COASTAL RESILIENCE CENTER

A U.S. Department of Homeland Security Center of Excellence

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

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Project Overview

Objective 1: Quantify surge/wave forces on near-coast structures and develop new predictive equations.

Objective 2: Develop the conditional probabilities (fragilities) for exceeding key thresholds.

Objective 3: Illustrate next-generation risk-informed decision support.

Technical Approach

Task 1: Hydraulic model test program at OSU and data analysis.

Task 2: Numerical model program at CSU. Verification and fragility development.

Task 3: Hindcast study to verify new methodology.

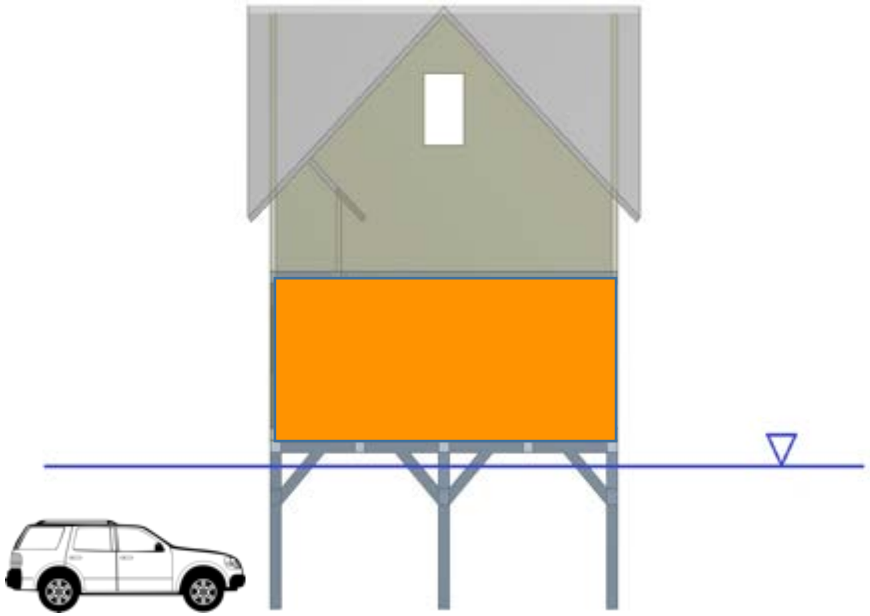
First comprehensive measurements of wave forces on elevated residential structures

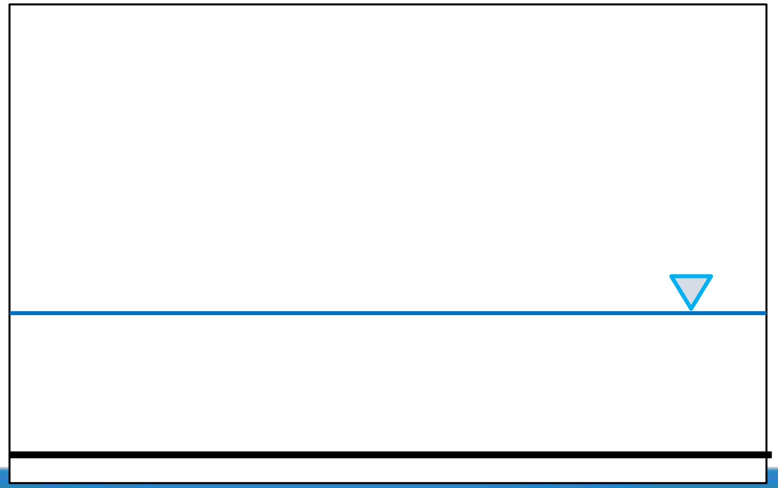
Simplifying Assumptions

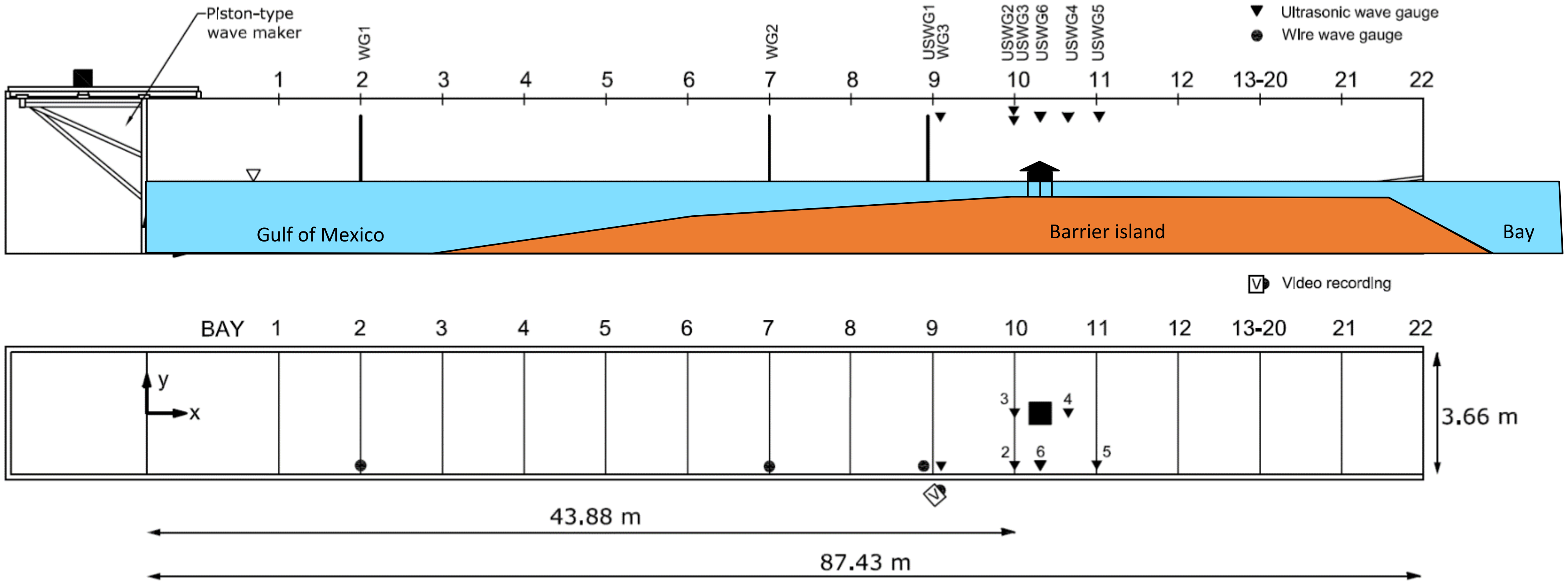
- No substructure
- No sediments, scour
- No debris
- No currents

Geometric scale 1:10
Wave height: 0.10 < H < 0.50 m
Inundation: 0.40 m
Specimen dimensions: 1.02 x 1.02 x 0.61 m

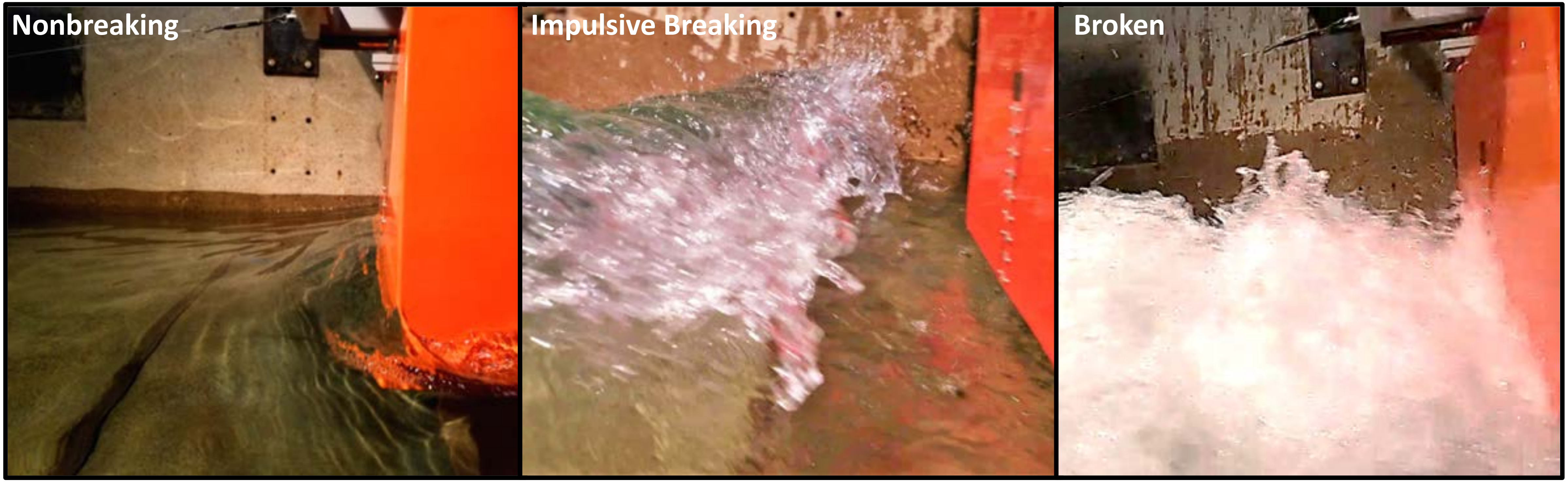
Froude similitude 1:3.16
Wave period: 2.5 < T < 5.0 s






Piston-type wave maker
WG1
WG2
USWG1
WG3
USWG2
USWG3
USWG6
USWG4
USWG5
Ultrasonic wave gauge
Wire wave gauge
1 2 3 4 5 6 7 8 9 10 11 12 13-20 21 22
Gulf of Mexico
Barrier island
Bay
Video recording
BAY 1 2 3 4 5 6 7 8 9 10 11 12 13-20 21 22
y
x
3.66 m
43.88 m
87.43 m

Wave Conditions



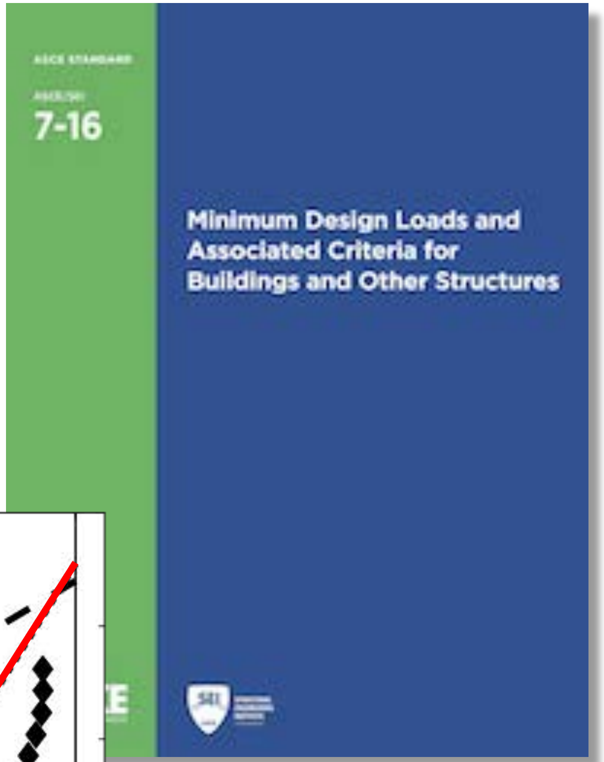
Exp.	$\overline{H}$ (m)	$\overline{T}$ (s)	*h (m)*
1	0.12	4.10	0.40
2	0.32	4.10	0.40
6	0.17	2.52	0.40

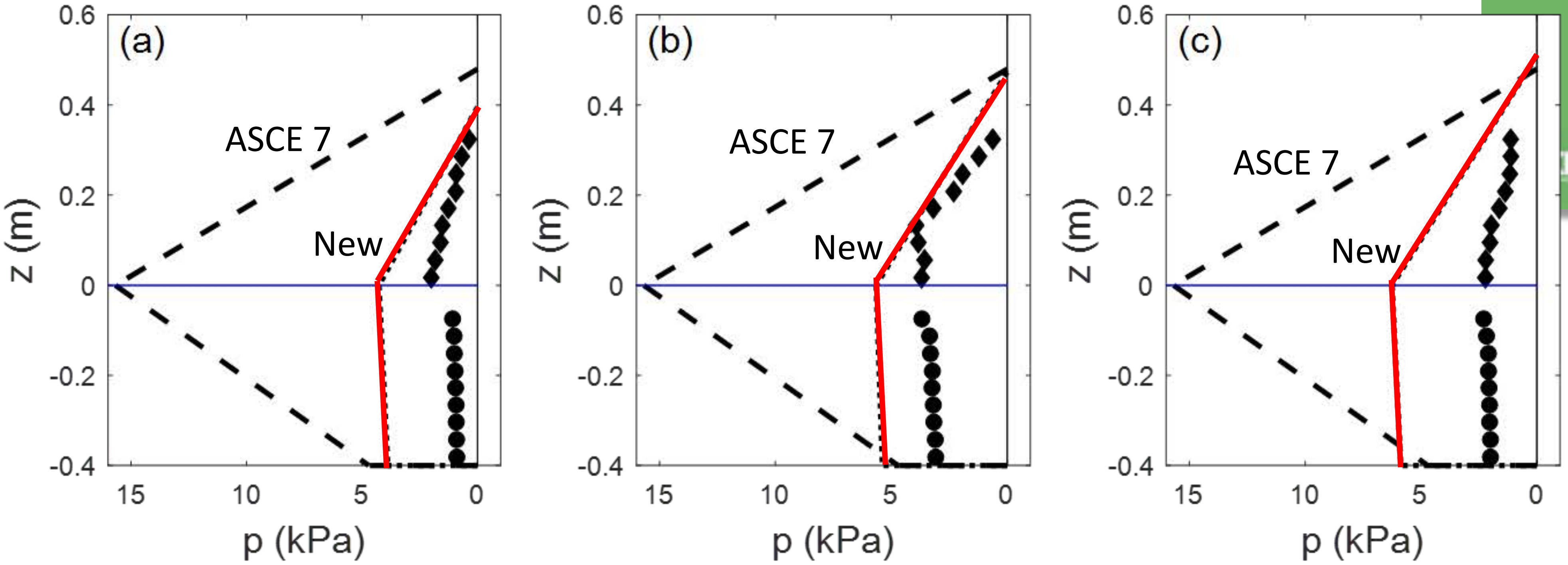
Exp.	$\overline{H}$ (m)	$\overline{T}$ (s)	*h (m)*
3	0.32	4.10	0.40
7	0.26	2.98	0.40
8	0.34	3.28	0.40

