COX, OSU
Van de LINDT, CSU
DHS COASTAL RESILIENCE CENTER
RESEARCH PROJECT
YEAR 3 PERFORMANCE REPORT
AND
FINAL PROJECT REPORT

Project Title: Experimental and Numerical Study to Improve Damage and Loss Estimation due to Overland Wave and Surge Hazards on Near-Coast Structures

Principal Investigator Name/Institution:
Dr. Daniel Cox, Professor, Oregon State University
Dr. John van de Lindt, Professor, Colorado State University

Co-Principal Investigators and Other Partners/Institutions:
Bill Coulbourne, Applied Technology Council
Chris Jones, consulting coastal engineer

Project Start and End Dates: 1/1/2016 – 6/30-2018

Short Project Description ("elevator speech"):

This project will develop an accurate method to determine damage to buildings subjected to extreme surge/wave forces during hurricanes. The methodology will use large-scale hydraulic model testing combined with numerical simulations to improve existing risk software used by DHS/FEMA and to advance risk-based design methodologies to enhance coastal infrastructure resilience. The method will be consistent with other multi-hazard frameworks such as earthquake and wind engineering

Summary Abstract:

This project focuses on Theme 1 – Coastal Infrastructure Resilience; Topic 1a – Coastal Infrastructure Planning and Design. As building stakeholders seek to mitigate damage, risk to property and structure loss it is becoming apparent that exiting design methodologies such as those outlined in the FEMA Coastal Construction Manual are inadequate to incorporate the range of building types, storm conditions, and potential for resulting damage. More effective decision support tools such as FEMA's HAZUS-MH rely on a framework of multi-hazard fragility curves to relate the hazard and affected buildings to compute/predict an expected level of damage and subsequent losses. Although there have been significant advances in this correlation for wind earthquake loading and some preliminary work for tsunamis, the coastal surge and wave response of structures remains poorly defined, primarily due to a lack of large-scale data and the complexity of the fluid/structure interaction modeling. This project will significantly improve HAZUS input fragilities for surge and wave through a robust experimental and numerical study of the interaction of surge and waves with near-coast structures. The overall goal of this project is to develop accurate fragilities for near-coastal structures against overland surge and wave forces for input to HAZUS-MH such that they can be used in a design framework consistent with the risk-based methods used in wind and earthquake engineering We outline these specific

objectives to be completed in two years in order to provide (1) improved accuracy for surge and wave analysis in HAZUS-MH; and (2) innovative advances in risk-informed design methodologies to enhance coastal infrastructure resilience:

- ***Objective 1:*** Quantify wave forces on near-coast structures for a range of surge levels based on a mid-scale hydraulic model test program, and develop new predictive equations for horizontal and vertical forces.
- ***Objective 2:*** Develop the conditional probabilities (fragilities) for exceeding key thresholds which will be linked to damage levels available in HAZUS-MH.
- ***Objective 3:*** Illustrate next-generation risk-informed design for near-coast structures that have been shown to be vulnerable to hurricane surge and waves using the fragilities developed in (2). This will improve the ability of building occupants to return following the hurricane thereby improving the resiliency of the community.

This project will have a direct impact on estimating probable damage and loss of existing coastal infrastructure by providing improved load-response relationships to HAZUS-MH for surge and wave and develop a risk-informed framework for future engineering design of near-coast structures. While beyond the scope of this study, the results could also help improve the potential designs associated with the retrofit of existing structures funded through FEMA hazard mitigation grant programs and the implementation of improved coastal building codes.

PROJECT NARRATIVE:

1. Research Need:

Hurricanes Sandy in 2012, Ike in 2008, and Katrina and Rita in 2005 have underscored the significant and growing risk to coastal communities due to surge and wave hazards. Hurricane-induced economic losses in the United States have increased steadily over the past 60 years and are now $35.8 billion *annually*. Approximately 50 percent of the U.S. population lives within 50 miles of a coastline, and the physical infrastructure to support this population was estimated in the 1990s to be over $3 trillion in the Gulf and Atlantic regions. These problems are compounded by global climate change resulting in increased sea levels and increases in the intensity and frequency of extreme windstorms. The overall vision for this project is to support the broader vision of the CRC to increase the resilience of near-coast structures to coastal hazards. Resilience is the ability of a system to absorb and recover from a sudden disturbance.

