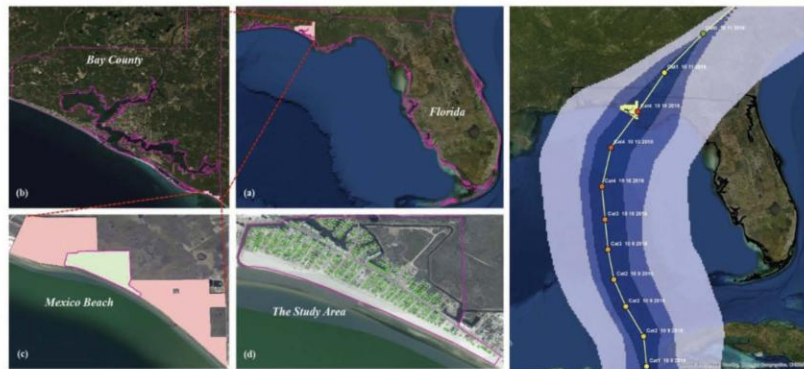
- Each component within the building could be vulnerable to one or multiple hazards depending on the component type and the hazard characteristics.
- The vulnerability of the structural components is calculated from the surge-wave and wind fragilities.
- The vulnerability of the interior contents is calculated from the flood fragility.



• Nofal et. al., 2020

## Example Community: Mexico Beach, FL

Mexico Beach was severely impacted by the 2018 Hurricane Michael causing damage to nearly all the buildings and destroying a huge number of these buildings. Therefore, Hurricane Michael was used to validating the developed multi-hazard hurricane vulnerability model. Detailed building information was collected about the buildings before and after Hurricane Michael.



Jaimlyn Sypniewski, Omar Nofal, Trung Do

## Example Community: Mexico Beach, FL

Mexico Beach color-coded buildings based on the data collected from several teams. There is some overlap in the collected data from each source which will be used to propagate uncertainties in the damage assessment process.



Jaimlyn Sypniewski, Omar Nofal, Trung Do


# Thank you!

Trung Do, Ph.D., P.E.

Assistant Professor, Department of Civil, Coastal, and Environmental Engineering,  
University of South Alabama

[trung.do@southalabama.edu](mailto:trung.do@southalabama.edu)

## B.13 Coulbourn



**Coastal Resilience Needs & Challenges  
from a Structural Engineering Perspective**

William L. Coulbourn, PE, F.SEI, F.ASCE

### What Currently Happens During Coastal Storms due to Storm Surge

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- Water/storm surge knocks down or damages buildings
- Buildings flood and contents are damaged
- Erosion damages foundations/buildings collapse
- Buildings float off their foundations

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## Results from Recent Hurricanes

- The following are recent examples of the damage from Hurricanes Michael (2018) and Ian (2022)
- Both hurricanes hit Florida where the strongest building codes in the nation exist for protection from high winds and storm surge

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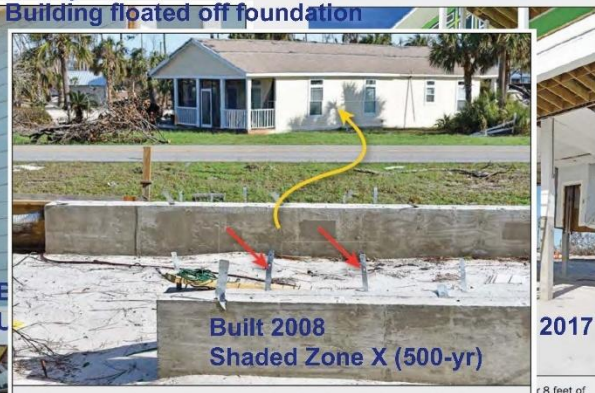


## Michael 2018

Damage from waves and storm surge



Erosion at foundation



In the foreground is former foundation with metal straps (red arrows). The home detached and floated approximately 80 feet across the street before striking a neighboring structure (yellow arrow).

8 feet of mate

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## Ian 2022

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### Erosion



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### Structural damage from flood debris



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## NIST Roadmap to Coastal Resilience

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- Report written in 2014
- Included 4 topic areas that relate to coastal inundation
  - Coastal Inundation Hazards
  - Coastal Inundation Loads
  - Resistance to Coastal Inundation
  - Performance-based Design for Coastal Inundation
- Each of the topics had specific research 'projects' identified that were deemed important to the 'coastal hazards community'

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## NIST Roadmap to Coastal Resilience

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- Definition of Resilience in the Roadmap is:
  - “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” (National Academies Press, 2012)
  - “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruption” (Presidential Policy Directive PPD-21, 2013)

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## NIST Roadmap Research Priorities

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- Coastal Inundation Hazards
  - Effects of sea level rise and future shoreline changes
  - Quantification of flood-borne debris hazards
  - Effects of over-land flow on waves and other coastal inundation hazards
  - ~~– Characterization of the coastal inundation hazard for low probability events (extreme or high MRI events)~~
- Coastal Inundation Loads
  - Field data collection of flood loads
  - ~~– Load combinations for simultaneous flood hazards~~
  - Validation of flood forces on buildings

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## NIST Roadmap Research Priorities

---

- Resistance to Coastal Inundation
  - Flood damage functions and fragility curves
  - Effects of erosion and scour on deep foundations
  - ~~– Test methods for materials and systems subject to flooding~~
- Performance-based Design for Coastal Inundation
  - Performance levels and acceptance criteria for buildings subject to coastal inundation
  - Sound engineering basis for flood resistant design that is not based on flood insurance requirements

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## NICHE Research

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- NSF funded program titled National Full-Scale Testing Infrastructure for Community Hardening in Extreme Wind, Wave and Surge Events (NICHE)
- Program is \$12.8 million over 4 years (began 2022)
- Program is to develop testing protocols and methods for a full scale facility that can generate 200 mph wind in a water basin to simulate storm surge and wave action
- Nine universities and one industry operate under cooperative agreements
- An Advisory Board offers guidance and feedback about the progress the NICHE is making toward their defined goals and objectives

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### ICC Testing



### Demonstration House



[www.hightidehomesinc.com](http://www.hightidehomesinc.com)



## Needs and Challenges in 2024 (1)

---

1. Find ways to better estimate wave metrics – wave height, period, velocity that are useable for all practitioners during design phase, not just modelers or researchers
2. Develop ways for practitioners to estimate structural reliability in order to practice performance-based design for coastal structures; this is in order to connect reliability to performance
3. Consider ways to require all coastal structures to be designed using performance methods instead of prescriptive metrics; this will require performance-based design processes to be developed

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## Needs and Challenges in 2024 (2)

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4. Develop methods to estimate building water leakage during coastal flooding
5. Improve building attachment methods to foundations
6. Improve foundation performance during and after coastal erosion occurs
7. Develop solutions to coastal storm problems that are not static; i.e. create ways for buildings to adapt to changing environmental conditions including increased water levels or wave heights

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## Needs and Challenges in 2024 (3)

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8. Develop design solutions with materials that can resist the environmental harshness of coastlines
9. Develop design methods that can either resist flood debris or perform with structural redundancy to prevent collapse
10. Design such that there is less reliance on beach re-nourishment projects to keep buildings from collapsing

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## Questions?

[bill@coulbournconsulting.com](mailto:bill@coulbournconsulting.com)

## B.14 Narayanaswamy

### Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience



May 16-17, 2024  
Princeton University

### Perspectives from Coastal Engineering Practitioners: Needs & Challenges

Muthu Narayanaswamy, PhD, PE

Director of Coastal and Compound Flood Risk

The Water Institute



### Key Takeaways - Challenges

- Numerous guidelines and manuals with inconsistent metocean design criteria and definitions for current conditions
  - DOT design Manuals, HEC design manuals, AASHTO studies, USACE CEM etc.
- Estimates of sea level rise and guidance on incorporation of sea level rise numerous and inconsistent
  - Difficult choices for practicing engineer
  - Difficult conversations with clients
- No guidance currently exists for meaningful assessment and incorporation of compounding impacts of surge and pluvial/fluvial events.
- Challenging to quantify (choice of GCMs, downscaling) for future precipitation and antecedent conditions.

## Key Takeaways - Needs

- Embrace and communicate uncertainty in design guidance with
  - an intentional move away from event based, prescriptive design criteria. (For e.g. deterministic 1% SWEL or the 10-year rain event).
  - Best practices on adaptive design (Designing for future uncertainty is not necessarily expensive)
- Unified guidance on Sea Level Rise including process to develop AEP curves for desired time horizons including uncertainty bounds.
- Guidance on choice of GCMs and methodology to downscale and obtain precipitation estimates for desired time horizons including quantification of bias and uncertainty.
- Guidance on future antecedent conditions
- Guidance on future rainfall and winds for inland water bodies
- Facilitation of tight coupling between research findings and design guidance
- Consistent guidance across federal and state levels for coastal design criteria (i.e single X-year response for example) would increase efficiencies and reduce design costs.

## Transportation Design in Texas

- Likely the best state DOT guidance on incorporation of coastal wave and hydrodynamics data for current and future conditions (TxDOT HDM, 2019)

(Year)	Region 1	Region 2	Region 3	Region 4
2020	0.8	0.8	0.7	0.6
2030	1.3	1.2	1.1	1.0
2040	1.7	1.6	1.5	1.3
2050	2.2	2.1	1.9	1.7
2060	2.8	2.6	2.4	2.2
2070	3.4	3.2	3.0	2.8
2080	4.1	3.9	3.6	3.3
2090	4.8	4.6	4.3	4.0
2100	5.5	5.2	5.0	4.6

**Notes:**

1. Projections are relative to 2000 and should be modified to a baseline for the estimated rise that has occurred between 2000 and the project start year to estimate the rise expected during the project life.
2. Projections are regional averages of projections calculated in the GLO Plan and include anticipated local subsidence.
3. Alternate RSLR scenarios and projections may be considered if it is determined that they are more appropriate for a given project's level of risk.

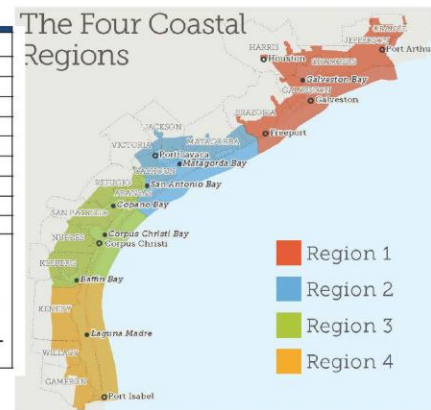
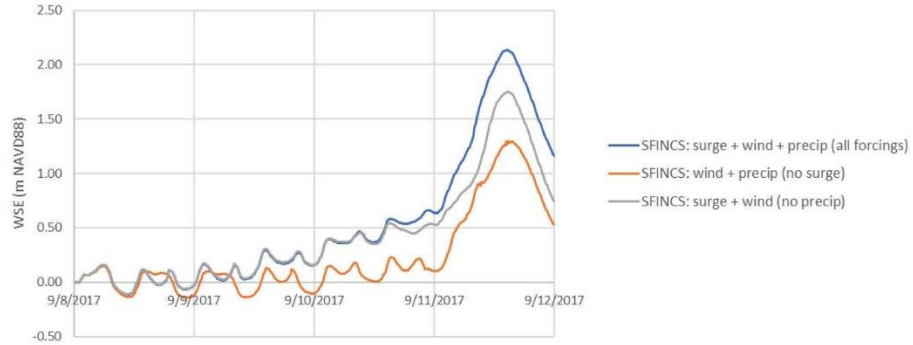


Figure 15-11. The GLO Texas Coastal Resiliency Master Plan's Four Coastal Regions (Tex General Land Office, 2019).