Exp.	$\overline{H}$ (m)	$\overline{T}$ (s)	*h (m)*
4	0.27	4.10	0.40
5	0.26	4.10	2.15
9	0.23	4.68	2.15
10	0.18	5.04	2.15

Pressure Distributions For Breaking Waves

Comparison of ASCE 7 and Goda Equations (CEM)

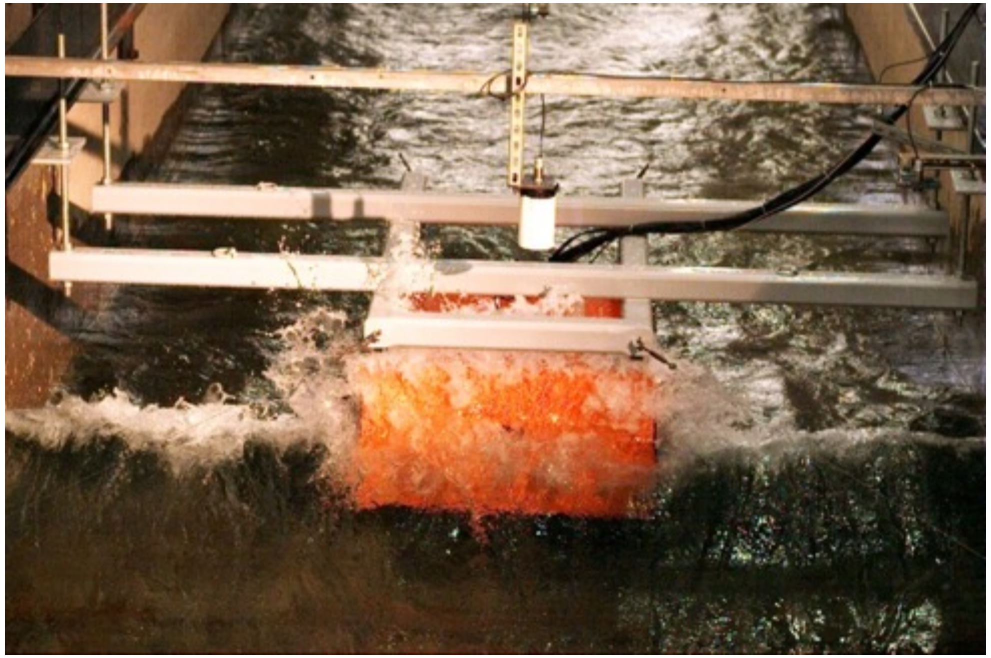




Proposed changes for ASCE 7-22

Year 5

Idealized/Elastic to Archetype/Inelastic



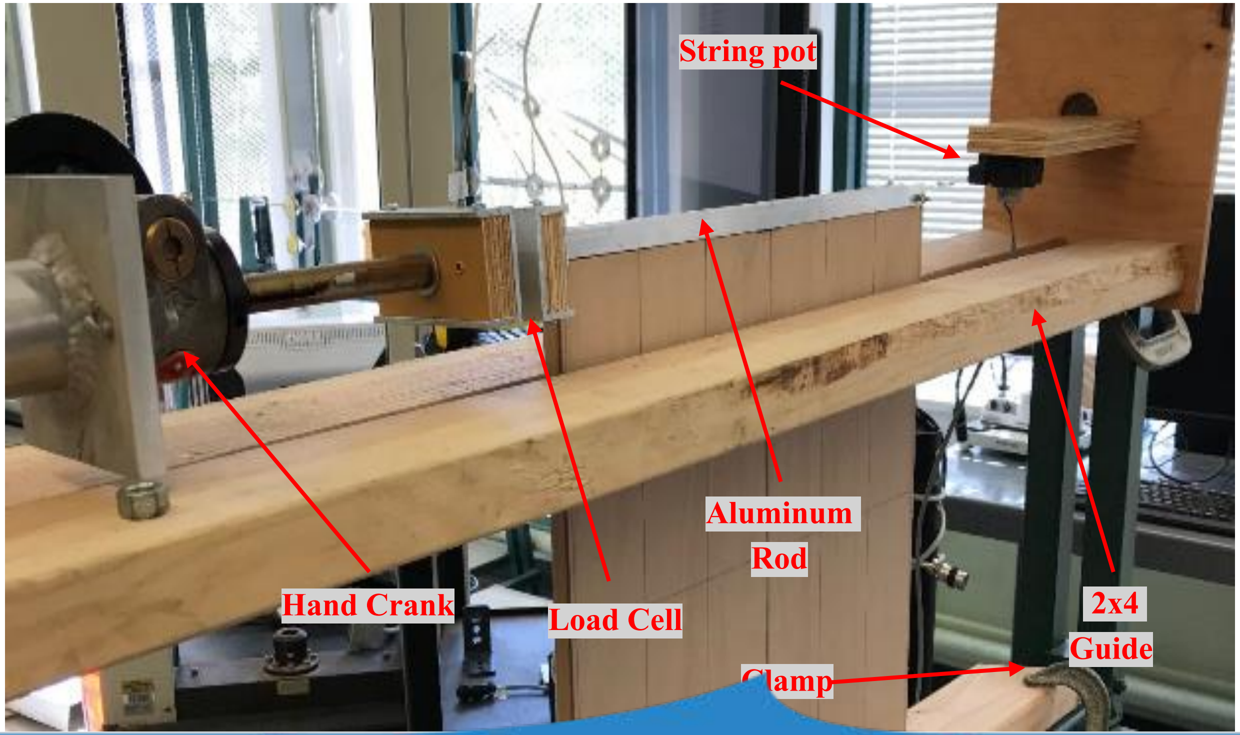
Research Question: Can we design and test a residential coastal structure for progressive damage and failure under surge/wave forcing conditions observed during recent hurricanes?





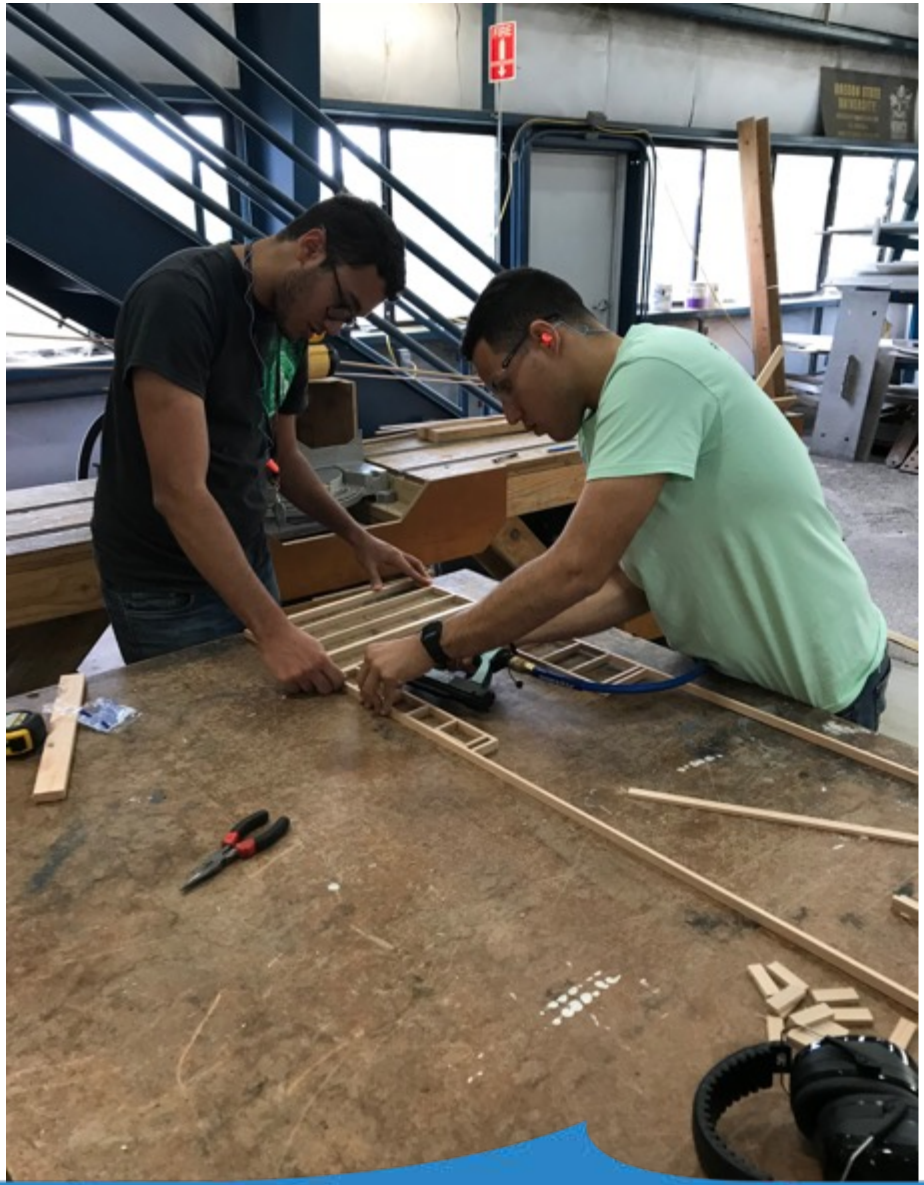

Subassembly Testing

- To accurately predict and describe damage in a real storm event means specimens must be similar in characteristics and construction methods to affected infrastructure.



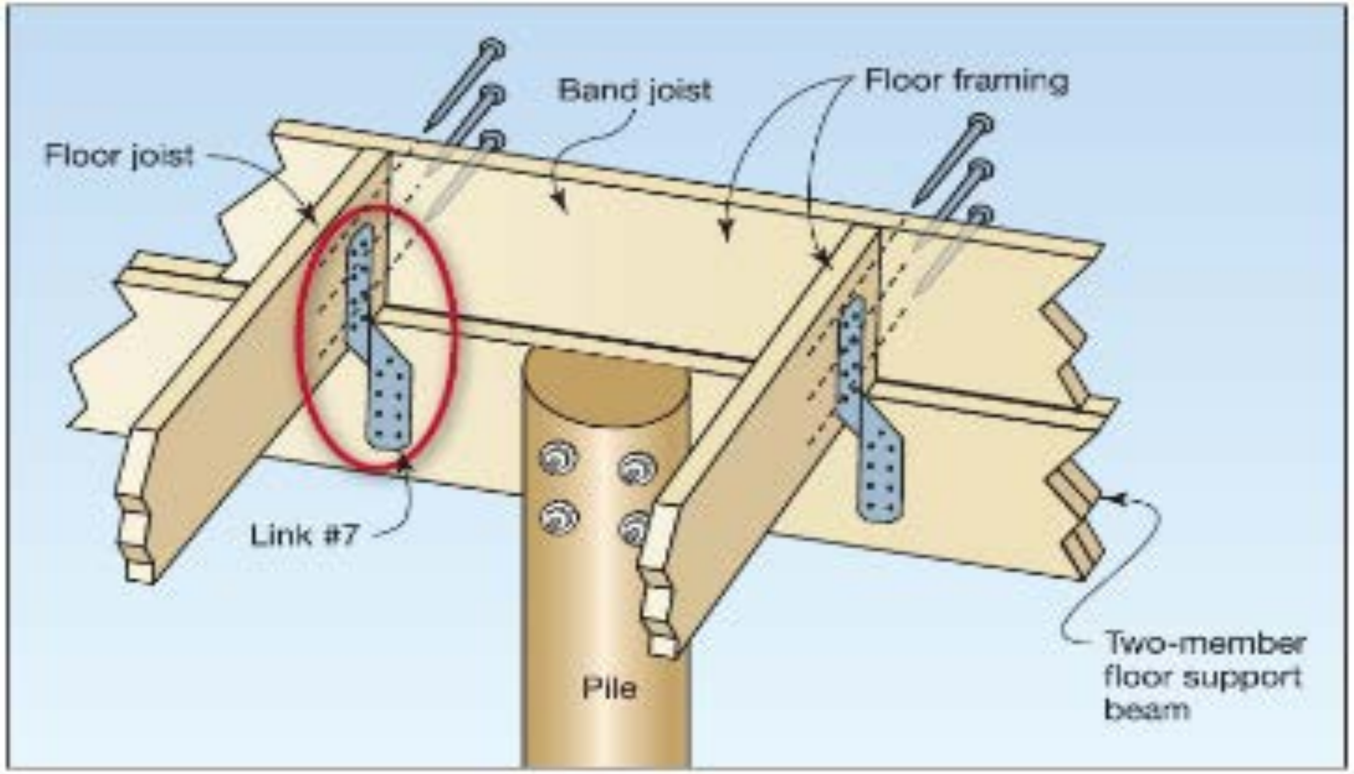
Specimen Construction

- Full-length wall assembly-line construction
  - Template Walls
  - Multiple nailers at one time
- Specimen assembled wall-by-wall
- Pre-drill LC/steel plate mounting holes
- Avg. 60 person-hrs/specimen



Elevated Structure Construction

- FEMA CCM
- Assumed rigid at soil
- 12-in square piles
- Floor diaphragm
  - Joists: 2x10s
  - Girders: (2) 2x12s
- Connections
  - Girder-to-pile
  - Joist-to-girder