Our project is linked to "Mission 5: Ensuring Resilience to Disasters" as listed in the DHS Strategic Plan Fiscal Years 2012 – 2016. Goal 5.1 is to Mitigate Hazards by "strengthening the capacity at all levels of society to withstand threats and hazards." Moreover, Objective 5.1.2 Mitigate Risk to Communities will "improve community capacity to withstand disasters by mitigating known and anticipated threads and hazards." Our project will link directly to Goal 5.1 and Objective 5.1.2 by understanding the damage to the built environment as a result of coastal hazards produced by hurricanes and other coastal windstorms. The overall aim of the DHS CRC is to improve the Nation's ability to safeguard people, infrastructure and economies from catastrophic coastal disasters. By improving FEMA's (HAZUS-MH) ability to predict damage and loss estimates due to waves and surge and developing a framework for new design

methodologies for near-coast structures, this project will enhance the resilience of the Nation's coastal infrastructure to hurricane and other coastal hazards. By improving the predictions of damage and loss, we will be better positioned to anticipate and manage cascading consequences and interactions between infrastructure and hazards. This project will help reduce losses from hurricanes in the United States. and will assist FEMA's mission in the National Windstorm Impact Reduction Program and the National Flood Insurance Program by improving damage and loss assessment tools consistent with FEMA's program for HAZUS modernization.

2. History:

Task 1.1 Experimental Design. We developed wave/surge boundary conditions; bathymetry; specimen design and placement; test matrix and protocols.

Task 1.2 Physical Model Testing. We conducted the physical model tests at the Hinsdale Wave Research Laboratory at Oregon State University. The test program included specimen construction, instrumentation setup, data acquisition, demobilization, and data QA/QC and data archive.

Task 2.1 Numerical Modeling. We developed a numerical model of archetype coastal residential structures and verified the structural model using existing experimental data.

Task 2.2 Fragility Formulation. We developed initial fragility limit states, producing fragility surfaces that can relate hurricane surge level and wave conditions to the expected building damage. These are intended to be used within DHS/FEMA's HAZUS.

3. Results:

The experimental work was completed successfully and fluid/structure interaction models validated and documented in several archival papers with peer review/feedback. A methodology was developed to combine a state-of-the-science numerical model with an array of surge and wave conditions to develop fragility surfaces. End user outreach was undertaken with the FEMA HAZUS group and plans to discuss implementation of the sample fragilities, as well as plans for additional fragilities discussed.

4. End Users and Transition Partners:

We have had the following people involved in the End-User Transition:

- FEMA HQ
- HAZUS Program Manager, FEMA HQ Risk Management Directorate
- Risk Analyst, FEMA Region VIII
- FEMA Building Science Division
- Chad Berginnis, ASFPM Executive Director and CRC Advisory Board Member

End User Meeting #1: Denver, CO. FEMA Region VIII (April 25, 2017). The meeting took place with Cox, van de Lindt and two end users, HAZUS Program Manager, FEMA HQ Risk Management Directorate, Actuarial and Catastrophic Modeling Branch, and Risk Analyst, FEMA Region VIII. Cox and van de Lindt presented their project results and discuss possible implementations

End User Meeting #2: Washington DC. FEMA HQ (May 19, 2017). The meeting was organized by FEMA HQ. Cox and van de Lindt gave a 1 hour presentation on the project to approximately 20 FEMA staff at the meeting and an addition 20 people participating via webinar. Question and answer session followed the presentation. A working lunch continued the discussion with about 3 FEMA personnel.

5. Project Impact:

The real world impact when the new fragilities are implemented in the HAZUS update over the next several years will be the ability to include more accurate loss estimation for near coastal structures. To this point in time loss estimates in HAZUS do not account for the wave climate for near coastal structures and have used flood fragilities. This is particularly critical for elevated coastal structures whose structural failure may occur as a result of wave action under and at the bottom of the structure.

6. Student involvement and awards:

Year 1: We hosted two SUMREX students from University of Puerto Rico - Mayaguez, Diego Delgado and Kevin Cueto. Kevin and Diego were on the Oregon State University campus from June 18, 2016, to August 5, 2017. Both students participated in an undergraduate research program with 9 other students and completed a project report and presentation on August 4. Kevin is currently enrolled as an MS student at UPR-M. Diego has applied to graduate school at the Univ. Cantabria in Spain.

In Year 2, Dr. Cox visited the Univ. Puerto Rico – Mayaguez. Dr. Cox visit Puerto Rico from March 5 to March 9, 2017, at the invitation of Professors Ismael Pagan and Ricardo Lopez. On March 7, Dr. Cox visited the campus of the University of Puerto Rico Mayaguez campus, met with faculty in civil engineering and marine sciences, met with students, toured the facilities, and gave a seminar on coastal hazards engineering and resilience. On March 8 and 9, Dr. Cox attended the research symposium organized by Profs. Pagan and Lopez in San Juan. Dr. Cox met with engineering practitioners from Puerto Rico and researchers from the USACE. Dr. Cox gave a keynote presentation on this research project.