# HURRICANE IRMA

NOAA 8720226, Southbank Riverwalk, St Johns River, FL (Main St Bridge)



## COMPOUND FLOODING

- JPM extended to include both tropical and non-tropical storm events.

Where:

- $\lambda_{TC}$ : Frequency of tropical cyclones
- $\lambda_{NT}$ : Frequency of nontropical cyclones
- $\lambda = \lambda_{TC} + \lambda_{NT}$ : Overall frequency of storms
- $\eta_{max}$ : Maximum flood depth
- $t$ : Time

$$p(\eta_{max}) = \frac{\lambda_{TC}}{\lambda} p_{TC}(\eta_{max}) + \frac{\lambda_{NT}}{\lambda} p_{NT}(\eta_{max})$$

$$p_{TC}(\eta; t) = \int \dots \int \underbrace{p_{TC}(\eta | \mathbf{x}_{TC}; t)}_{\text{Flood depth response function}} \underbrace{p(\mathbf{x}_{TC}; t)}_{\text{Probability distribution of tropical cyclone storm and hydrologic conditions}} d^n \mathbf{x}_{TC}$$

$$p_{NT}(\eta; t) = \int \dots \int \underbrace{p_{NT}(\eta | \mathbf{x}_{NT}; t)}_{\text{Flood depth response function}} \underbrace{p(\mathbf{x}_{NT}; t)}_{\text{Probability distribution of Non-tropical storm and hydrologic conditions}} d^n \mathbf{x}_{NT}$$

# COMPOUND FLOODING

R. Jane et al.: Multivariate statistical modelling of the drivers of compound flood events in south Florida 2691

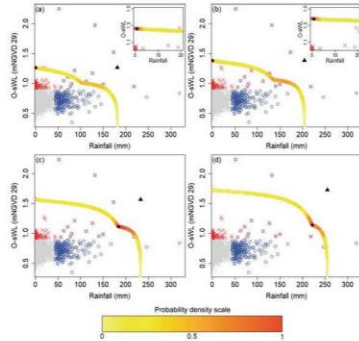


Figure 5. Comparison of the design events (diamonds) obtained using the two-sided conditional sampling approach and the approach used in the original design (triangles) for return periods of (a) 10, (b) 20, (c) 50, and (d) 100 years. Quantile-isolines are superimposed onto plots of the observations, with blue circles (red crosses) denoting observations exceeding the rainfall (G-WL) threshold and those exceeding neither threshold plotted in grey. Coloured contours signify the relative likelihood of events along an isoline, where the point with the highest density is selected as the most-likely design event. Insets in (a) and (b) magnify the isoline about the associated most-likely design event.

- Bivariate analyses are fast and efficient but limited geospatially
- Extended JPM robust and relatively time intensive
- Ongoing work to leverage bivariate + Extended JPM to produce actionable design criteria in coastal Louisiana and Jacksonville.

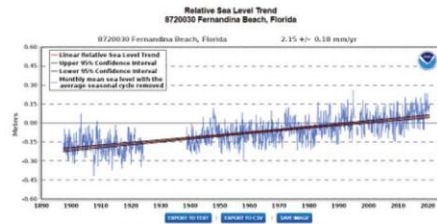
## Transportation Design in FL

- Guidance inadequate for resilient design
- Future rainfall distributions important but unavailable
- Communities use NOAA, USACE SLR projections for planning for FDEP Sea Level Rise Vulnerability assessments
- Can lead to widely varying design and planning guidance at a single location!

network (FVCCO) and managed by FDEP.

[https://tidesandcurrents.noaa.gov/sltrends/sltrends\\_states.html?gid=1238](https://tidesandcurrents.noaa.gov/sltrends/sltrends_states.html?gid=1238)

NOAA manages tidal gage stations located around the state of Florida. Use the station nearest the site for analysis. Analysis must consist of straight-line extrapolation based on the design service life of the project. Consider existing system criticality/vulnerability and project costs when implementing this best practice analysis.



The plot shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinity, winds, atmospheric pressures, and ocean currents. The long-term linear trend is also shown, including its 95% confidence interval. The plotted values are relative to the most recent Mean Sea Level datum established by CGD155. The calculated trends for all stations are available at a table in millimeters/year and in feet/year (0.3 meters = 1 foot). If present, solid vertical lines indicate times of any major perturbations in the quality of the station and dashed vertical lines indicate any periods of questionable data or datum shift.

Figure 3-1: Relative Sea Level Trend Data Example

## Jacksonville, FL



## Jacksonville, FL – Draft Rainfall Guidance (CDM Smith)

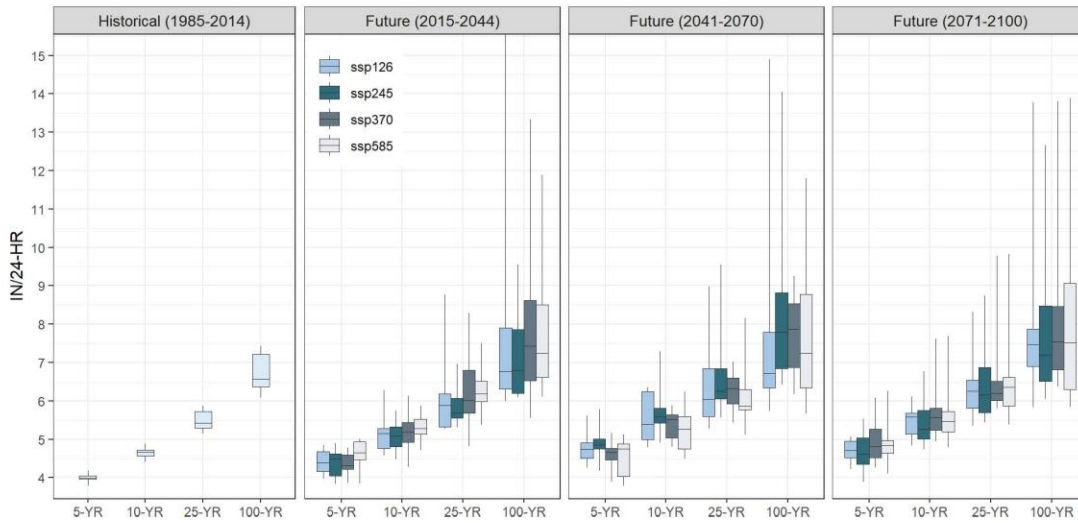
Year	24-hour Rainfall (inches) <sup>2</sup>		
	10-year	25-year	100-year
2020	6.8	8.1	11.0
2040	7.7	9.8	13.8
2070	8.2	10.4	15.0

Notes:

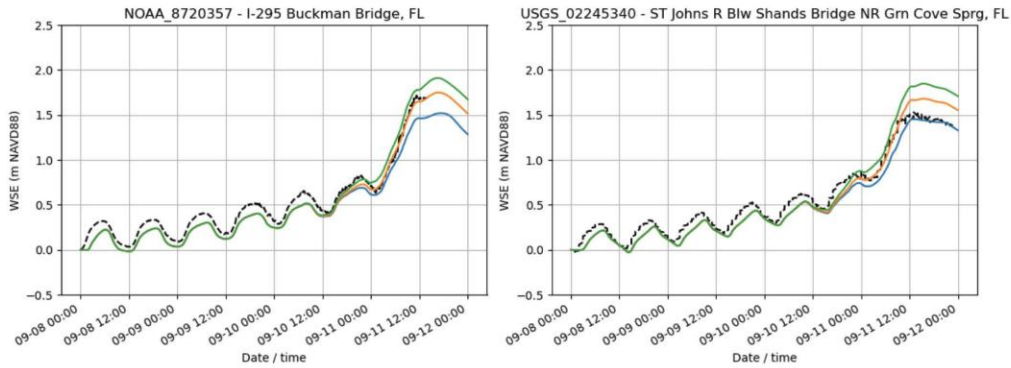
1. Design storms for future scenarios are 24-hr duration using an SJRWMD distribution. Rainfall projections are based on RCP8.5, median of all GCMs.
2. Current (2020) rainfall is based on median of 6 stations in City of Jacksonville for tidal basins, and on the MSMP values for each major riverine basin.

12

## Jacksonville, FL – Rainfall Estimates (Villarini et.al.)



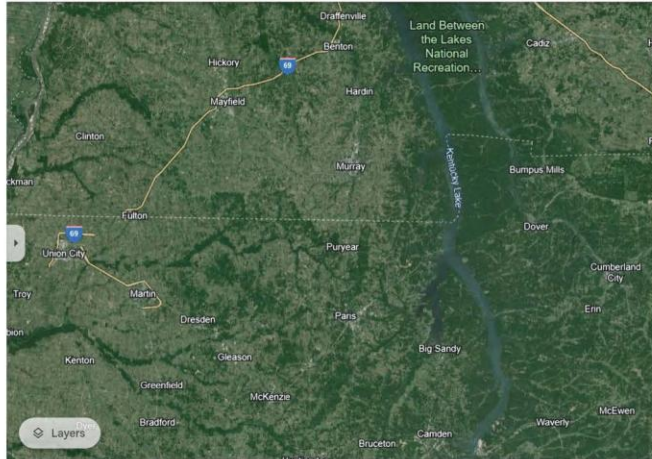
## Jacksonville, FL – Soil Moisture Impacts



Characterization of future antecedent conditions important

## Inland Design Considerations – Kentucky Lake

- Characterization of waves important for scour, overtopping, and loads
- Design impacted by future rainfall and wind projections




## Key Takeaways - Needs

- Embrace and communicate uncertainty in design guidance with
  - an intentional move away from event based, prescriptive design criteria. (For e.g. deterministic 1% SWEL or the 10-year rain event).
  - Best practices on adaptive design (Designing for future uncertainty is not necessarily expensive)
- Unified guidance on Sea Level Rise including process to develop AEP curves for desired time horizons including uncertainty bounds.
- Guidance on choice of GCMs and methodology to downscale and obtain precipitation estimates for desired time horizons including quantification of bias and uncertainty.
- Guidance on future antecedent conditions
- Guidance on future rainfall and winds for inland water bodies
- Facilitation of tight coupling between research findings and design guidance
- Consistent guidance across federal and state levels for coastal design criteria (i.e single X-year response for example) would increase efficiencies and reduce design costs.