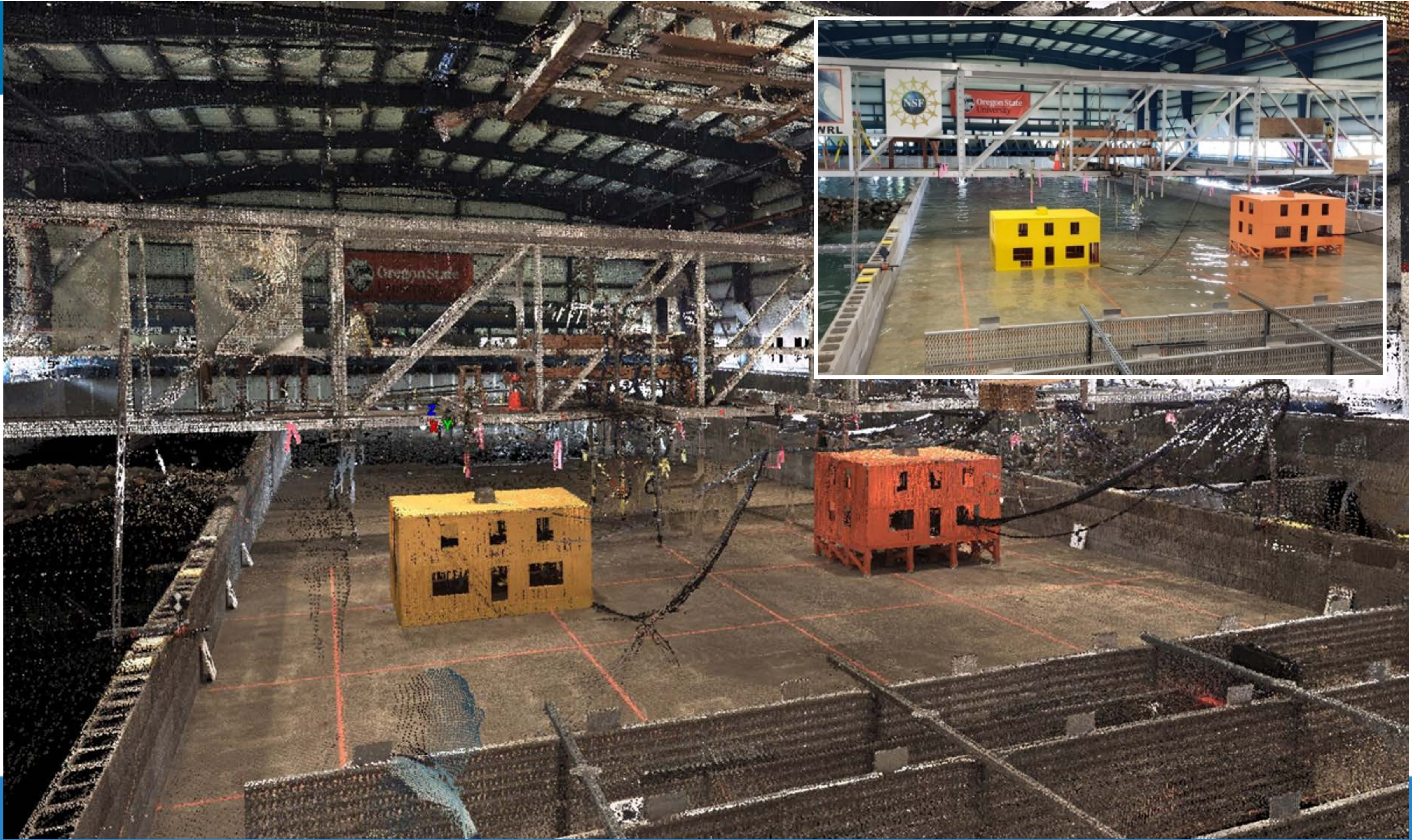
Constructing the Building, 2011

Progressive Damage Observations

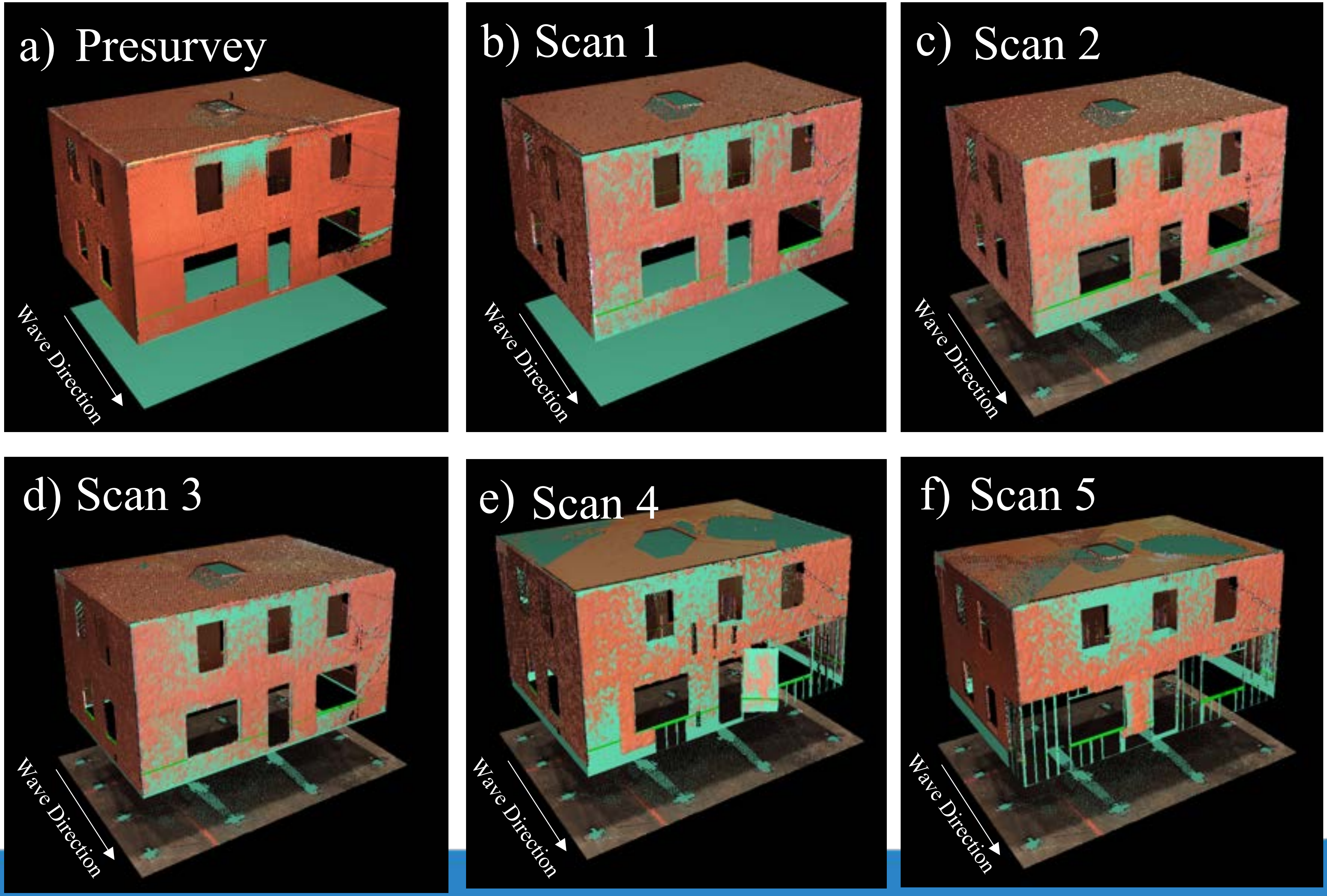

HWRL
NSF
Oregon State University


HWRL
NSF


NSF

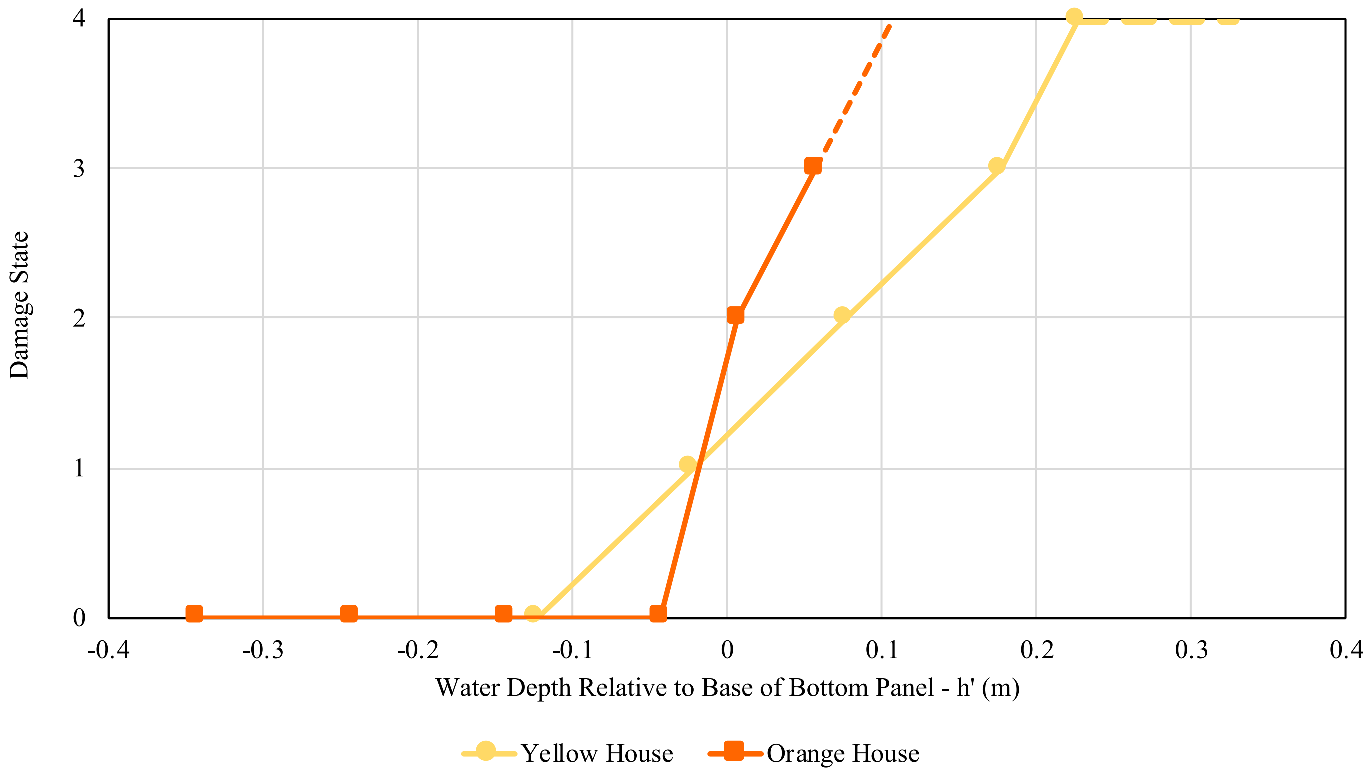


Oregon State
NSF
WRL
Oregon State University



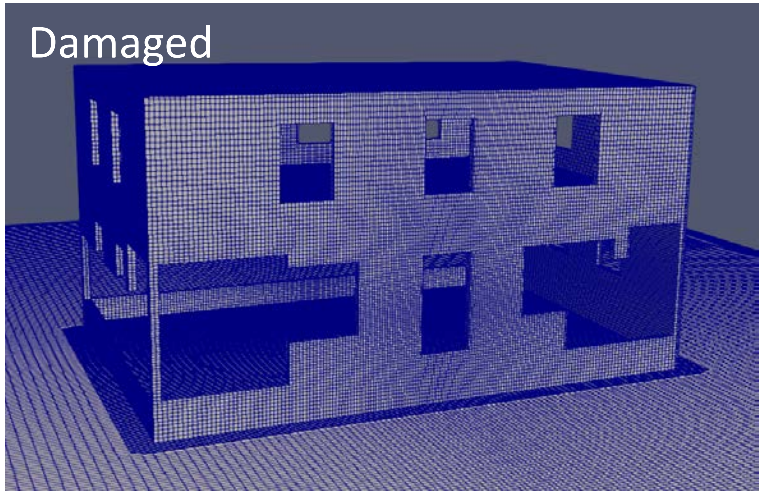
(Left) Point cloud of each scan shown in orange, with fitted planar "patches" shown in green. Damages are cropped regions of green patches.

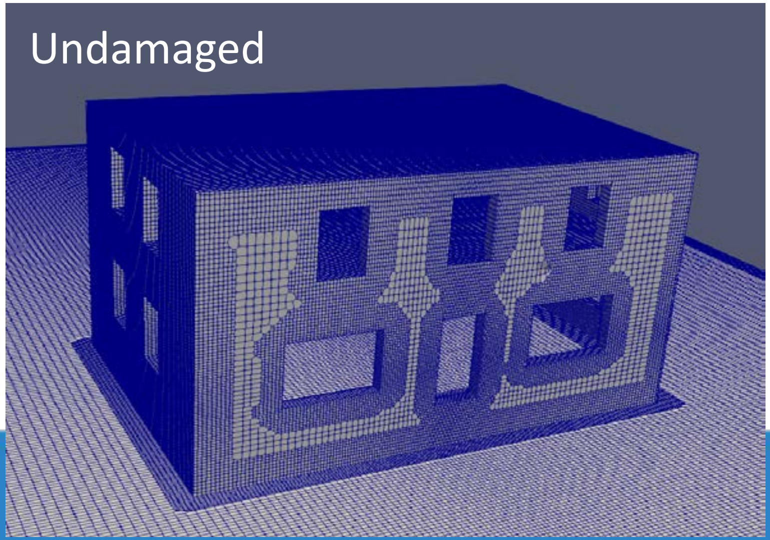
Damage state				
0	1	2	3	4
• No visible damage	• < 15% damage to normally oriented walls • loose or partially removed panels	• > 15% cumulative damage to normally oriented walls	• > 40% cumulative damage to normally oriented walls	• Walls have collapsed



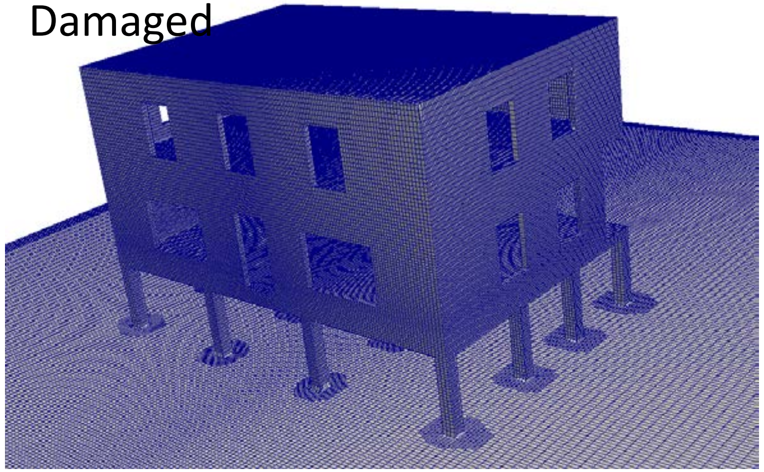
Evaluating "Damaged" and Undamaged" mesh conditions (OpenFOAM)