In Year 2, we hosted two SUMEX students from UPR-M**,** Hector Colon and Peter Rivera. Hector and Peter were on the Oregon State University campus from June 18, 2017, to August 12, 2017. Both students are participating in an undergraduate research program with 17 other students and will complete a project report and presentation on August 9. Both students gave presentations of their project at the International Conference on Coastal Engineering (ICCE) in Baltimore in August, 2018.

In Year 3, hosted two SUMREX student from UPR-M, Bryan Acevedo-Adames and Jorge Santiago Hernández. Bryan and Jorge were on the Oregon State University campus from June

17, 2018, to August 17, 2018. Both students are participating in an undergraduate research program with several other students and will complete a project report.

Degrees Obtained

Trung Quang Do, Ph.D., Civil Engineering

7. Interactions with education projects:

We have worked with a total of 6 SUMREX students, 2 each summer and all from the University of Puerto Rico – Mayaguez. We visited UPR-M once during this project in Year 2.

8. Publications:

1. Do, T., van de Lindt, J., Cox, D. "Hurricane Surge-Wave Building Fragility Methodology for Use with HAZUS-MH," (submitted 2018)
2. Tomiczek, T., Wyman, A., Park, H., Cox, D.T. "Application and Modification of Goda's Formulae to Estimate Horizontal and Vertical Forces on Elevated Coastal Structures. Part 1: Nonbreaking Waves," *Coastal Engineering* (re-submitted 2018)
3. Park, H., Do, T., Tomiczek, T., Cox, D.T., van de Lindt, J.W. (2018) "Numerical Modeling of Non-breaking, Impulsive Breaking, and Broken Wave Interaction with Elevated Coastal Structures: Laboratory Validation and Inter-Model Comparisons," *Ocean Engineering*, 158, 15, 78-98. doi: 10.1016/j.oceaneng.2018.03.088
4. Tomiczek, T., Park, H., Cox, D.T., van de Lindt, J.W., Lomonaco, P. (2017) "Experimental Modeling of Horizontal and Vertical Wave Forces on an Elevated Coastal Structure," *Coastal Engineering*, 128, 58-74.
5. Do, Trung, van de Lindt, J., Cox, D.T. (2016) "Performance-Based Design Methodology for Inundated Elevated Coastal Structures Subjected to Wave Load Engineering Structures," *Engineering Structures*, 117, 250 – 262.

REPORTS

6. William Short. *A laboratory study of horizontal and vertical regular wave forces on an elevated structure*. (2016). MS Thesis, Oregon State University.

7. Benjamin Hunter. *Exceedance Probabilities of Hurricane Wave Forces on Elevated Structures*. (2016). MS Thesis, Oregon State University.

CONFERENCE PAPERS

8. Park, H., Do, T., Tomiczek, T., Cox, D., van de Lindt, J.W. (2018) "Laboratory Validation and Inter-Model Comparisons of Non-breaking, Impulsive Breaking, and Broken Wave Interaction with Elevated Coastal Structures using IHFOAM and FLUENT," *International Conference on Coastal Engineering*, ASCE.

9. Lomonaco, P., P. Arduino, A. Barbosa, D. Cox, T. Do, M. Eberhard, M. Motley, K. Shekhar, T. Tomiczek, H. Park, J. W. van de Lindt, A. Winter "Experimental Modeling of Wave Forces and Hydrodynamics on Elevated Coastal Structures Subject to Waves, Surge or Tsunamis: The Effect of Breaking, Shielding and Debris, *International Conference on Coastal Engineering*, ASCE.

10. Tomiczek, T., Wyman, A., Park, H., Cox, D.T. (2018) "Application and modification of Goda Formulae for Non-impulsive Wave Forces on Elevated Coastal Structures," *International Conference on Coastal Engineering,* ASCE.

9. Tables: Complete the following tables

Table 1: Documenting CRC Research Product Delivery
Table 2A: Documenting External Funding
Table 2B: Documenting Leveraged Support
Table 3: Performance Metrics

Table 1: Documenting CRC Research Project Product Delivery

Product Name	**Product Type** (e.g., software, guidance document)	**Delivery Date**	**Recipient or End User**
n/a			

Table 2A: Documenting External Funding

Title	**PI**	**Total Amount**	**Source**
n/a			

Table 2B: Documenting Leveraged Support

Description (e.g., free office space; portion of university indirects returned to project; university-provided student support)	**Estimated Total Value**
n/a	

Table 3: Performance Metrics:

Please fill in the Year 3 column of the Metrics column with numbers only. The Year 1 and Year 2 columns reflect the metrics you reported in each of those years.