## B.15 McQuade

**Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience**



May 16-17, 2024  
Princeton University

**PRACTITIONERS PERSPECTIVES | ARCHITECTS AND PLANNERS**

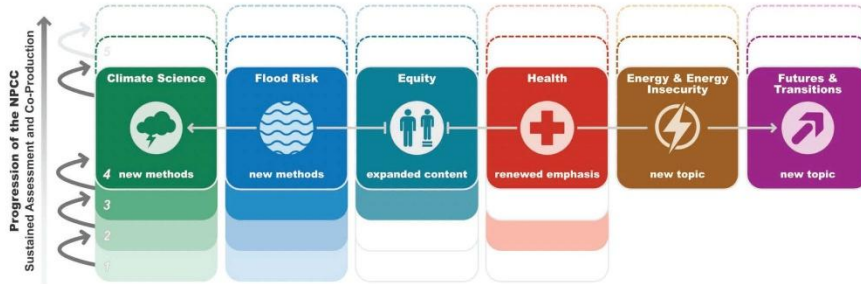
ELIZABETH HODGES MCQUADE, ARCHITECTURE BACKGROUND OFFICE

**1. CLIMATE PROJECTIONS FACILITATE ENVISIONING OUR FUTURE CITIES**

PALISADE BAY  
2007

LATROBE PRIZE RESEARCH AND PUBLICATION  
W/GUY NORDENSON, CATHERINE SEAVITT, ADAM YARINSKY

<p>2007</p>	<p>2013</p>	<p>2015</p>	<p>2021</p>	<p>2023</p>
<p>2002</p>	<p>2011</p>	<p>2011</p>	<p>2016</p>	<p>2021</p>



The current NPCC assessment (4) expands and updates topics from previous NPCCs and adds new topics to inform future assessments.



Coastal planning is all about people



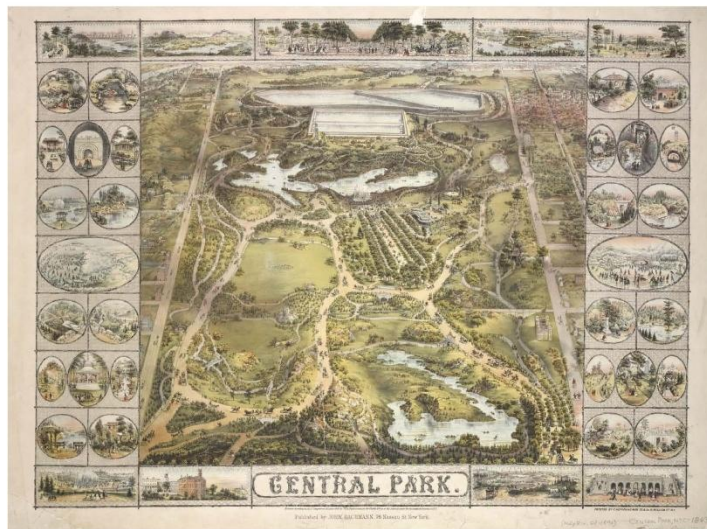
IMAGES: VARIOUS VIEWS OF REBUILD BY DESIGN AWARDED PLANS FOR NEW YORK CITY





NEW CROTON AQUEDUCT  
1899

Lionel Pincus and Princess Firyal Map Division, The New York Public Library, "Map of the route of the new Croton Aqueduct, old aqueduct and Bronx River pipe line" *The New York Public Library Digital Collections*, 1899.



VIEW OF CENTRAL PARK  
1863

Lionel Pincus and Princess Firyal Map Division, The New York Public Library, "Central Park" *The New York Public Library Digital Collections*, 1863.

## 2. OPPORTUNITY SPACE FOR FUNDING COASTAL INFRASTRUCTURE

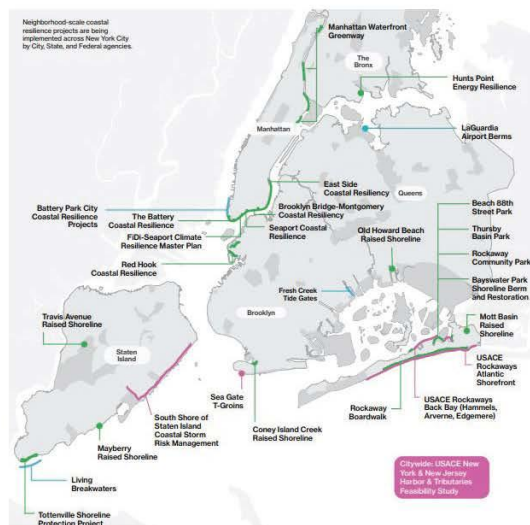
### THE POST DISASTER CONTEXT:

NYC WAS AWARDED \$15B  
FOR HURRICANE SANDY RECOVERY PROJECTS:

- FEMA PUBLIC ASSISTANCE
- HUD CDBG-DR
- FTA
- FHA

### LIMITING FACTORS:

- BCA CONSTRAINTS
- UNCERTAIN DESIGN CRITERIA
- LONG TIMEFRAMES

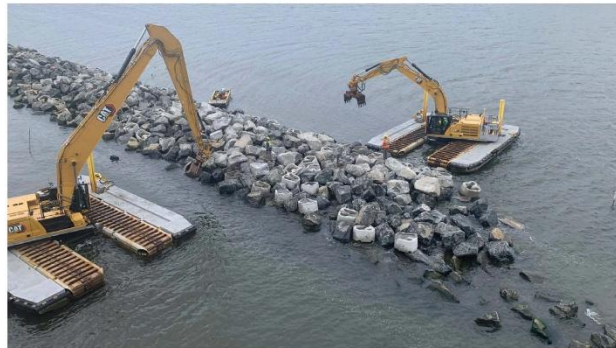


EAST SIDE COASTAL  
RESILIENCE FLOOD  
GATES  
2024 COMPLETION

Photo: NYC DEP 2024



REINFORCED DUNE,  
ROCKAWAYS BEACH



LIVING BREAKWATERS  
STATEN ISLAND  
2024 COMPLETION

Photo: Dezeen

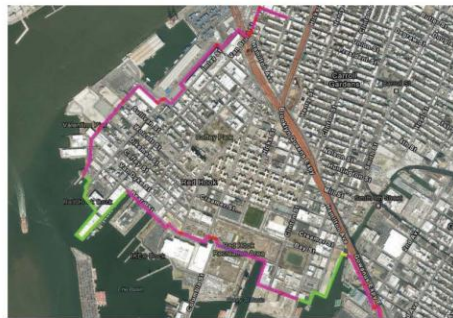
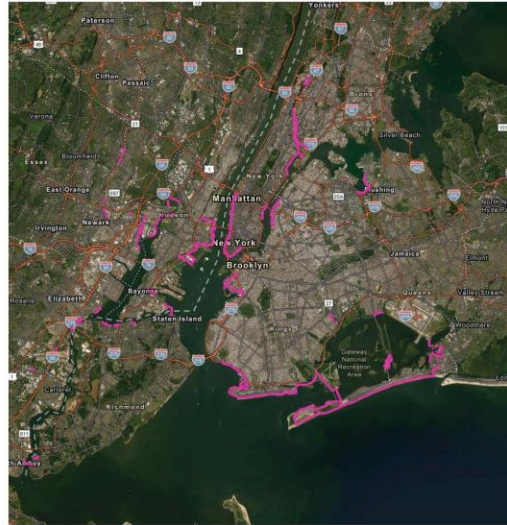
USACE NJ/NY HATS  
OPTION 3B

**THE MITIGATION CONTEXT:**

- FEDERAL GRANTS
- USACE NJ/NJ HARBOR AND TRIBUTARIES STUDY

**CONSTRAINTS:**

- FUNDS CONDITIONAL
- UNCLEAR TIMELINES
- BCA > 1
- LOCAL COST SHARE
- FEASIBLE CONSTRUCTION
- ENVIRONMENTAL REVIEW
- COMPLEXITY DUE TO DENSE WATERFRONT

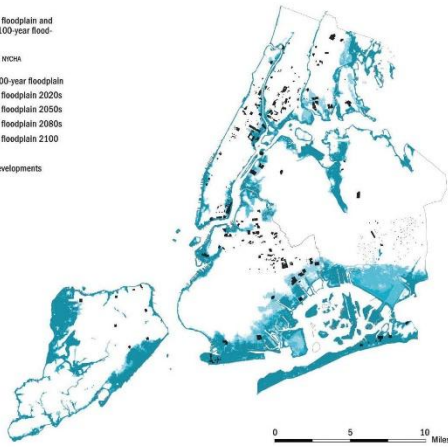


## 1. PLANNING PROTECTIONS / BUILDING RESILIENCY

**Figure 1**  
Current 100-year floodplain and projected future 100-year floodplain extents

DATA: FEMA, NPCC & NYCHA

- Current 100-year floodplain
- Projected Floodplain 2020s
- Projected Floodplain 2050s
- Projected Floodplain 2080s
- Projected Floodplain 2100
- NYCHA Developments










	Number of NYCHA Buildings within 100-year Flood Zone
Effective Flood Insurance rate Maps (2007)	185
Preliminary Flood Insurance Rate Maps (2015)	275
Projected 100-year Floodplain, 2020s (NPCC)	315
Projected 100-year Floodplain, 2050s (NPCC)	473
Projected 100-year Floodplain, 2080s (NPCC)	791
Projected 100-year Floodplain, 2100 (NPCC)	921

**FIGURE 4**

East Harlem Developments closest to the coast have buildings within the current 100-year floodplain. By 2100, the 100-year floodplain will extend farther inland.

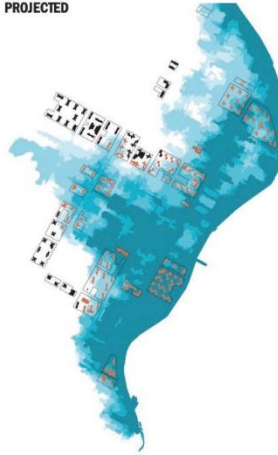
DATA: FEMA, NPCC & NYCHA

-  Current 100-year floodplain
-  Projected floodplain 2020s
-  Projected floodplain 2050s
-  Projected floodplain 2080s
-  Projected floodplain 2100
  
-  NYCHA buildings
-  NYCHA buildings in the floodplain
-  NYCHA development boundaries

CURRENT



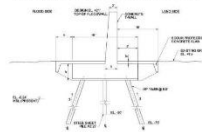
PROJECTED



**PROPOSED CONCEPT (DIGITAL RENDERING - SUNNY DAY)**



**TYPICAL LARGE FLOODWALL CROSS-SECTION**



**PROPOSED CONCEPT (DIGITAL RENDERING - STORM CONDITION)**



**LOCATION MAP**





BROOKLYN AND THE ROCKAWAYS,  
AERIAL VIEW

Credit: Lindsey Nicholson/UCG/Universal  
Images Group via Getty Images.