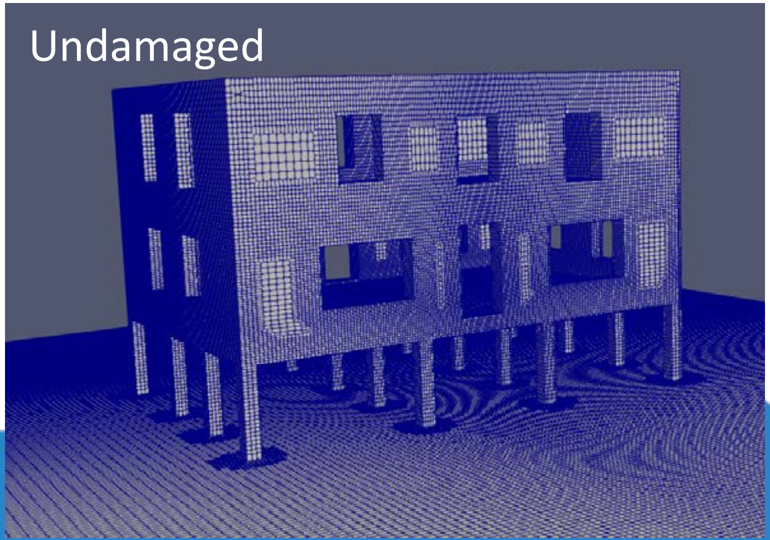
Slab on Grade (Yellow)





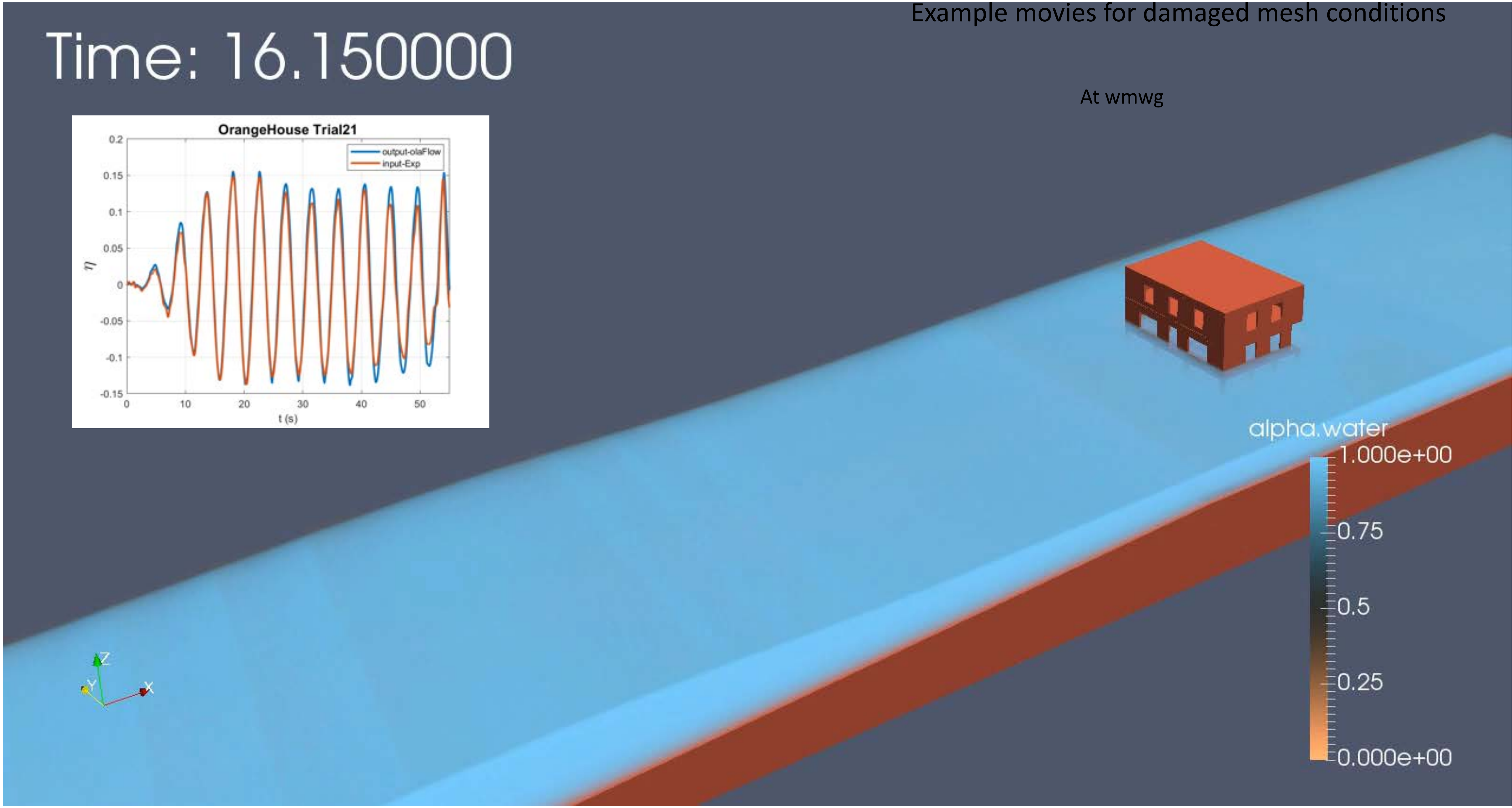
Elevated (Orange)



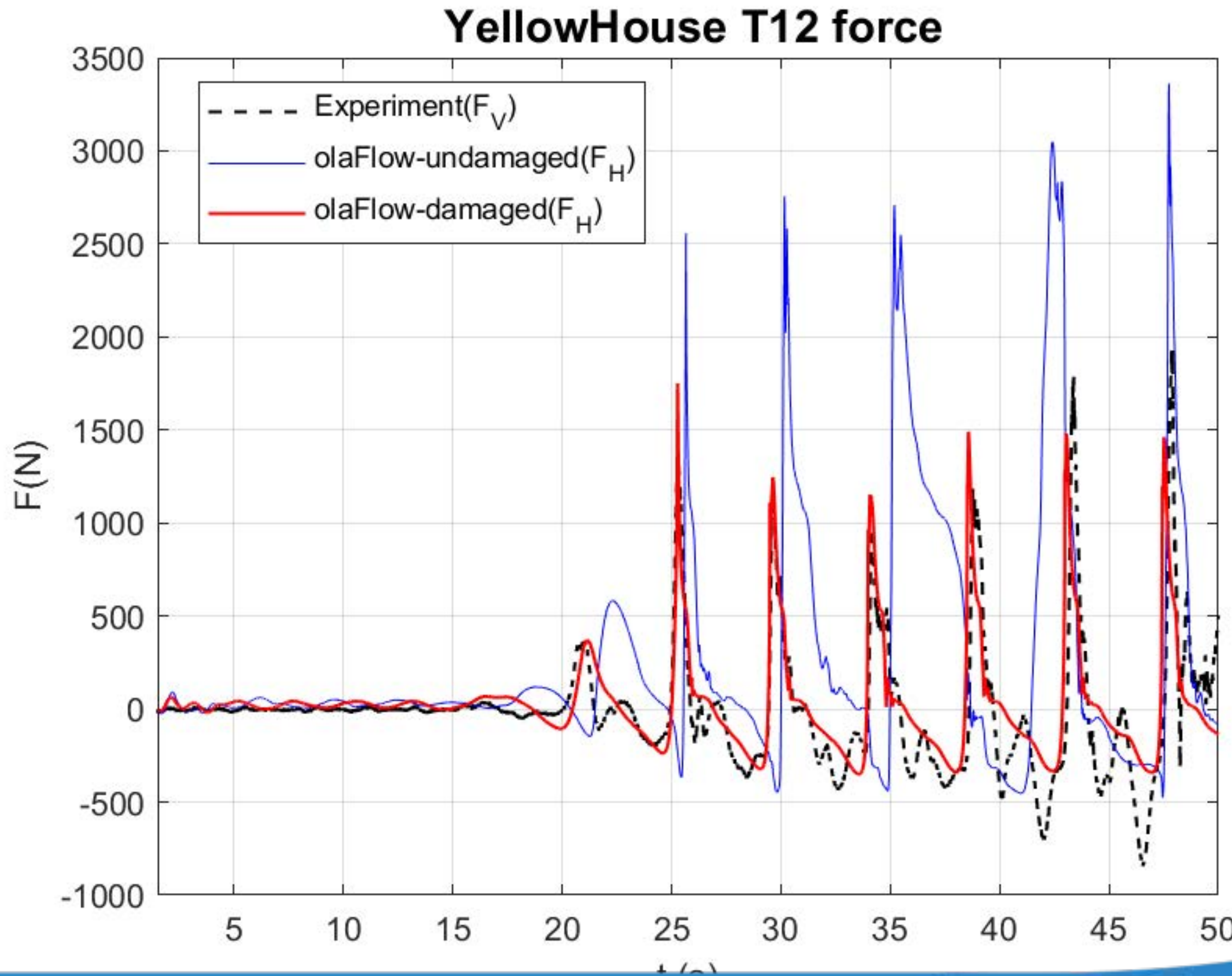


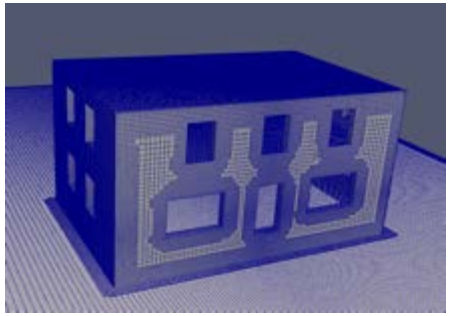
Example movies for damaged mesh conditions

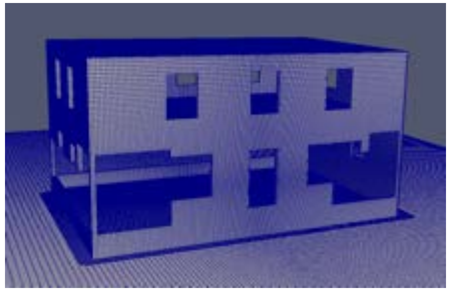
At wmwg



- Comparison results of “damaged” and ‘undamaged” (Yellow house)
- 50% of deduction on the horizontal force. (Opening effects)

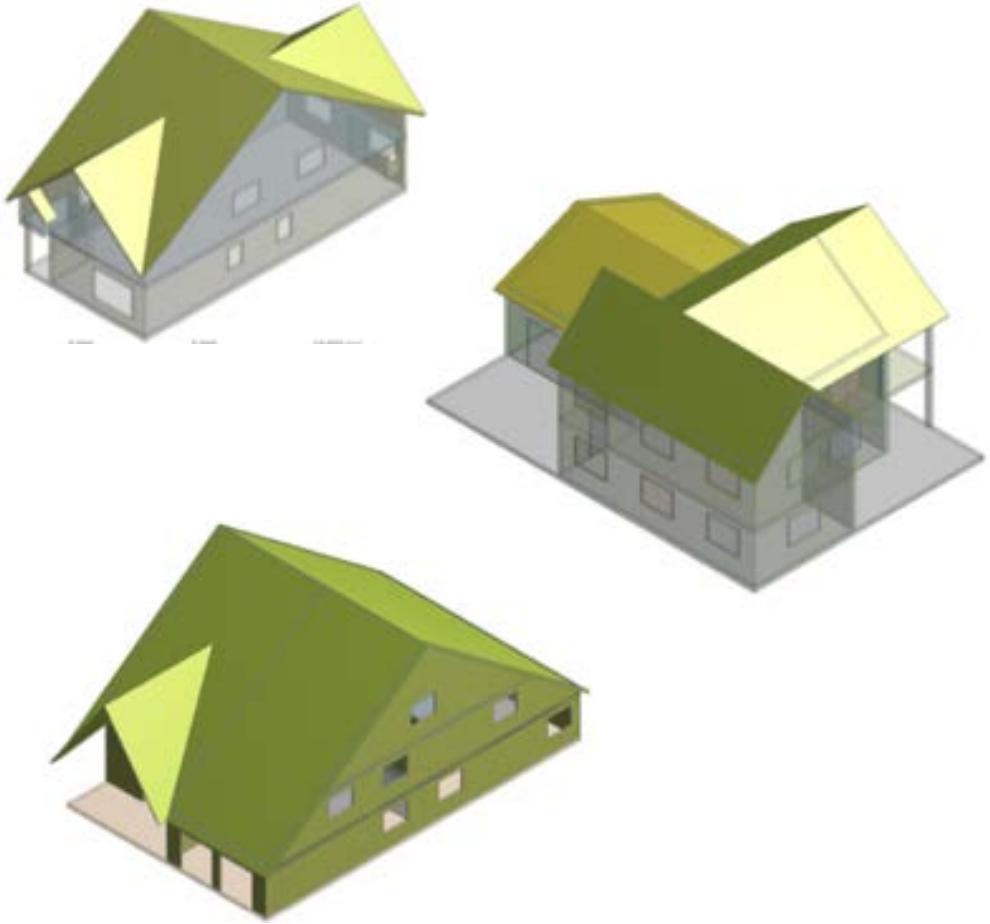






Task 2: Numerical model program at CSU. Verification and fragility development.