COX/van de LINDT PERFORMANCE METRICS

Metric	Year 1 (1/1/16 – 6/30/16)	Year 2 (7/1/16 – 6/30/17)	Year 3 (7/1/17- 6/30/18)
HS-related internships (number)			
Undergraduates provided tuition/fee support (number)	0	0	0
Undergraduate students provided stipends (number)	0	0	0
Graduate students provided tuition/fee support (number)	2	2	2
Graduate students provided stipends (number)	0	2	2
Undergraduates who received HS-related degrees (number)	0	0	0
Graduate students who received HS-related degrees (number)	0	0	0
Graduates who obtained HS-related employment (number)	0	0	0
SUMREX program students hosted (number)	2	2	2
Lectures/presentations/seminars at Center partners (number)	0	3	0
DHS MSI Summer Research Teams hosted (number)	0	0	0
Journal articles submitted (number)	0	2	2
Journal articles published (number)	0	2	0
Conference presentations made (number)	0	1	2
Other presentations, interviews, etc. (number)	0	0	2
Patent applications filed (number)	0	0	0
Patents awarded (number)	0	0	0
Trademarks/copyrights filed (number)	0	0	0
Requests for assistance/advice from DHS agencies (number)	0	0	0
Requests for assistance/advice from other agencies or governments	0	0	0
Total milestones for reporting period (research activity/milestone)*	4	5	4
Accomplished fully (research activity/milestone)	0	2	3
Accomplished partially (research activity/milestone)	4	3	1
Not accomplished (research activity/milestone)	0	0	0

10. Year 3 Research Activity and Milestone Achievement:

Research Activities and Milestones: Final Status as of 2018
Reporting Period 7/1/2017 – 6/30/2018

Research Activities	Proposed Completion Date	% Completed	Explanation of why activity/ milestone was not reached
Task 3: Performance-Based Wave-Surge Design for Near-Coast Structures (CSU/OSU) -- A performance-based design example for a representative archetype near-coast structures will be conducted to illustrate the new methodology for engineering practice	12/31/2017	100%	
Design and construction of retrofitted specimens at OSU	6/30/2018	0%	Funds for this time period were not secured in time to reserve wave basin time. Testing was undertaken on an existing specimen at large scale to examine scaling approaches.
Application of validated numerical model for scale model design and development of fragilities for retrofitted specimens use in year 4 and 5	6/30/2018	50%	These have been developed but not validated experimentally. The submitted scope of year 4 and 5 changed slightly after discussion with FEMA HAZUS end-user group.
Meeting with FEMA in either Washington D.C. with invitation/participation by Region VIII (HAZUS leads), or meeting at Region VIII with Washington D.C. participants.	6/30/2018	100%	This was an on-line meeting organized by DHS.
Research Milestones			
Progress Report 9: Performance-Based Wave-Surge Design for Near-Coast Structures	12/31/2017	100%	
Final Report submission: Synthesis of			

Progress Reports with overall project summary and recommendations.	6/30/2018	100%	
Progress reporting in the form of a journal paper documenting the scale specimen design method which is an area lacking in near coast structural modeling that can benefit HAZUS fragility development substantially.	6/30/2018	100%	Submitted 8/1/2018
Progress reporting in the form of two journal papers explaining (1) the modeling methodology for scale wood modeling; and (2) the resulting fragilities for HAZUS.	6/30/2018	50%	Load cell issue on scale model. Finalizing in early Fall.

11. Year 3 Transition Activity and Milestone Status:

Transition Activities and Milestones: Final Status as of 2018
Reporting Period 7/1/2017 – 6/30/2018

Transition Activities	Proposed completion date	% completed	Explanation of why activity / milestone was not reached
Develop written report and final presentation to FEMA officials, HAZUS User Group and CRC	12/31/2017	100%	
Submit written report and present at annual meeting or other specified time.	12/31/2017	100%	
Present additional/new scope at CRC Annual Meeting	3/1/18	100%	
Document feedback from FEMA regarding adoption of new fragilities	6/30/18	100%	

Transition Milestones			
New fragilities are implemented into IN-CORE by the National Center for Supercomputing Application (IN-CORE development/programmers)	12/31/2017	100%	They are available and were provided, but IN-CORE development is not at the point that it can use the fragilities – it is close. They will be applied when it is ready.
FEMA agrees to use new fragilities in HAZUS update	12/31/2017	50%	Good discussion with FEMA and research team is waiting for additional feedback from FEMA on data sharing and their study areas for coordination.
Conference presentation at domestic conference	6/30/18	100%	