## B.16 Wang

### EDUCATIONAL EFFORTS:

#### STRUCTURAL ENGINEERING AND THE OCEAN ENVIRONMENT



#### SHENGZHE (JACKSON) WANG

Assistant Professor  
Department of Civil Engineering  
University of Colorado Denver

[shengzhe\\_2.wang@ucdenver.edu](mailto:shengzhe_2.wang@ucdenver.edu)

05.17.2024



## BACKGROUND

### FUTURE CITIES & CLIMATE CHANGE

- Megalopolises powering the US and global economy are mostly within coastal areas (< 100 km to the ocean) and will be at the forefront of climate hazards including sea level rise, storm surge, and tsunami flooding
- 15 of the 24 cities (63%) classified as Alpha ++, Alpha +, and Alpha are located within 100 km of the ocean
- This includes 7 of the 9 cities (78%) classified as Alpha ++ and Alpha +
- Both (100%) Alpha ++ cities (London & NYC) will be severely impacted



#### Alpha ++

- London
- New York City

#### Alpha +

- Beijing
- Shanghai
- Dubai
- Singapore
- Hong Kong
- Tokyo
- Paris

#### Alpha

- Amsterdam
- Mexico City
- Brussels
- Milan
- Chicago
- Moscow
- Frankfurt
- Mumbai
- Jakarta
- São Paulo
- Kuala Lumpur
- Sydney
- Los Angeles
- Toronto
- Madrid



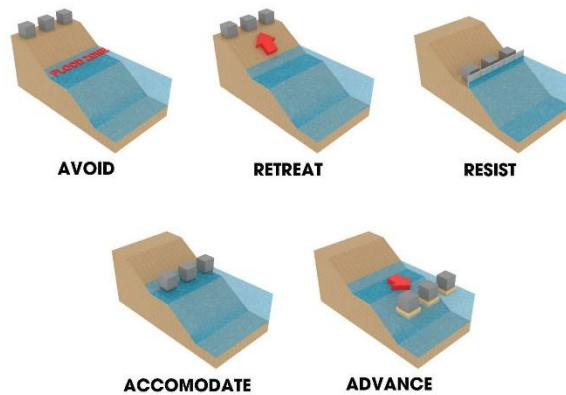
2

# CONTEXT

The structural engineering profession must play an active role in shaping the built environment for climate **adaptation**

Solutions must be **sustainable**

- Resilient and robust
- Socially and environmentally conscious



3

# PROBLEM STATEMENT

How can we encourage future structural engineers to approach the design of climate adaptable infrastructure with social and environmental considerations in mind?

More innovative approaches to structural engineering education must be sought to equip graduates with a more holistic "toolbox" for design (from a technical or policy perspective)

- New types of design loads (waves, buoyancy, etc.)
- New approaches to climate adaptation (floating structures, hybrid green-gray infrastructure, etc.)



4

# ASCE INITIATIVES

Committee on the reform of structural engineering education report to the SEI board of governors (April 2022)

**“Recommendation:** Develop a repository of curricular materials that support structural engineering relevant topics and skills to address climate change.”

**“Examples and ideas:** specific technical offerings could include circular economies in construction, deconstructability, embodied carbon and energy accounting, light-weighting and material efficiency, mass timber design, life-cycle analysis, changes in environmental loads due to climate changes, coastal loads on structures (e.g., wave theory, wave attenuation, wave impact loads), and floating structures.”

**“Goal:** By 2040 climate change understanding, mitigation and adaptation will be a central part of structural engineering curriculum.”

## Educating the Structural Engineer of 2040 and Beyond



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# STRUCTURAL ENGINEERING AND THE OCEAN ENVIRONMENT

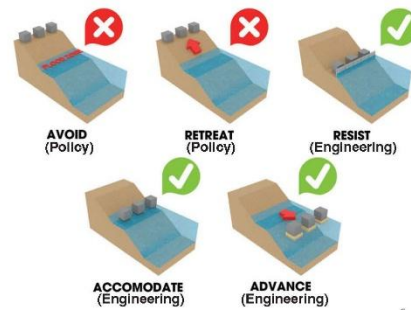
The current state of structural engineering education places little emphasis on water and waves interacting with large-scale structures

“*Structural Engineering and the Ocean Environment*” serves as an introduction for students in structural engineering to topics including:

- Water wave mechanics
- Tropical cyclones and tsunamis
- Design of “gray” and “green” infrastructure
- Floating structures

Open to senior undergraduate and graduate students. Taught at CU Denver every fall

Knowledge gained will be applicable towards adaptation strategies that are “engineering focused” and **NOT** those that are “policy focused”



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# COURSE OUTLINE

Course is broadly separated into **three main sections** encompassing 15 topics

- 1. **Wave mechanics** (6 topics)
- 2. **Fixed structures** (5 topics)
- 3. **Floating structures** (4 topics)

Accompanying notes “*Applied ocean mechanics for structural engineering and climate adaptation*” available at: <https://www.caselab.dev/teaching>

Each topic builds upon knowledge introduced in previous topics following a logical order of progression. Aim is to provide a complete walkthrough from theory to application

Topics are largely self-contained

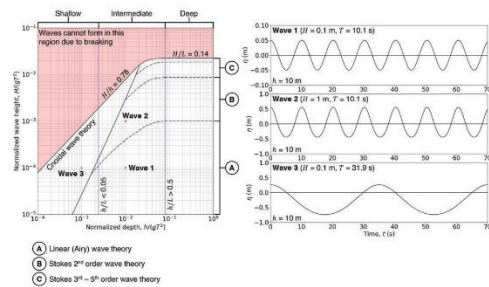
- A basic understanding of structural mechanics and partial differential equations is required
- No prior knowledge of fluid/wave mechanics, physical oceanography, etc. needed

The foundations of this course were developed by S. Wang and M. Garlock at Princeton University in 2021. First taught in Spring 2022 as “*CEE 540: Structural Engineering for Climate Adaptation*”

# WAVE MECHANICS

**OBJECTIVE:** Introduce fundamental ocean engineering principles to structural engineering students

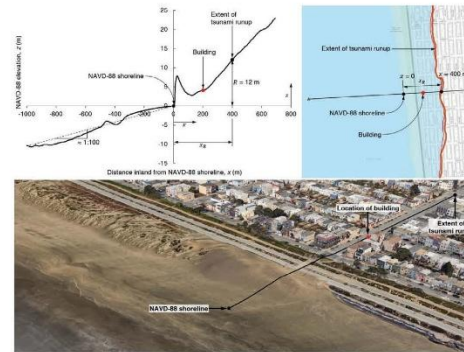
1. Introduction to Fluid Dynamics
2. The Navier-Stokes and Bernoulli Equations
3. Linear Wave Theory and Surface Gravity Waves
4. Wave Energetics
5. Irregular Waves and the Wave Spectrum
6. Wind and Waves in Tropical Cyclones



# FIXED STRUCTURES

**OBJECTIVE:** Introduce how forces from wind waves and tsunamis can be integrated into structural design in addition to how they can be attenuated using vegetation

- 7. Hydrostatic Pressure
- 8. Wave Forces on Walls
- 9. Wave Forces on Piles
- 10. Tsunami Forces on Overland Structures
- 11. Wave Attenuation Over Vegetated Terrain

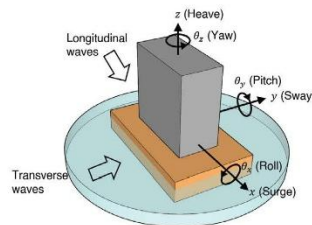
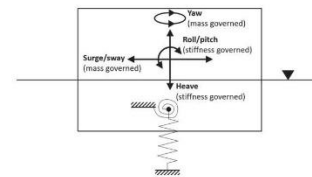


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# FLOATING STRUCTURES

**OBJECTIVE:** Introduce hydrostatic stability and dynamics of floating bodies under different wave conditions

- 12. Static Analysis and Stability of Floating Structures
- 13. Rigid-body Dynamics of Floating Structures
- 14. Floating Structures under Regular Waves
- 15. Floating Structures under Irregular Waves



Degree of freedom	Response governed by
$x$	Surge Mass
$y$	Sway Mass
$z$	Heave Stiffness
$\theta_x$	Roll Stiffness
$\theta_y$	Pitch Stiffness
$\theta_z$	Yaw Mass

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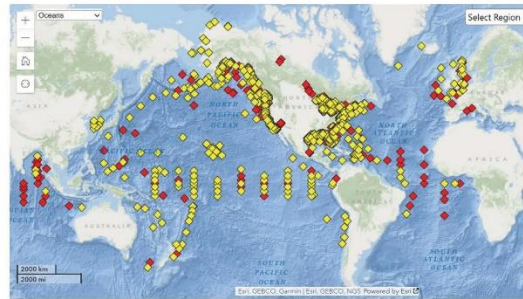
## DESIGN TOOLS

Students are introduced to the following tools for design:

- USACE Coastal Engineering Manual
- NOAA National Data Buoy Center
- NOAA National Hurricane Center
- ASCE Tsunami Design Geodatabase
- FEMA National Flood Hazard Layer
- Google Earth Pro

Students are expected to use these resources when working on assignments/projects

The hope is that students will incorporate these tools into their engineering "toolbox" post graduation



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## EVALUATION

7 bi-weekly assignments (individual)

- Assess understanding of each topic covered

Mid-term project (group)

- Mostly "qualitative"

Final design project (group)

- Mostly "quantitative"

Students are encouraged to work together and collaborate

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## MID-TERM PROJECT

Students are asked to select a **real-world case study** that is relevant to the theme of coastal/climate resilience then to write a report discussing:

- Description of the project and its aims
- Interpretation of the potential advantages and disadvantages of the project
- Public perception towards the project
- Personal impressions of the project and thoughts about its appropriateness and/or feasibility
- Potential improvements/modifications that may help the project better address its aims

Students must also give an in-class presentation of their project

Example student submissions:

- Mississippi Coastal Improvements Program (MsCIP)
- Singapore Marina Barrage
- Egypt Nile Delta Protection Project
- Japan N-ARK Floating City
- London Thames Barrier



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## FINAL PROJECT

Students are asked to analyze the structural response of a structure exposed to water/waves. Can be a real-world structure or one designed by the student. Structure must be in a **real-world location**.