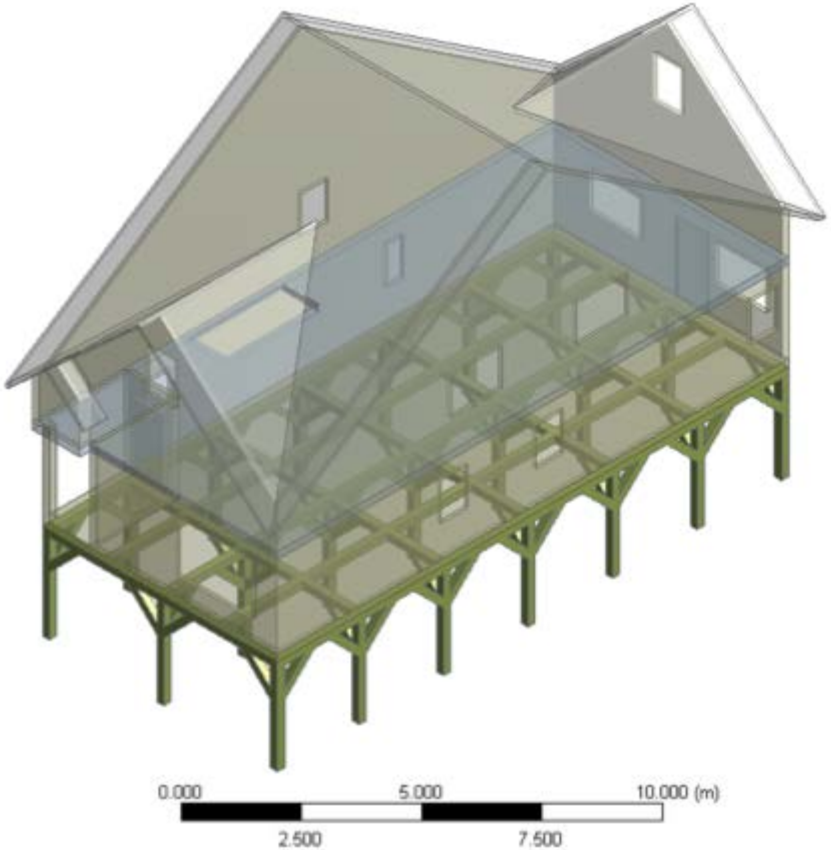
- Fragility development (Year 3-5)
  - 5 Building archetypes are selected from 6 residential wood building archetypes of the hurricane wind project
  - Set up numerical model and collect total uplift and shear as well as force on components such as doors, windows, and walls
  - Establish damage states based on damage of components such as door, windows, and nails connection of wood walls.
  - Generate fragility surfaces based on both significant wave heights and flood levels



Building models (Year 3-5)

- The buildings are modeled in ANSYS Fluent
- Piles rising from 0, 1 m, 2 m, and 3 m, from the ground

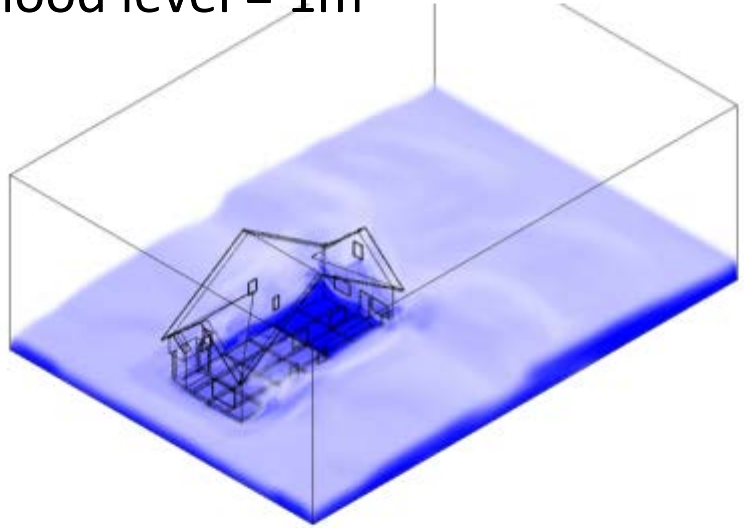
- TMA spectrum for hurricane waves with H_s = 1, 2 , and 3 m, and wave peak period, T_p, from 8s to 14s
- Surge (SWL) levels h = 1, 2, and 3 m

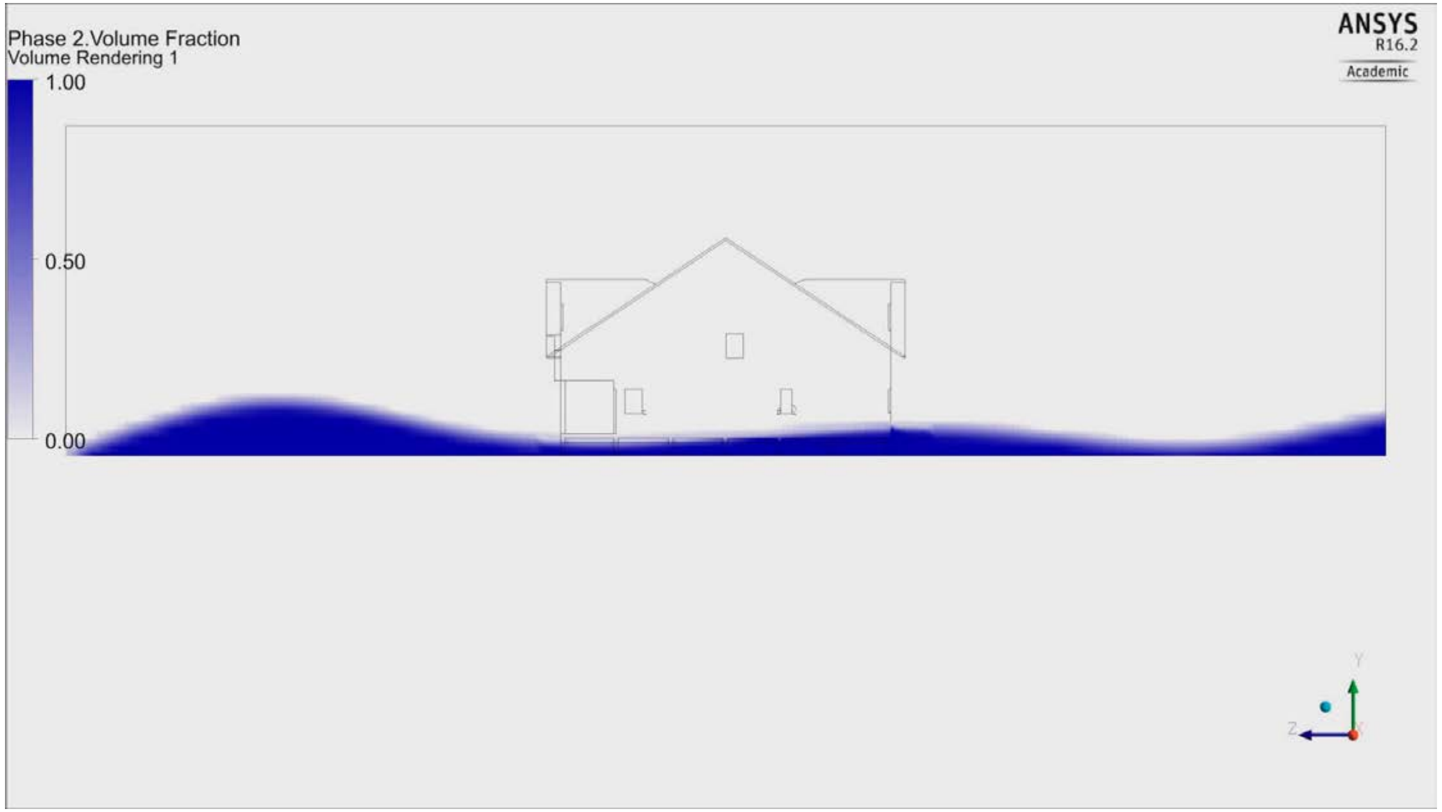


Archetype 1 With 3-m elevated pile from ground

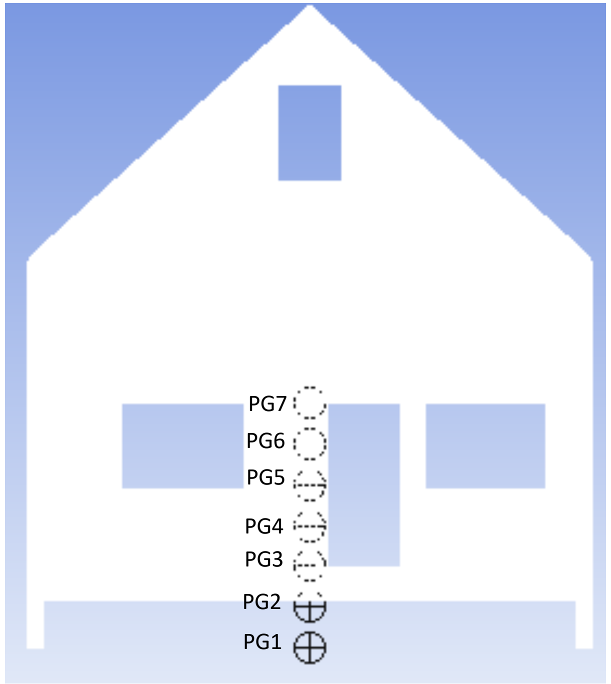
Example of wave impact on building archetype 1

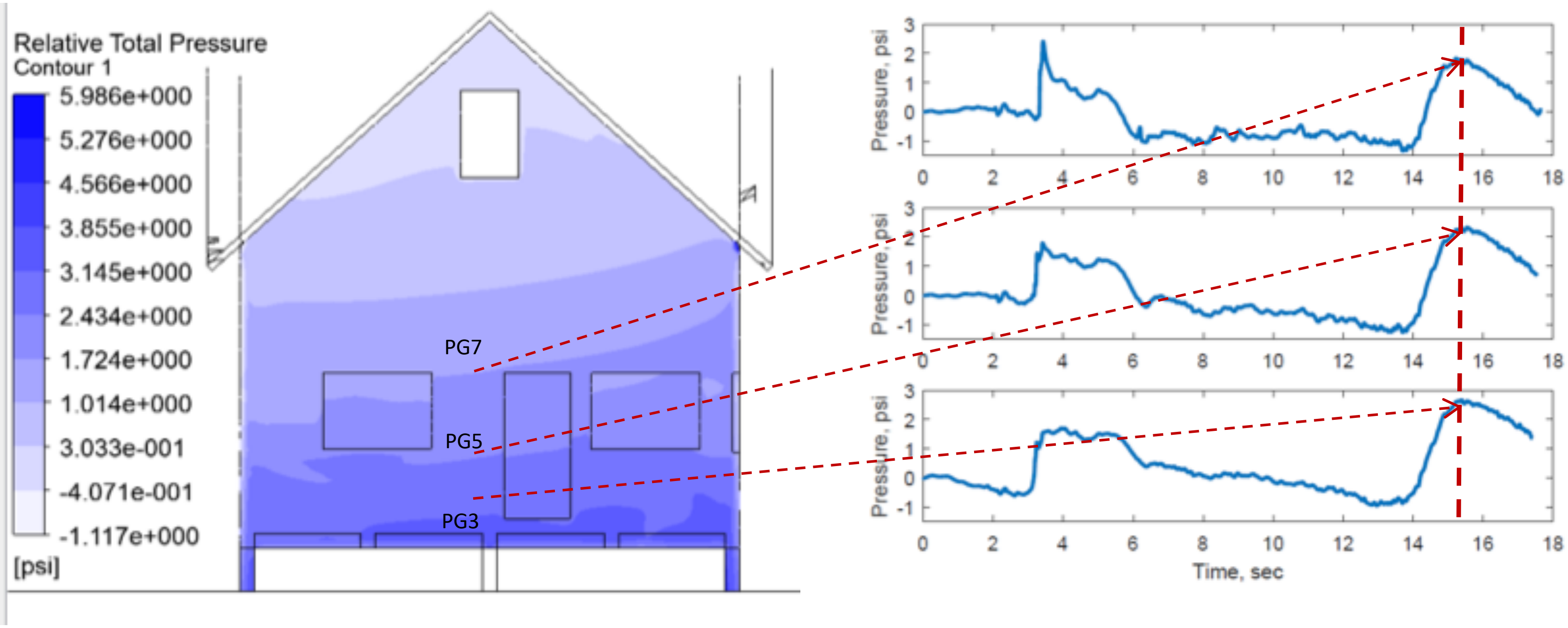
- Piles rising 1m from the ground
- Significant wave height = 1m
- Flood level = 1m