Students must incorporate either:  
Two or more design concepts from List A  
**OR**  
One design concept from List B

List A	List B
1. Wave forces on walls	1. Tsunami forces on overland structures
2. Wave forces on piles	2. Dynamic analysis of floating structures
3. Wind and/or waves in tropic cyclones	
4. Wave attenuation using vegetation	
5. Static stability of floating structures	

Examples:

- A **breakwater** after waves have been attenuated by submerged vegetation (items 1 and 4 in List A)
- Wave forces on the piles and superstructure of a **pile-elevated building** (items 1 and 2 in List A)
- Stability of a **floating structure** under tropical cyclone wind forces (items 3 and 5 in List A)
- Analysis of cyclone wave forces on a **bridge pier** after their attenuation by vegetation (items 2, 3, and 4 in List A)
- Design of a **tsunami shelter** (item 1 in List B)

Students are encouraged to consult a wide array of library and/or online resources to find interesting ideas for their project

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# COURSE DELIVERY

Goal is to give students a **conceptual** understanding of the topics covered

Students must be able to immediately see how each lecture relates back to the “real-world”

- Ample real-world design examples (e.g., Ibaraki Port breakwater, Japan)
- Multimedia content delivery (e.g., 3 – 10 min videos)
- Guest lectures



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# COURSE EVALUATION

Feedback from students suggest that the **aims of the course were largely achieved**

- Dr. Wang is extremely knowledgeable. I strongly enjoyed taking this course because the topic was unique, interesting and related to what I want to do. I loved how the course was organized. I enjoyed the infrequent, but heavy assignments. I feel like replacing exams with projects, in tandem with the robust assignments, allowed me to practice every topic we learned in class in a practical way. I'm happy that CU offered a class about climate change adaptation and coastal infrastructure.
- The information presented during lectures was explained very well and the course note was incredibly helpful. Jackson was very interested in the subject, which made lectures fun and full of information that I would not have gotten if someone else taught the class. The projects were very informative and the homework was the perfect balance of challenging to not overwhelming.
- The structure of the course is effective. I enjoyed the lectures, learning the theory and application, and the assignments gave opportunity to practice theory and gain deeper understanding of course content.
- Dr. Wang is the ideal instructor for a higher education classroom. He consistently brings prepared and well thought out material to present during class. The material presented is gathered from an industry (oceanic structures engineering) where design guidance could be defined as loose at best from a structures engineering standpoint. Dr. Wang has compiled information from many sources and has been able to seemingly capture a wide array of structural engineering principles for off and near coastal structures. I am very happy with how this course was taught and I think the emphasis on engineering application towards the second half of the course will be really helpful in my professional career. Thanks again Dr. Wang, hope you have a happy holiday!

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# ACKNOWLEDGEMENTS

This course would not exist without support from Prof. Maria Garlock

Additional inspiration came from courses taught by the following Princeton faculty:

- Gabriel Vecchi (Geosciences)
- Sonya Legg (Atmospheric and Oceanic Sciences)
- Marcus Hultmark (Mechanical & Aerospace Engineering)

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**THANK YOU!**

**SHENGZHE (JACKSON) WANG**

Assistant Professor  
Department of Civil Engineering  
University of Colorado Denver




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05.17.2024





## B.17 Hering

Climate Adaptation Workshop: Structural Design for Coastal Flood Resilience

   **PRINCETON UNIVERSITY** May 16-17, 2024  
Princeton University

An Interdisciplinary Course:  
Building Design for Climate Change Adaptation

Gordana Hering

 **Olin College of Engineering**  **Wesleyan University**





*Rick Miller, Founding President  
Olin College of Engineering*

“We got fascinated by the idea that projects have this amazing ability to penetrate your understanding and to **stick with you** for generations later. This experiential learning thing is not better by a fraction of a percent, it’s orders of magnitude better in terms of sticking in your head.”

“The bottom line is **creativity** as a way of thinking, which **requires courage** and requires a sense of **belief in your ability** to do something before you can get serious in trying it.

Creativity is **not something you can learn from a book**. Reading a book about creativity is about as useful as reading a book about swimming. You have to **get in the water and move your arms around**.”

*Penprase & Pickus (2024)*



*Gilda Barabino, President  
Olin College of Engineering*

On being a “tempered radical” – If you think about “**tempered**” in the sense of a metal becoming tougher from alternately being heated up and cooled down – if you’re a tempered radical, maybe in a certain setting you increase the heat, you push harder, you put on more pressure.

It’s the tempering that allows you, hopefully, to be more effective, because **different situations call for different kinds of reactions**.”

---

## Olin's Climate Action Plan

Climate action and sustainability – concern for Olin community for years

Operations team implemented campus changes (substantial reduction of greenhouse gases, improved resource management)

Changes to courses led by faculty

**Climate Action Team** (2022) – concerted effort:

- Review prior work of institutions around the country

- Review multiple climate action frameworks

- Enable climate and sustainability action across entire college

## Campus as a Living Lab

Curriculum with emphasis on climate and sustainability

- technical skills

- modules built into every course

- focused or integrated depth courses

Connect theoretical principles with real-world examples

Campus as a model of a net-zero emissions working, living, and learning community

---

## Building Design for Climate Change Adaptation

Introduce **interdisciplinary** perspectives of challenges and opportunities in developing energy-efficient and resilient infrastructure.

Explore design for improving environmental performance of buildings and infrastructure in the context of **climate resilience and adaptation**.

Concepts related to regional **energy grid** operation, **renewable energy** generation, and **efficient use of water, energy, and materials** serve to develop design strategies to help Olin College implement its Climate Action Plan.



Imagine the worst natural hazard you have ever experienced



## Building Materials

Student presentations + Discussion

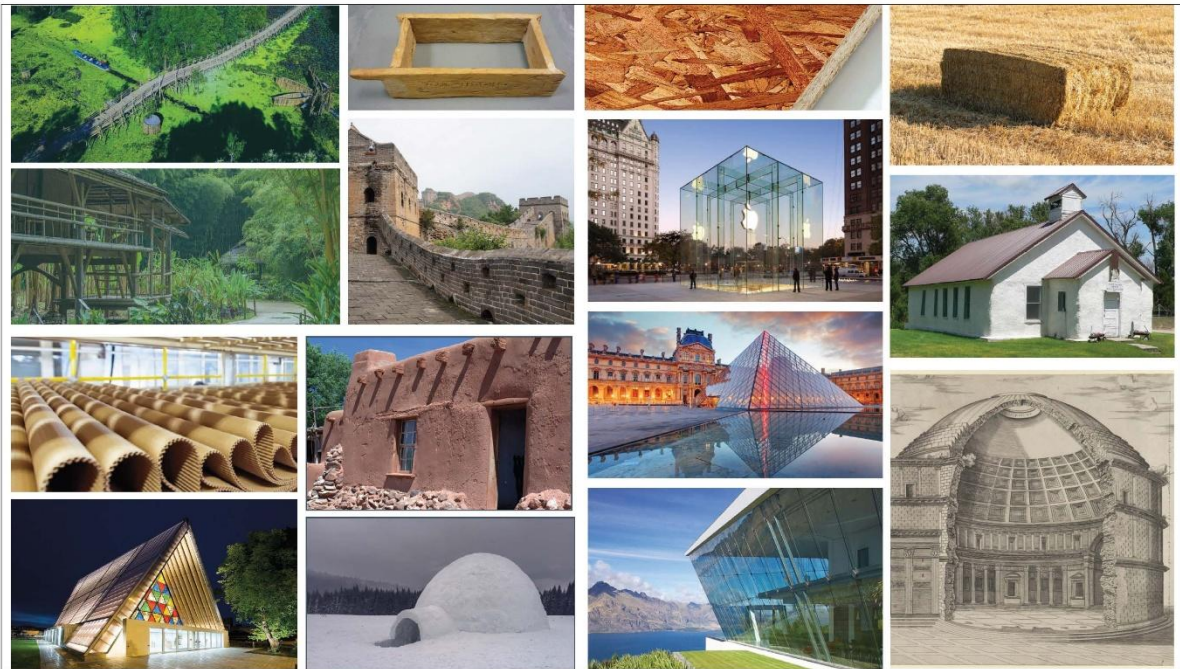
Conventional and alternative materials

Material characteristics, notable examples of use in structures

New applications such as 3D printing

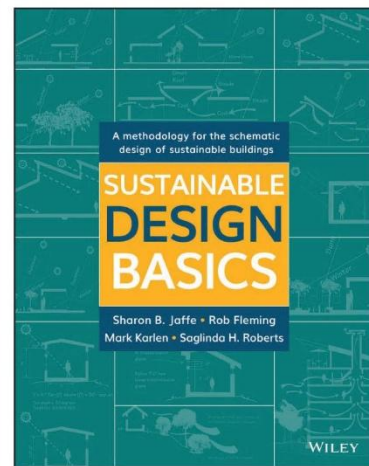
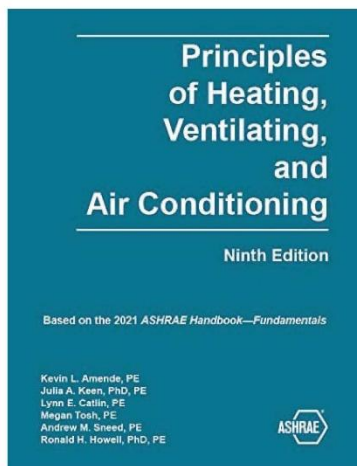
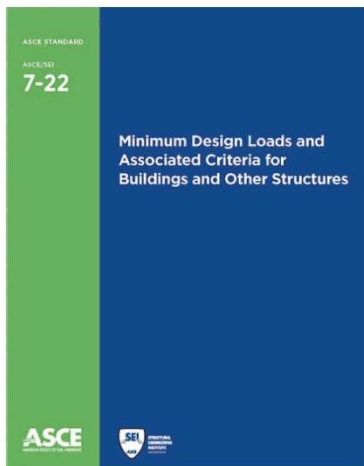
Procurement (e.g., extraction, recycling, reuse)

Environmental impact relative to other building materials

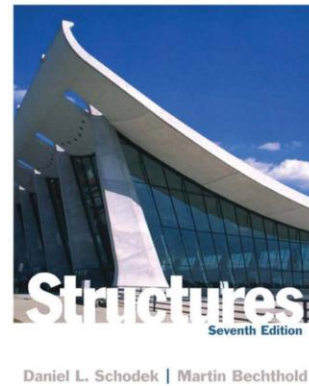
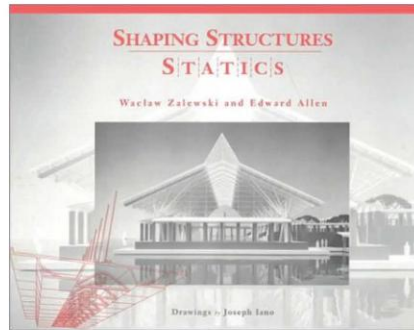
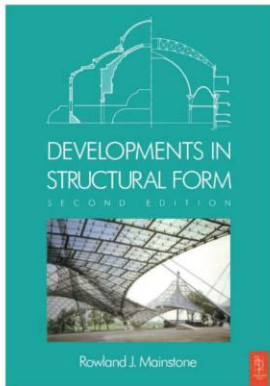


Introduce building codes through  
design exercises

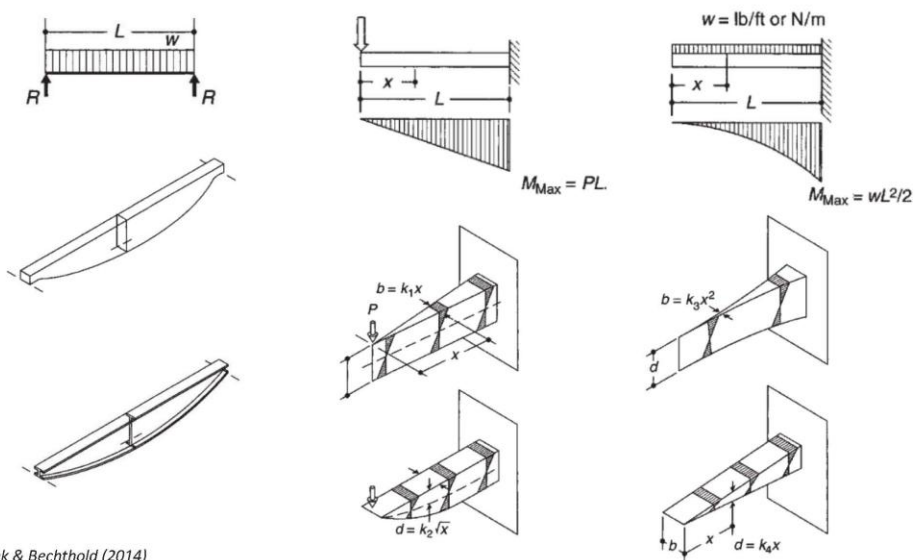
Cross-disciplinary  
methodology



Introduce structural engineering like architectural engineering:  
 fundamental technical concepts, load paths, geometry

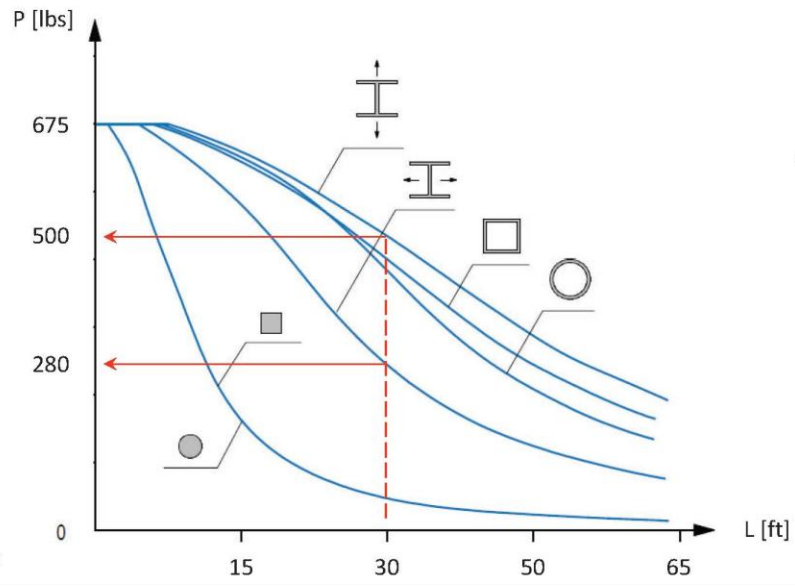


Shaping beams based on bending moment and stress



Schodek & Bechthold (2014)

### Strength of column shapes with constant area



After Block & Schwartz





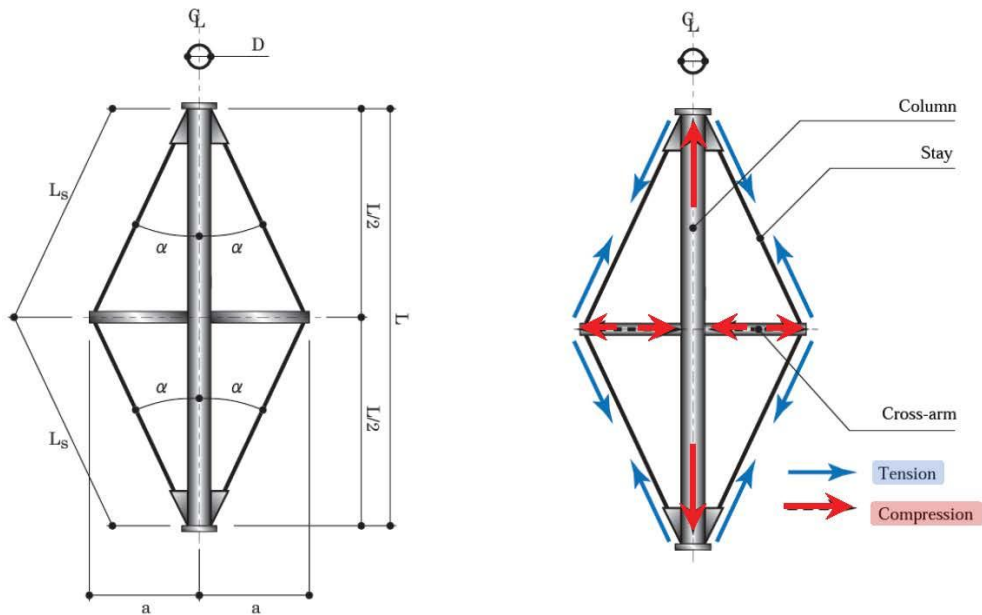
## Prestressed stayed columns

Geometric configurations of the system

Applied loads

Load paths

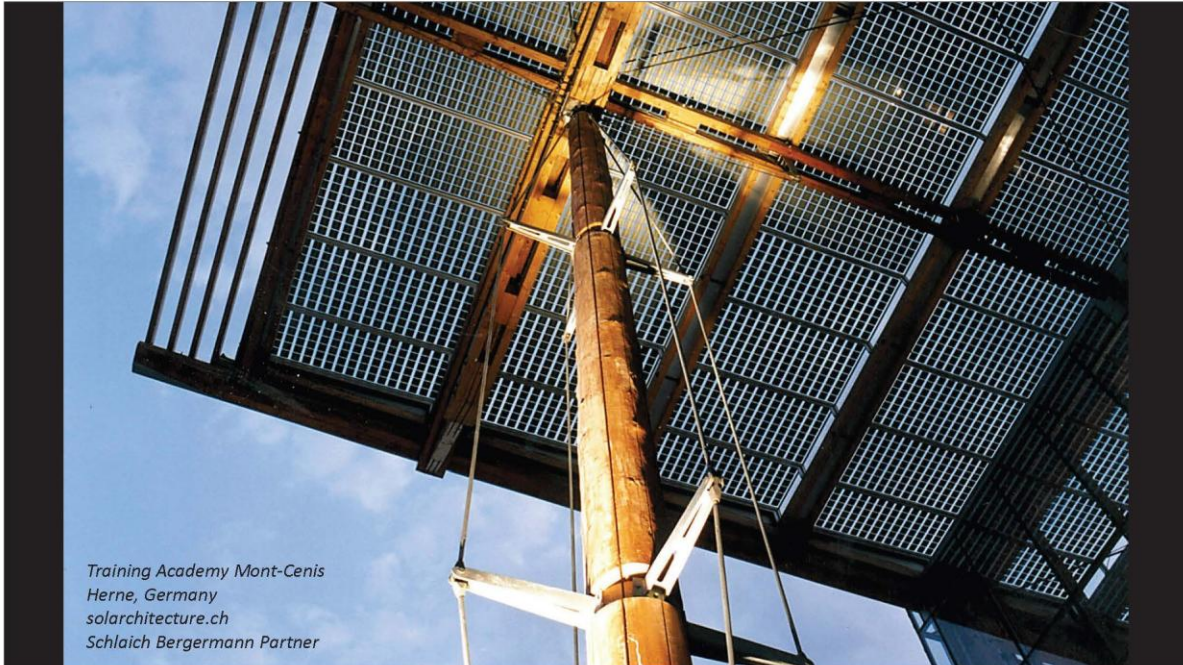
Chiswick Park, London  
Image: Wade et al. 2013



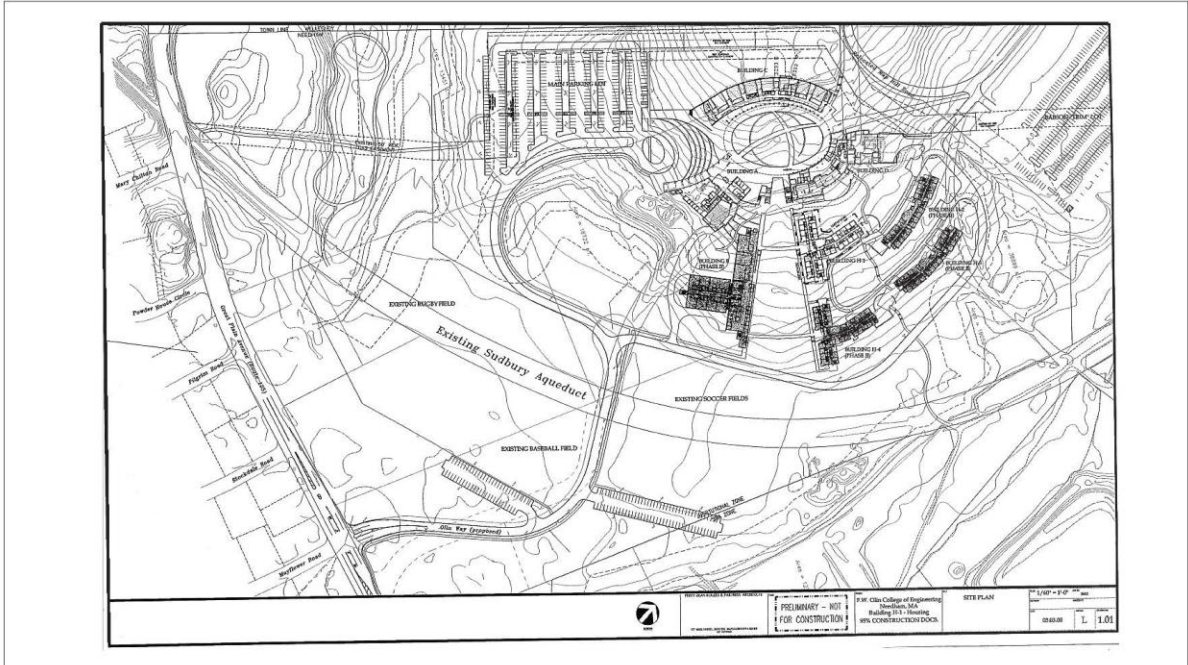
Wadee et al. 2013



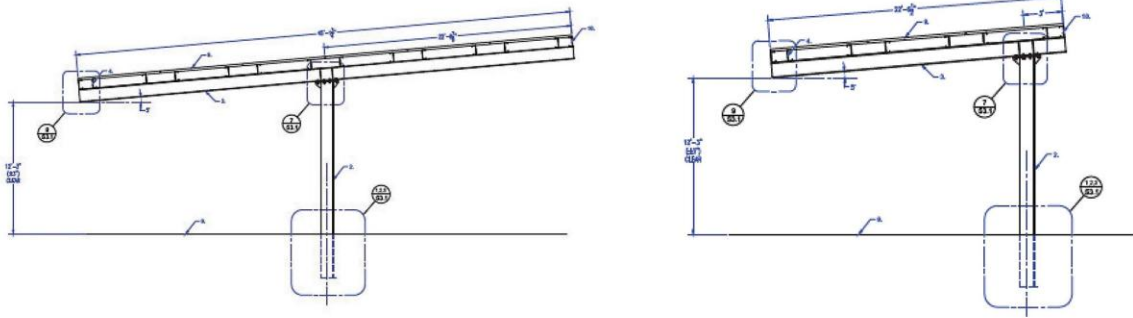
*Training Academy Mont-Cenis  
Herne, Germany  
solarchitecture.ch  
Schlaich Bergemann Partner*