Pressure measured location and distribution at one wave impact event

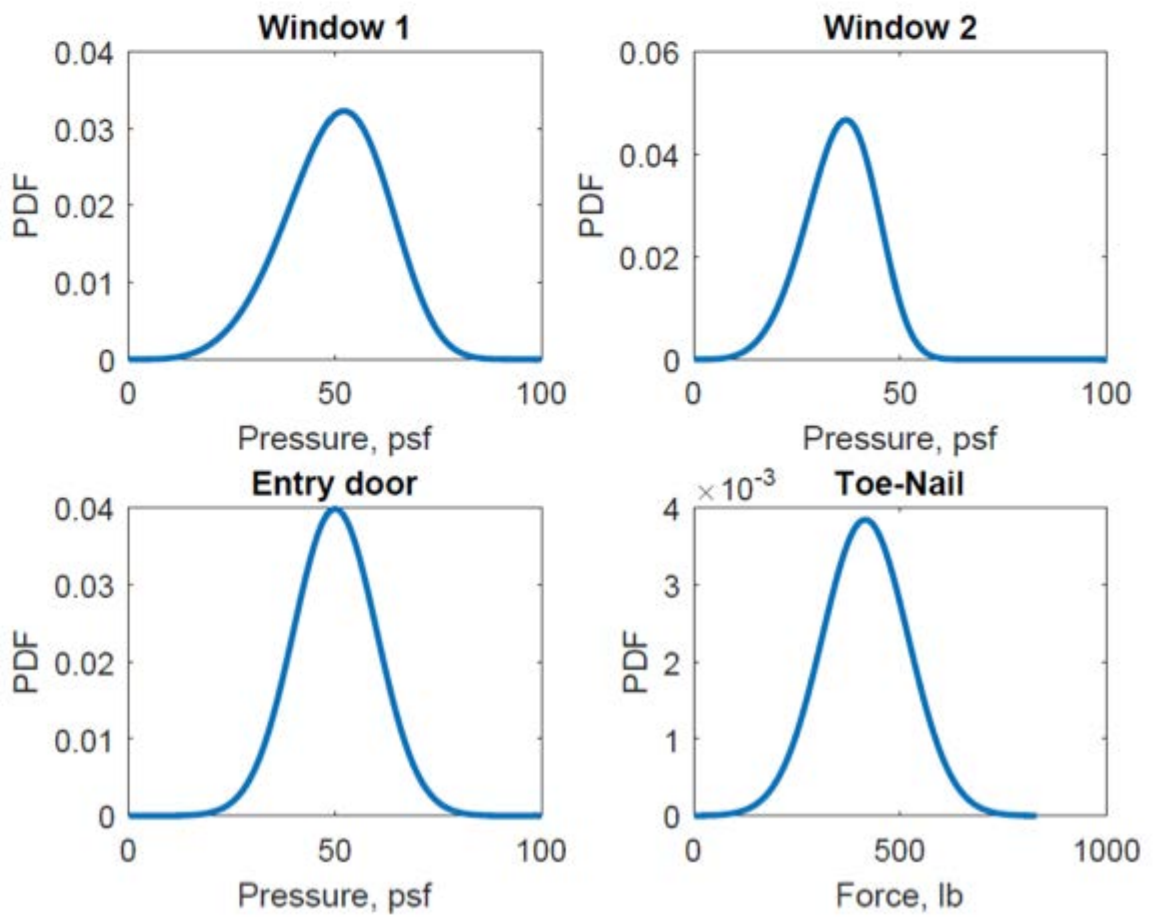




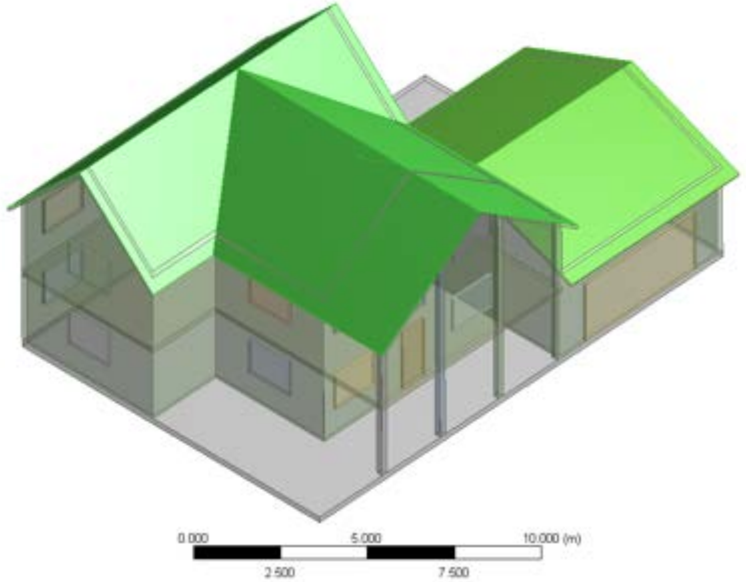
Damage State	Window/ door failure	Wall failure	Floor failure
0 (no damage)	<1%	No	No
1 (Minor damage)	>1% and <5%	No	No
2 (Moderate)	>5% and <25%	>5% and <25%	>5% and <25%
3 (Severe damage)	>25% and <50%	>25% and <50%	>25% and <50%
4 (Destruction)	>50%	>50%	>50%

Component Resistance Values Used to Model Residential Buildings (Hazus 2.1- Hurricane)

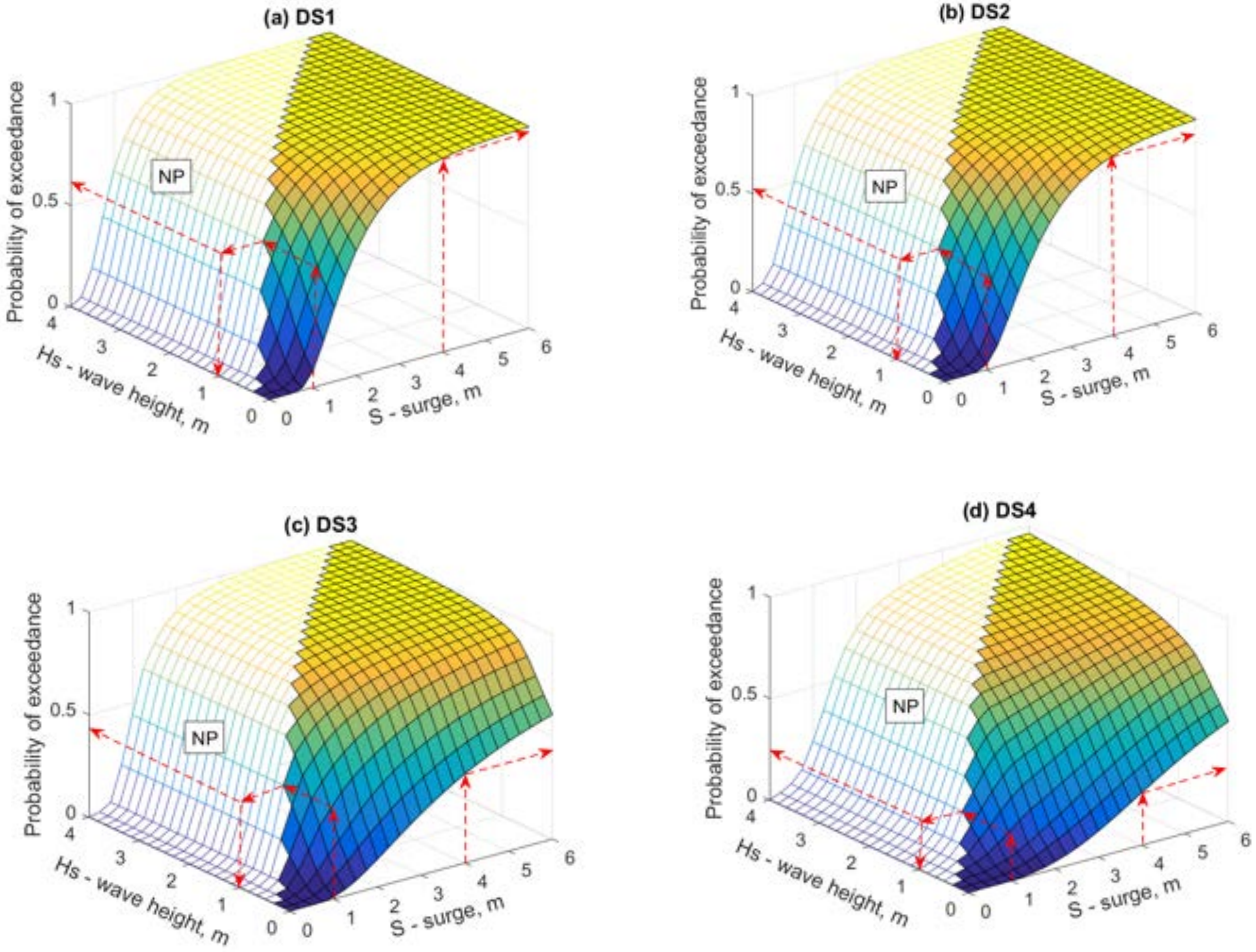
Component	Distribution	Parameters
Window on 1 story	Weibull	C = 54.49psf, k = 4.7
Window on 2 story	Weibull	C = 38.7psf, k = 4.8
Entry door	Normal	Mean=50psf, COV=0.2
Toe-nail	Normal	Mean=415lb, COV=0.25