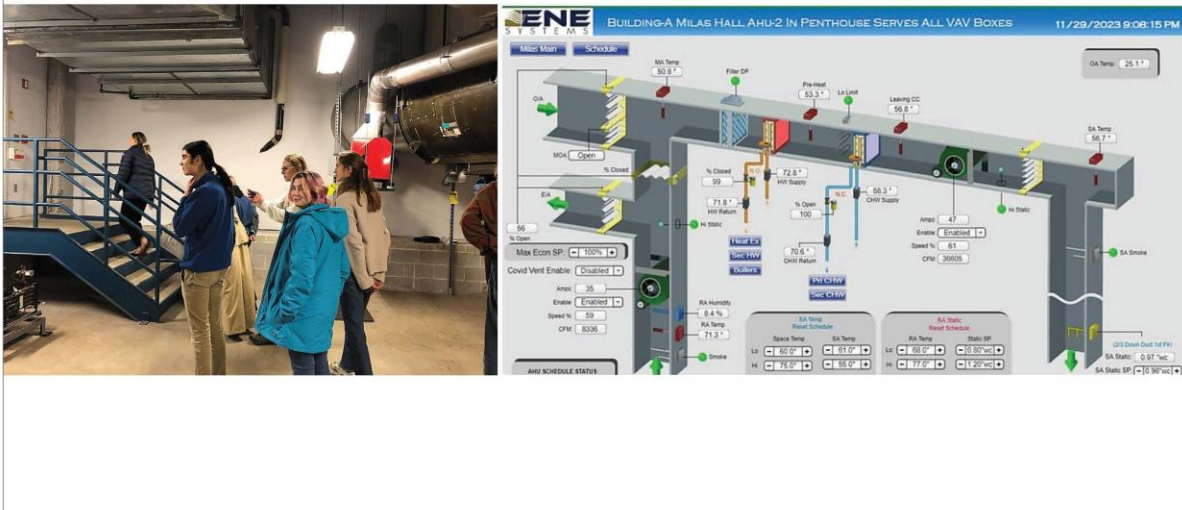
*Training Academy Mont-Cenis  
Herne, Germany  
solarchitecture.ch  
Schlaich Bergemann Partner*



## Structural analysis • solar project



## Penthouse tour • HVAC system



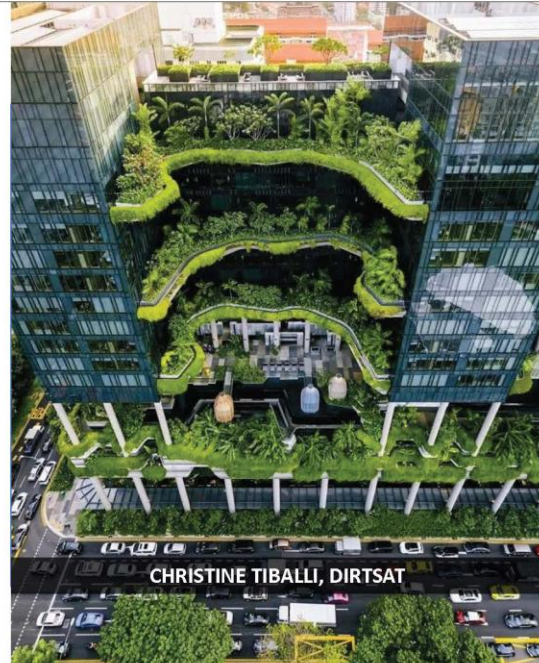


Jim Brown • Getty Images

## Multifunctional roofs

- Reduce potential for severe flooding
- Stormwater retention during storm events
- Restore ecosystem and pollinator habitat
- Impact ambient temperature through evapotranspiration
- Use of satellite data and AI to assess feasibility of green roofs

Image by Christine Tiballi



CHRISTINE TIBALLI, DIRTSAT

## Multifunctional roofs

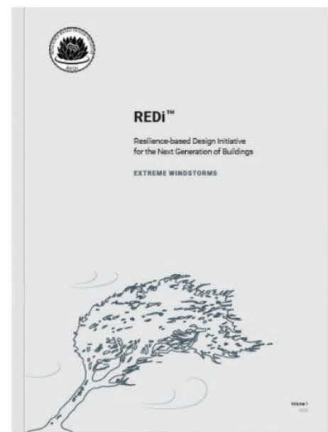
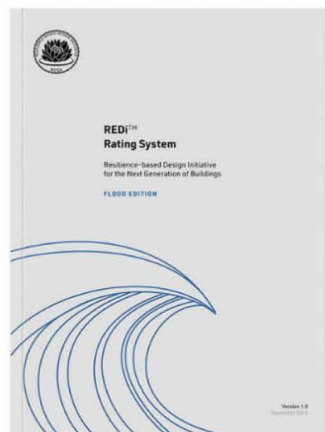
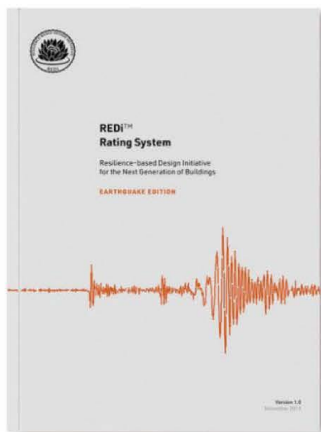
Code-based vs. Performance-based design

Seismic and windstorm resilience

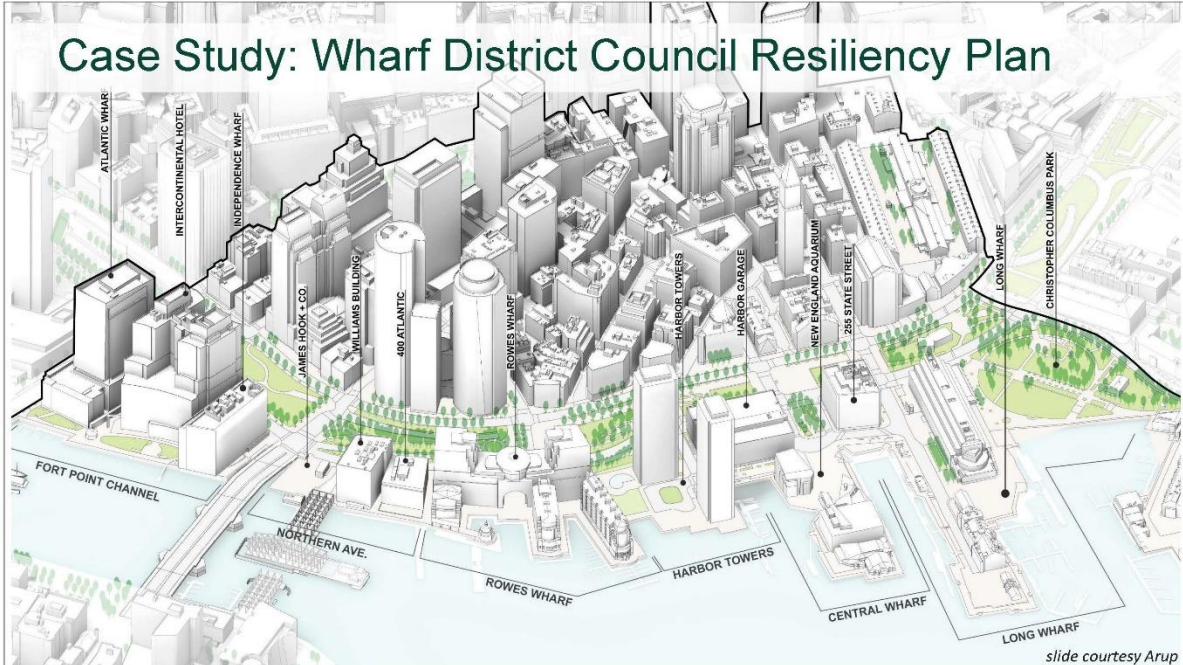
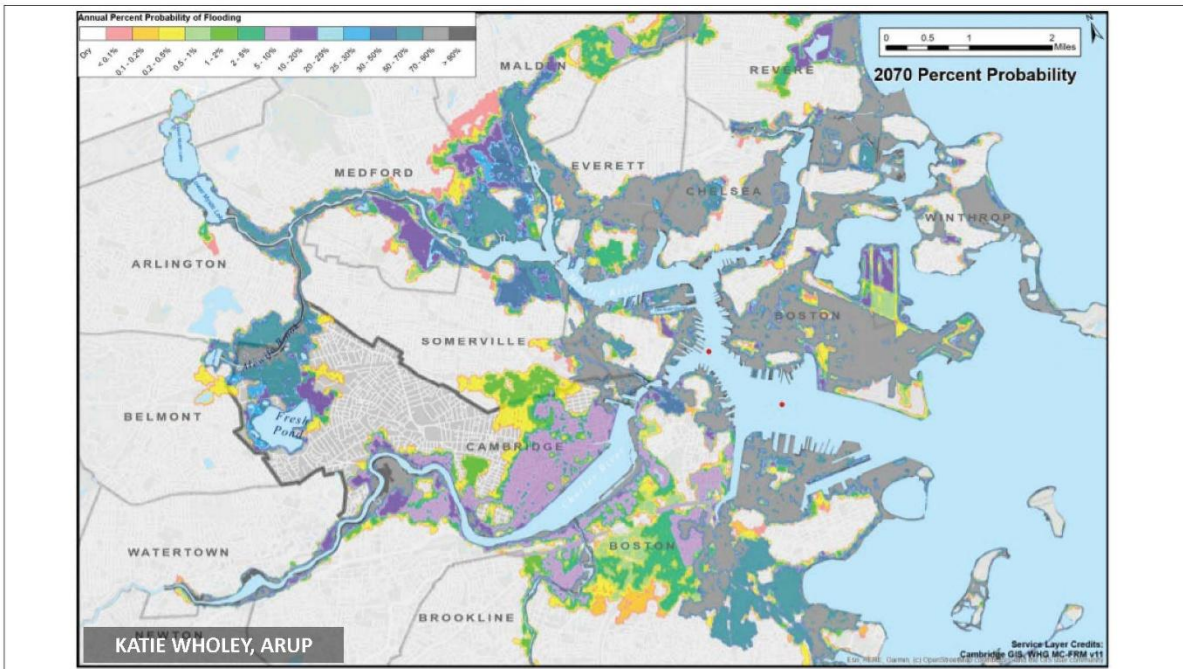
181 Fremont Tower designed to be essentially undamaged in a 475-year earthquake