Fragility surfaces for component damage

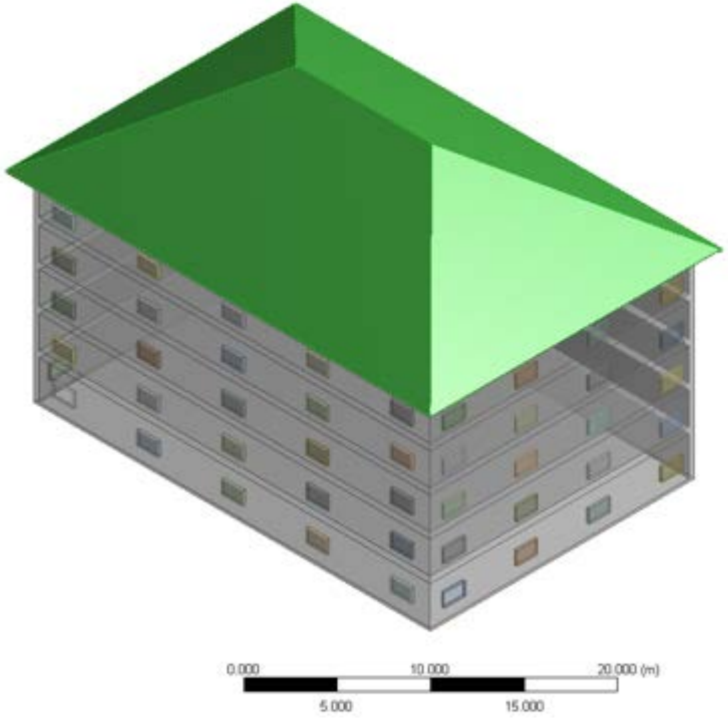


Achetype 2
2-story regular house
2000 sqft

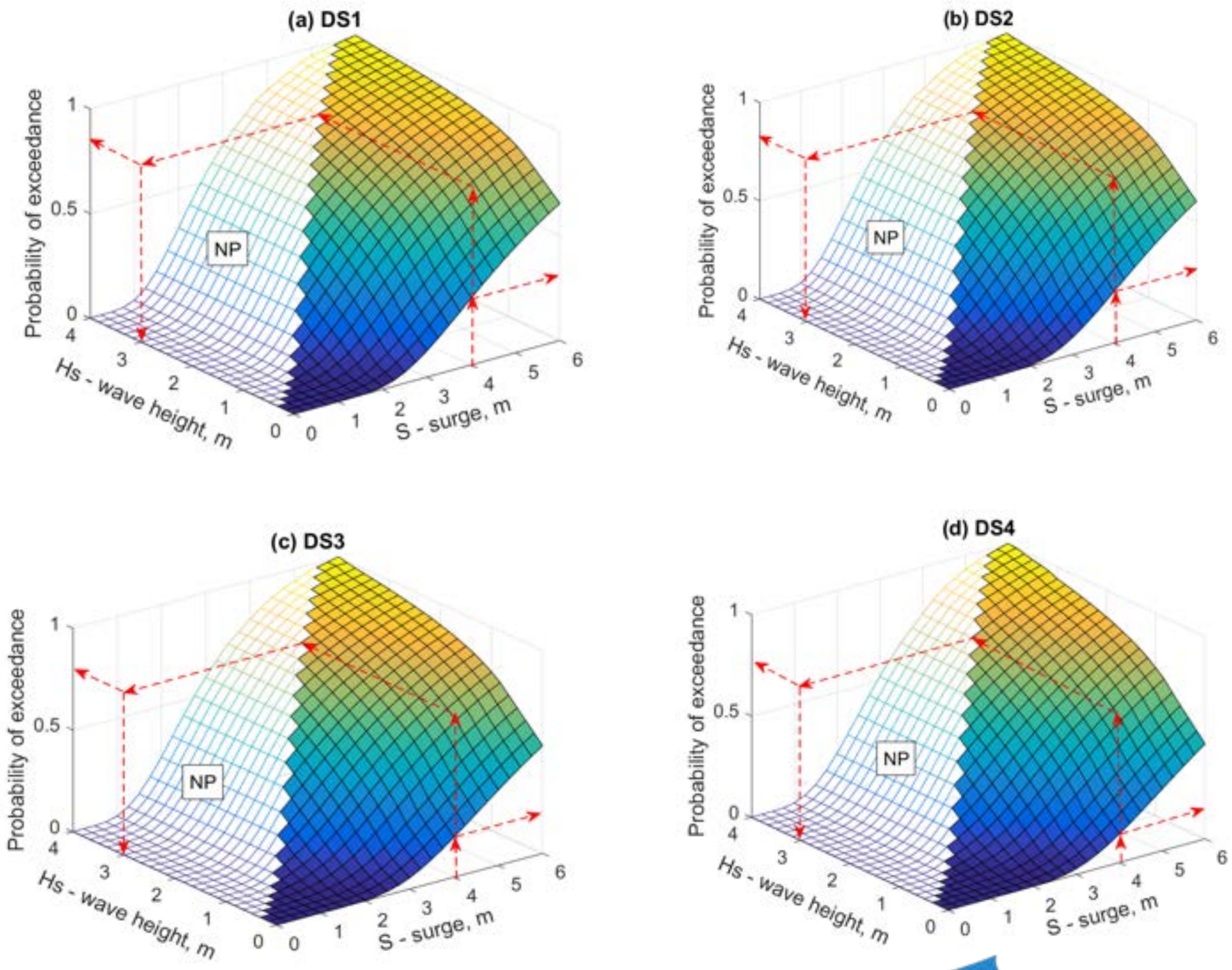


NP = Not Possible combination of $\boldsymbol{H_s - S}$

Fragility surfaces for component damage

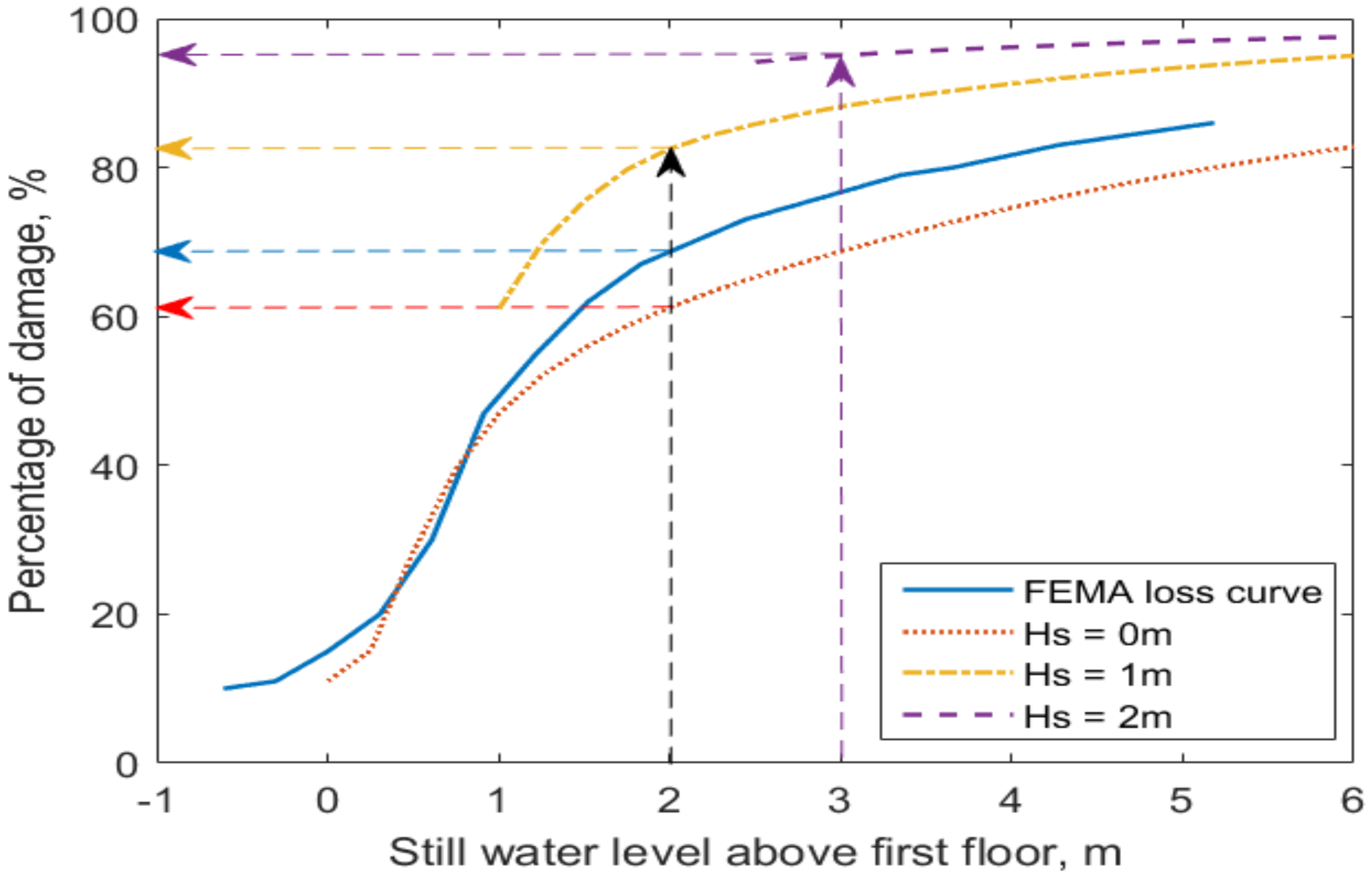


Achetype 4
5-story apartment complex



NP = Not Possible combination of $H_S - S$

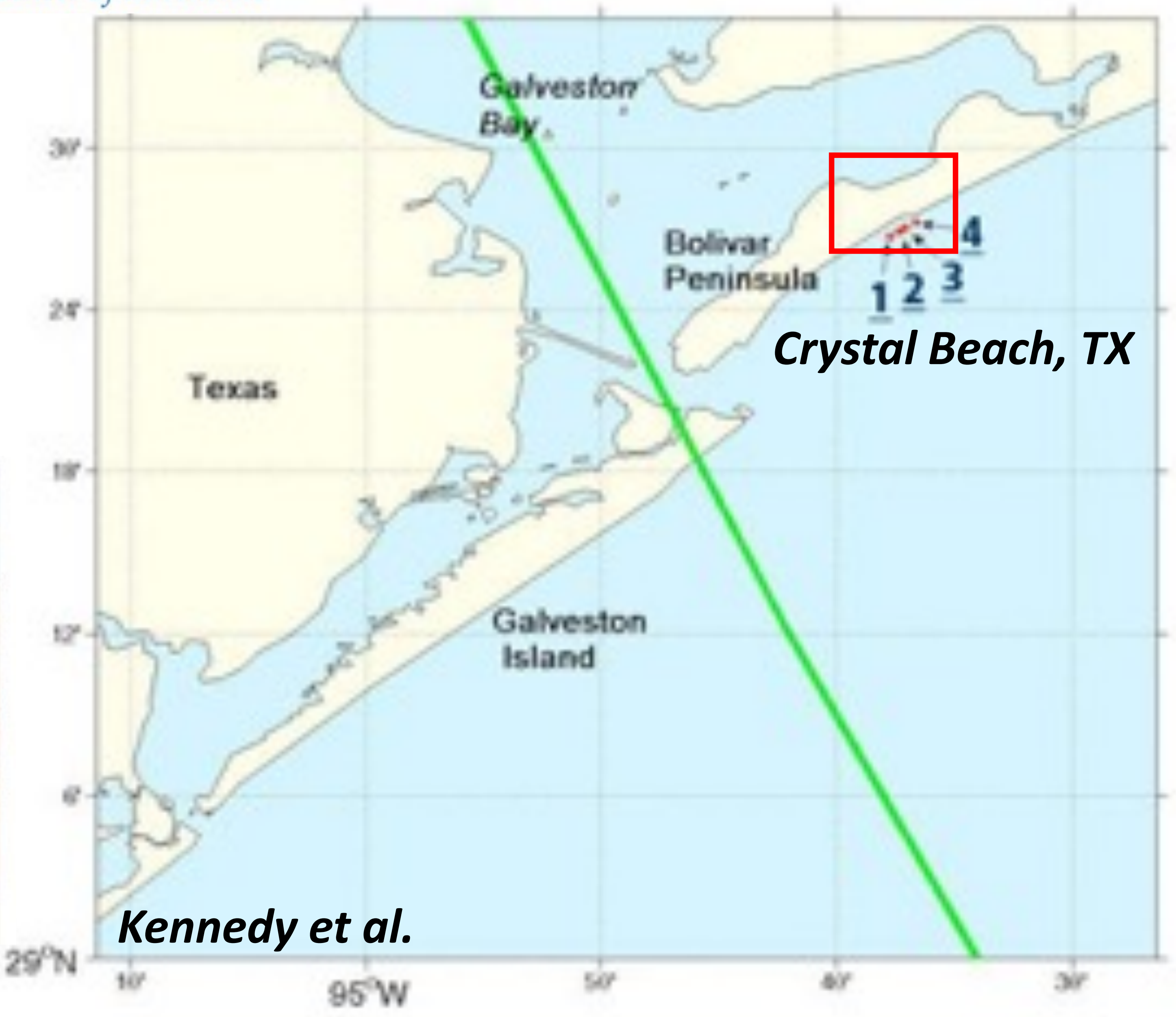
Comparison of total loss to FEMA cost damage estimate for single-family dwelling in coastal V-zone, no obstruction



Task 3: Hindcast for fragility model validation (Started in Yr 4.5)

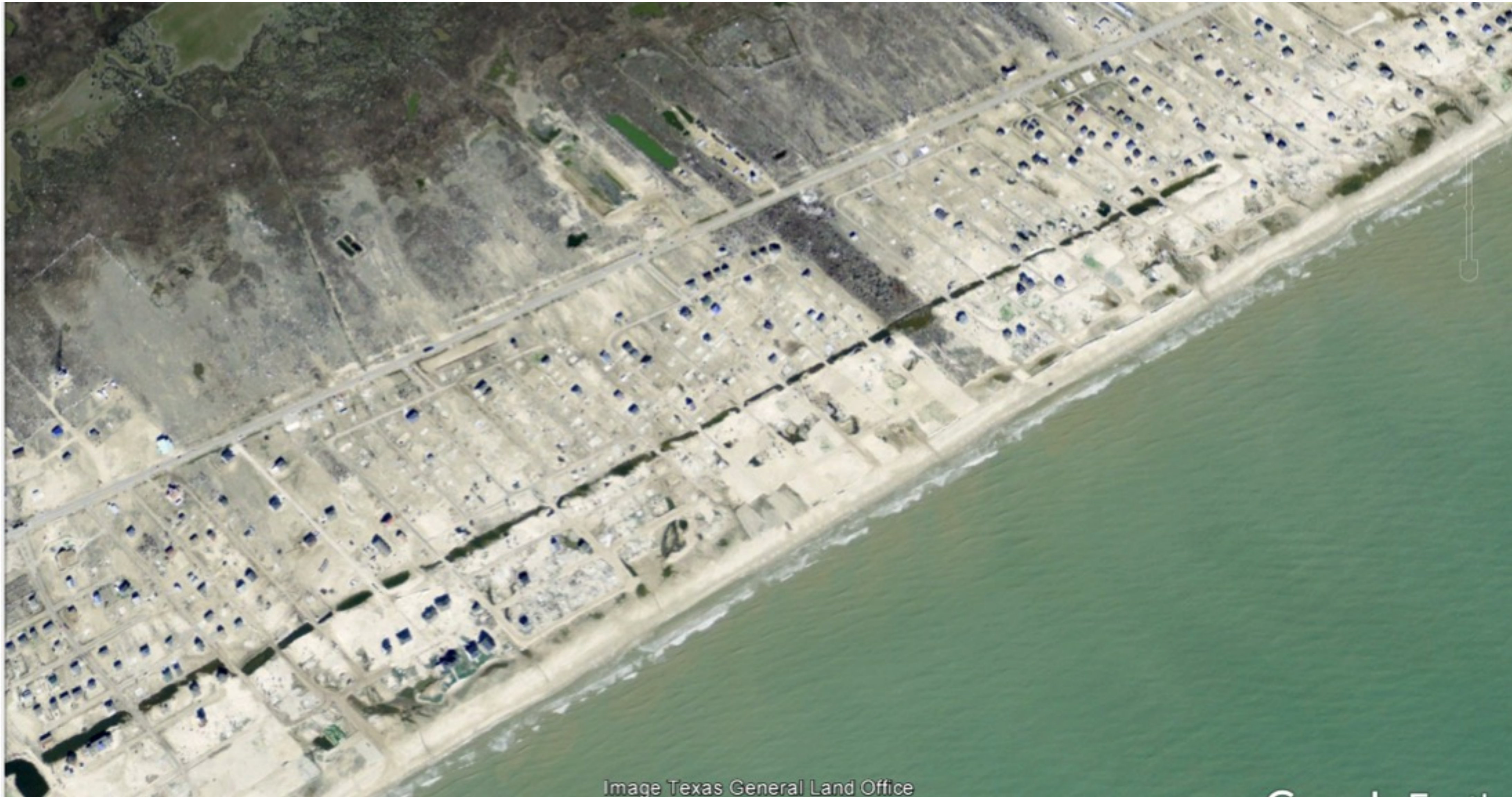
Application to Galveston, TX

- Damage to residential housing
- Crystal Beach, TX
- Hurricane Ike (2008)