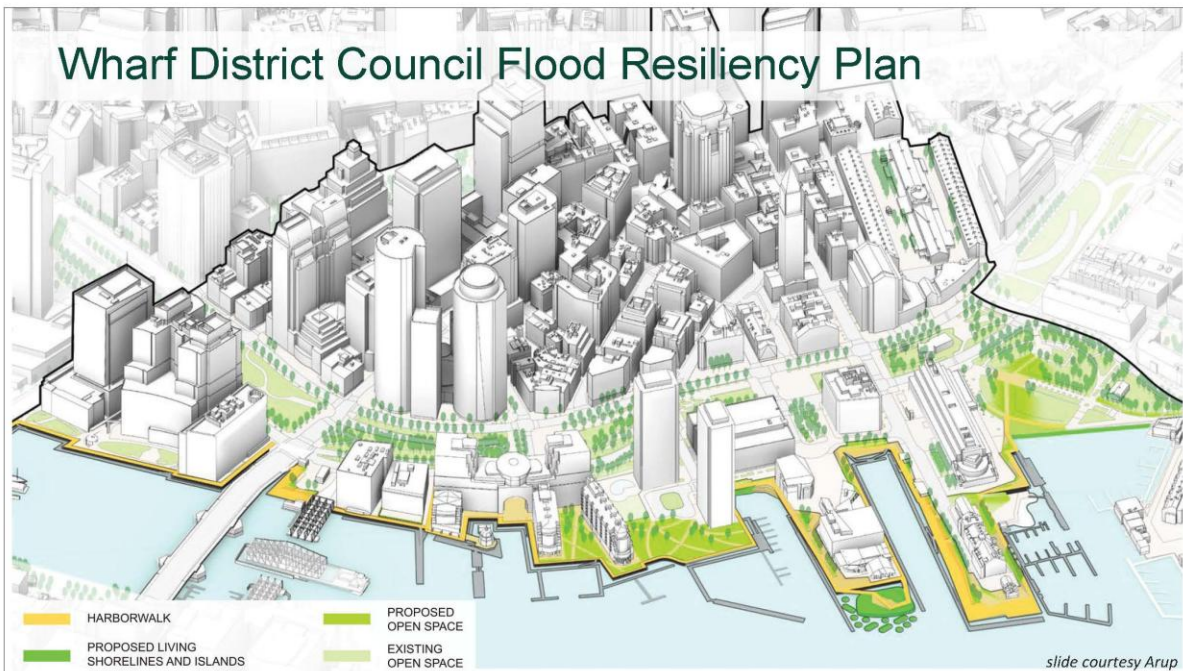


## REDi: Design Guidelines for New Buildings by Arup









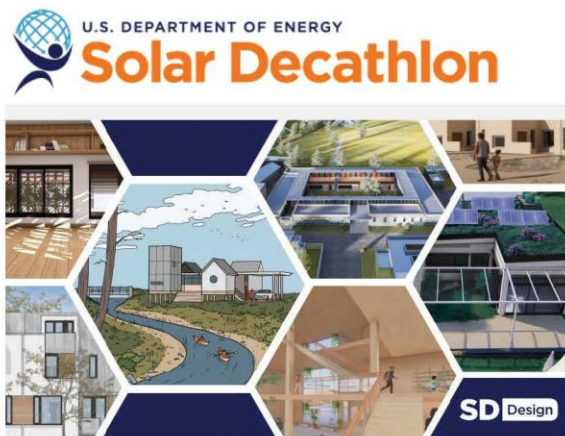
## Students' feedback

- It was really cool to see how resilience is thought about and designed for at different scales. This is a field I would personally love to work in but I'm not sure how to get into it.
- Katie's presentation was so captivating, and I'm genuinely interested in pursuing a career path similar to hers - something in the urban planning / climate resilience space.
- Really cool to see a city-wide perspective of climate change resilience. Boston's unique geography definitely makes it very vulnerable to rising sea levels. It's also at least somewhat hopeful to see that the private property owners of coastline properties are willing to collaborate with the city and each other on the flood protection goals.
- I loved our guest speaker today. It was really interesting to connect her talk with my work in researching coastal adaptation to climate change. I love that this is a connection between my projects in different classes!

## Basis for Term Project / Contest

"We can't meaningfully address climate change while continuing to design buildings the way we always have. These collegiate scholars impressed jurors by reimagining buildings as responsive to people and the planet."

- Holly Jamesen Carr, Solar Decathlon director at DOE



Images: energy.gov, solardecathlon.gov

Shift from resource-intensive to zero energy buildings:

Design professionals with **interdisciplinary** skills & diverse experiences

High-performance strategies for deep energy **retrofits and new** construction

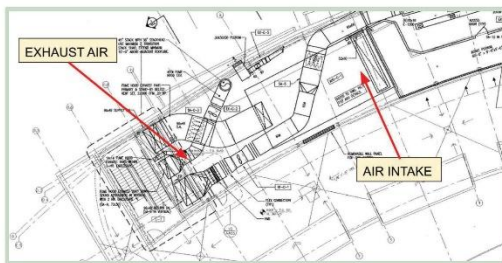
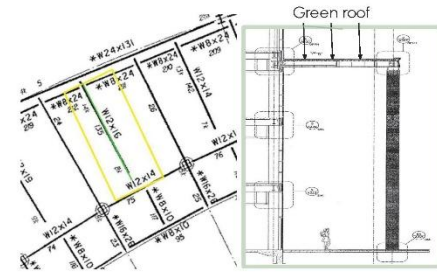
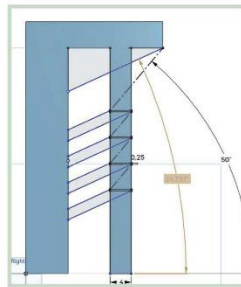
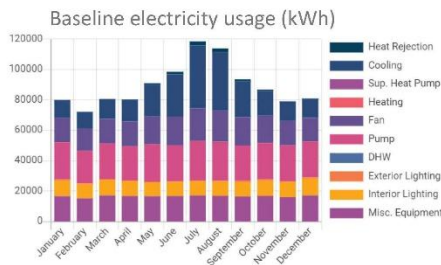


## Term Project / Contest

- Architecture** (site, form+function, integration)
- Engineering** (optimize long-term performance)
- Envelope** (balance comfort, performance, durability)
- Efficiency** (whole building, active+passive systems)
- Grid-interactivity** (resiliency during disruptions)
- Life-cycle** (operational + embodied carbon)
- Health** (systems + space design)
- Community** (equity, economy, culture, displacement)

ASHRAE, IECC, BERDO, ASCE 7, IBC, LEED, LBC, WELL

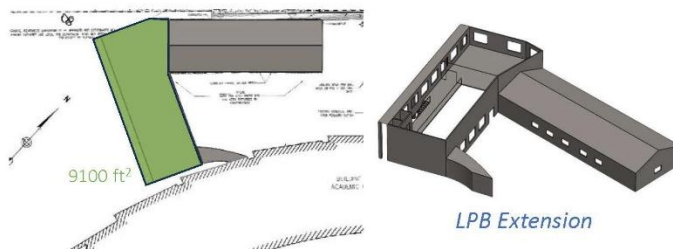
## Examples of project studies



## Project proposals for renovation and addition



*A Net-zero Miller Academic Center*



*LPB Extension*

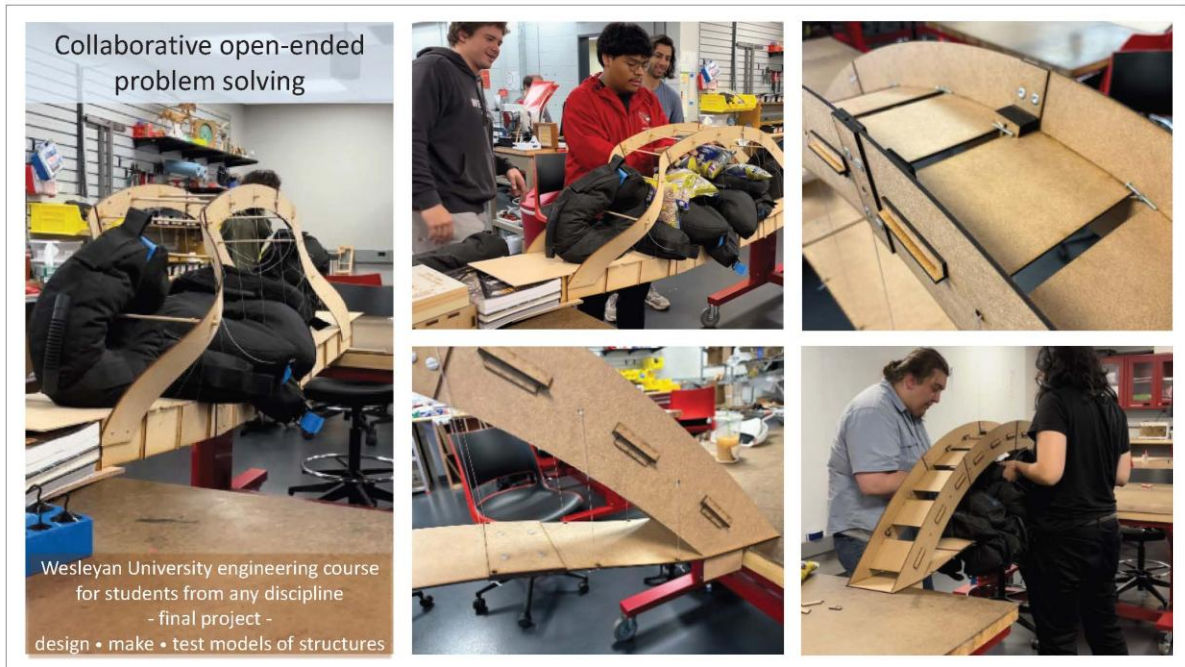
Building energy modeling –  
Sketchbox

Embodied carbon evaluation –  
Ansys Granta Eco Audit tool

Glulam timber, steel, concrete

## Course evaluations

- This course was a great example of a way that Olin courses can use our campus as a living lab. The combination of deep specific knowledge about campus system with a diverse selection of guest speakers created a very effective class.
- This course was challenging, and parts of it were not quite what I expected from the course description, but I really enjoyed it and got a lot out of it. I would love for this course to be offered again, and feel that it has given me a lot of information that I can bring forward in my Olin education and beyond.
- I've always had an interest in architecture so this course was great and a lot of fun. I definitely learned a lot in the process.



## Future work

- Curricular materials
  - interdisciplinary, team-based, hands-on learning experiences
  - connections between technical and societal perspectives
  - building and testing scaled structures
- Synthesis of fundamental engineering principles and open-ended projects
- Accessibility for students of various backgrounds and interests

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Claire Rodgers • Olin College of Engineering

Wesleyan University

Thank You

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