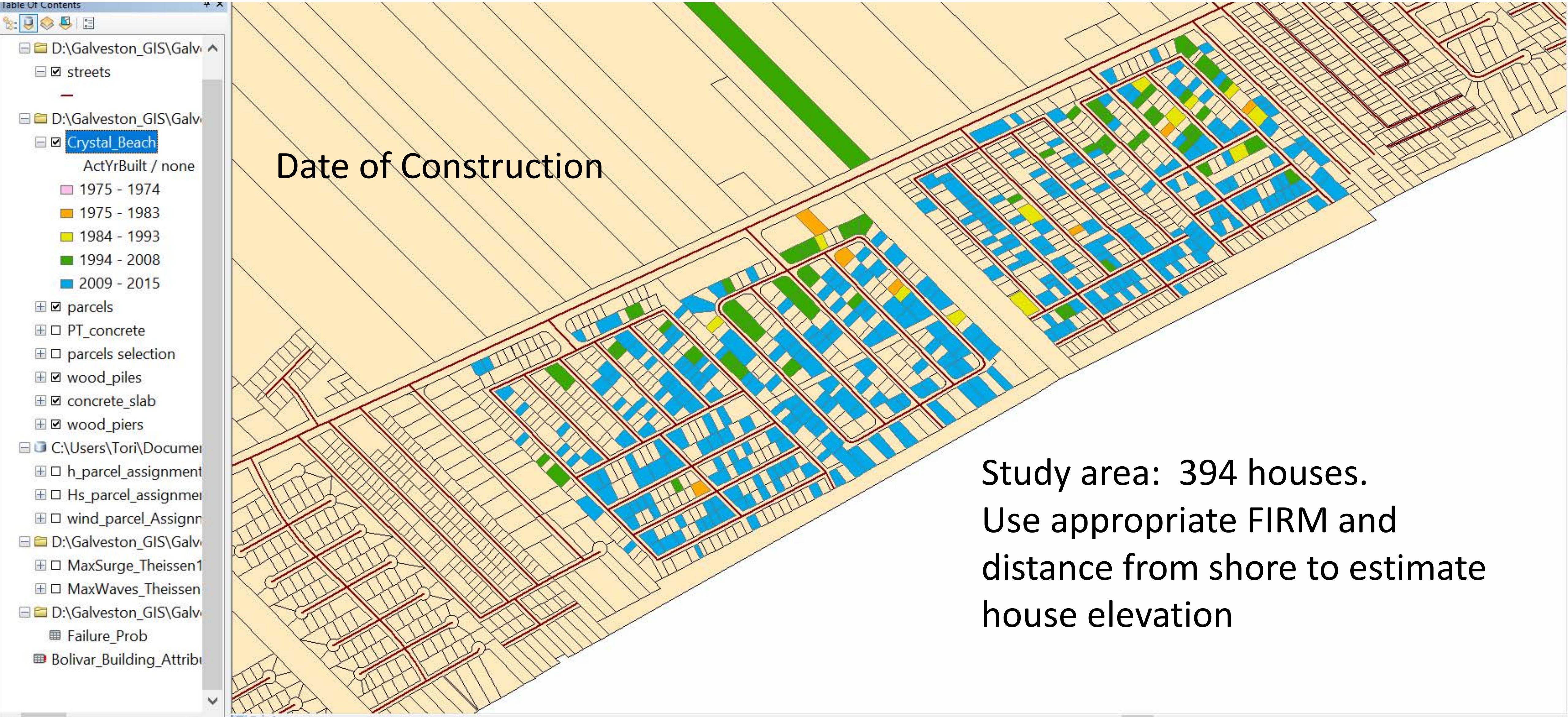


Bolivar Peninsula, TX, after Hurricane Ike 2008

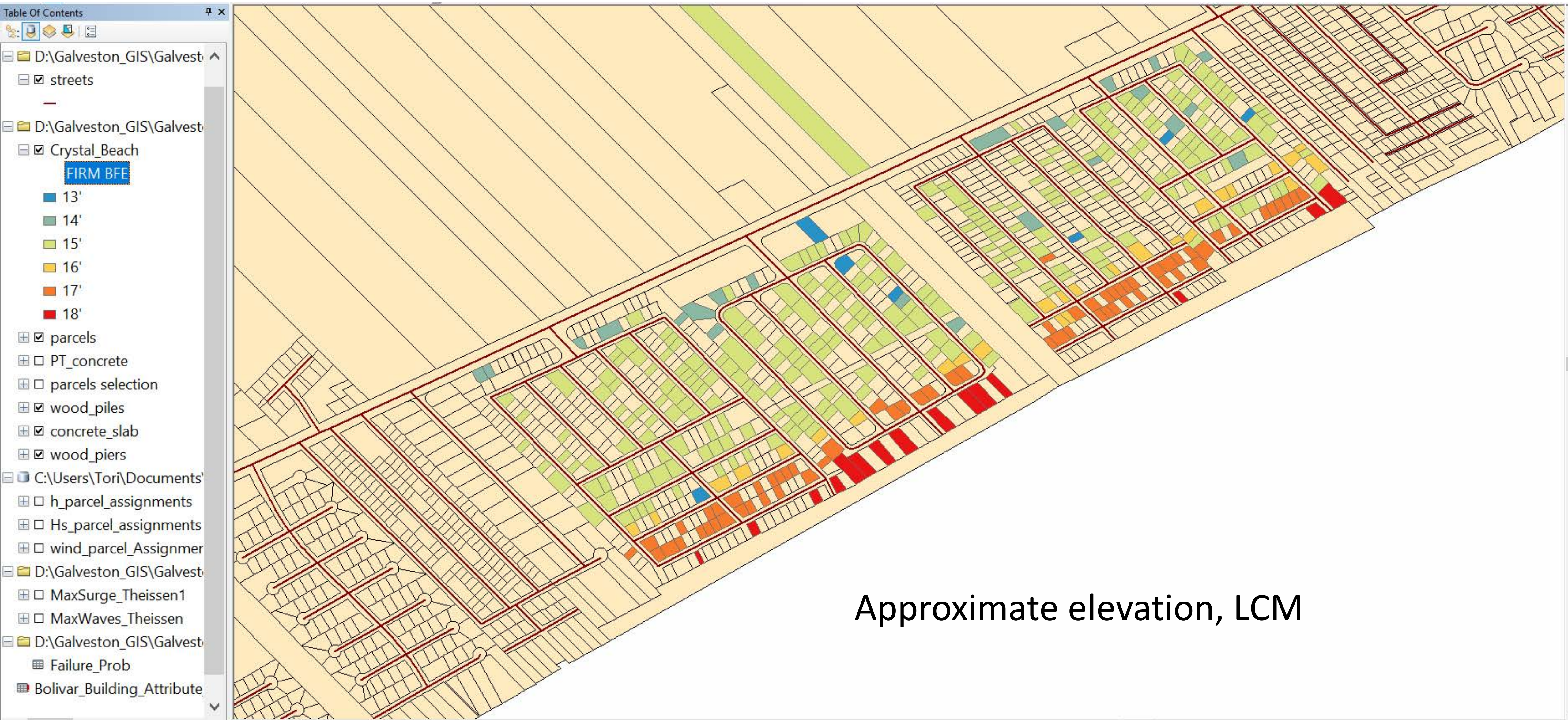
Bolivar Peninsula, TX, after Hurricane Ike 2008



Date of Construction



Study area: 394 houses.
Use appropriate FIRM and distance from shore to estimate house elevation



Approximate elevation, LCM

BUILDING ARCHETYPE PHYSICAL DESCRIPTIONS

3 typical residential wood buildings:

- 1-story, small rectangular house (1000- 1500 sqft)
- 2-story medium house (1500-2500 sqft)
- 2-story large house (2500-3000 sqft)

3 elevations:

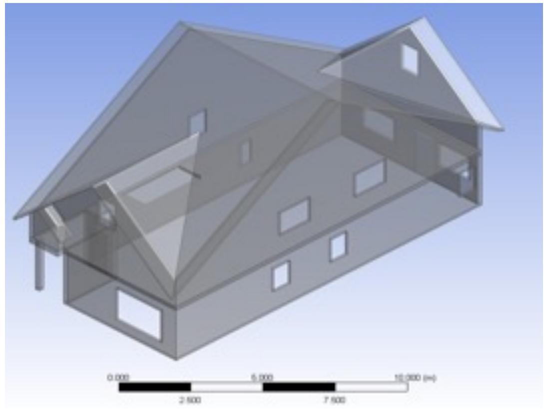
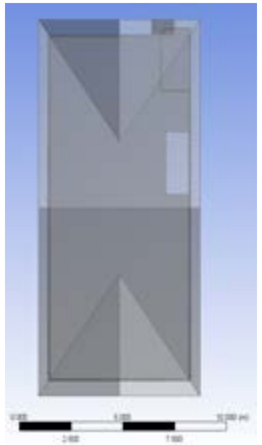
Slab-on-grade

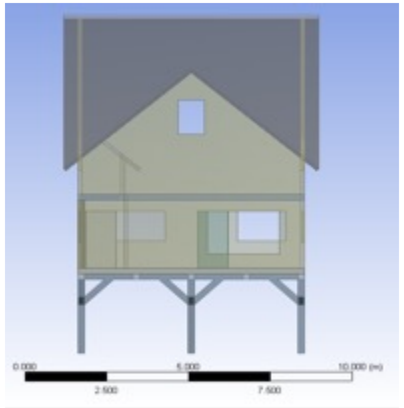
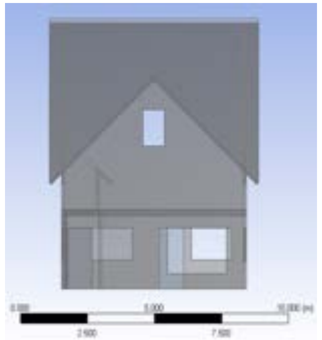
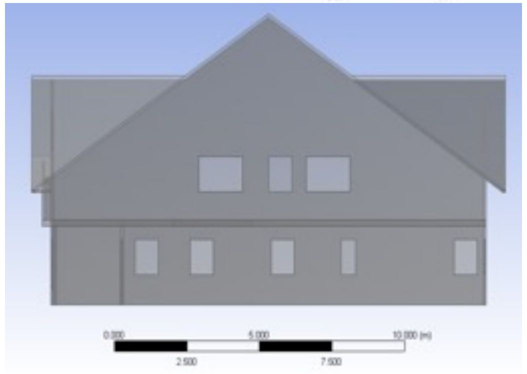
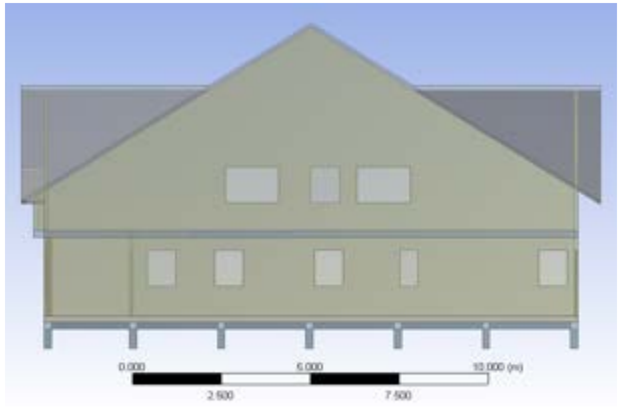
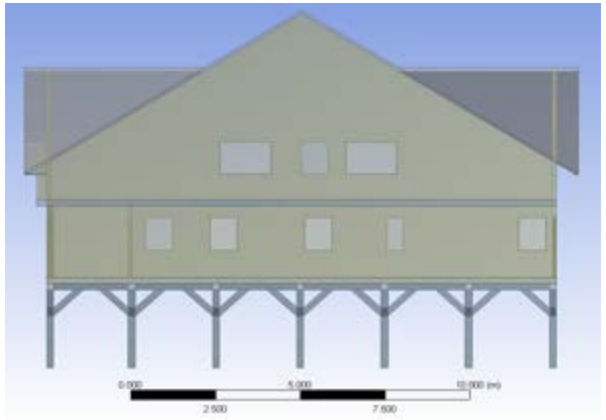
0.5-1.5 m elevated

2.0-4.0 m elevated

BUILDING ARCHETYPE PHYSICAL DESCRIPTIONS

Archetype 1,2,3: 1-story, small rectangular house (1000- 1500 sqft)

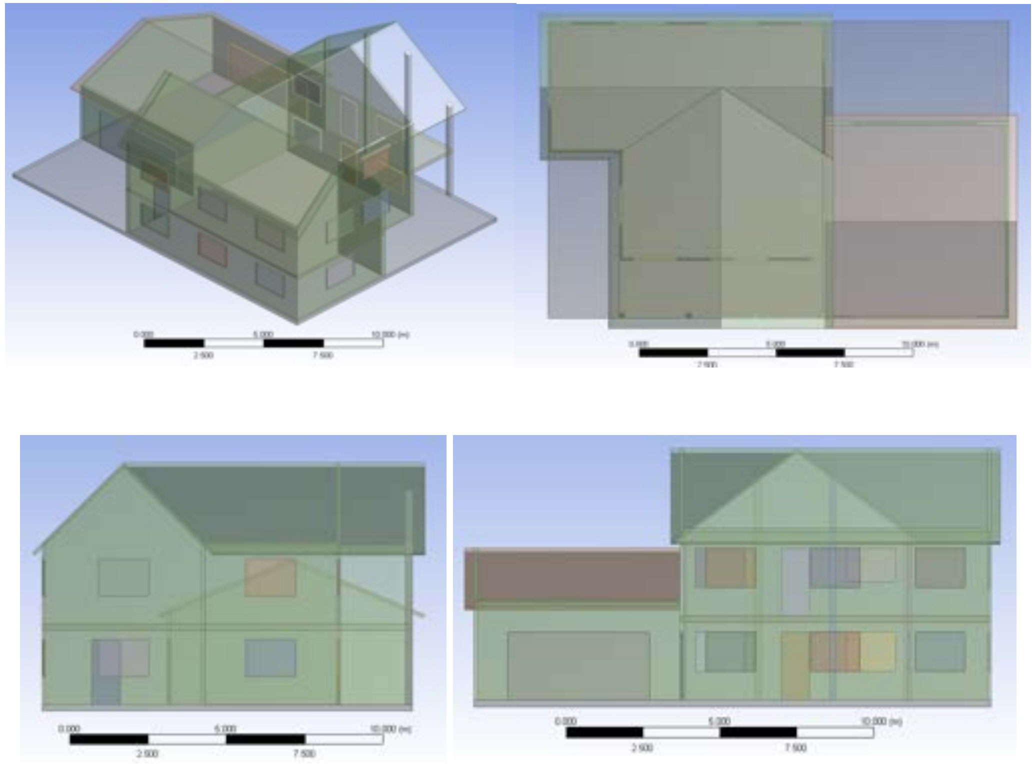
Archetype 1 (slab-on-grade)

Archetype 2 (0.5-1.5m- elevated)

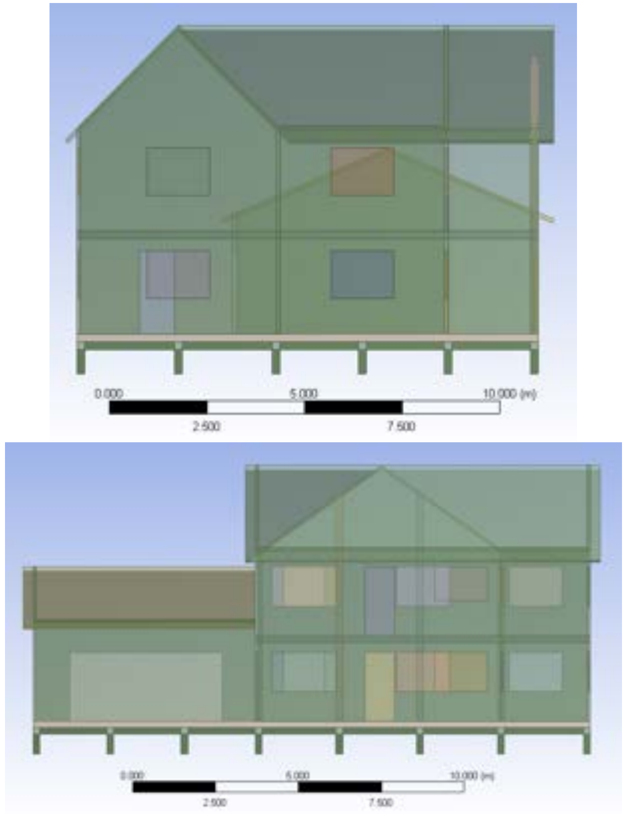
Archetype 3 (2-4m-elevated)

BUILDING ARCHETYPE PHYSICAL DESCRIPTIONS

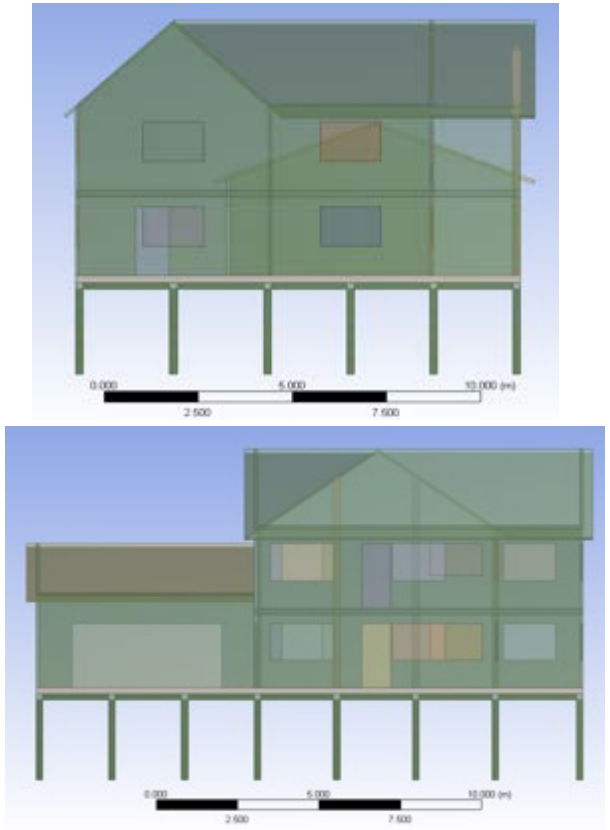
Archetype 4,5,6: 2-story, medium house (1500- 2500 sqft)



Archetype 4 (slab-on-grade)



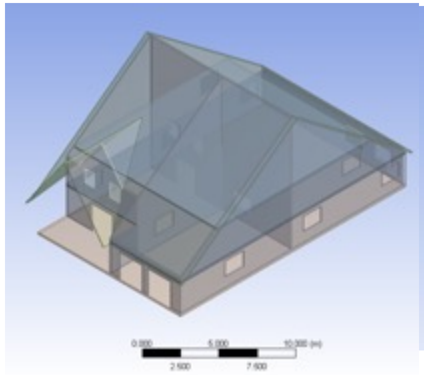
Archetype 5 (0.5-1.5m- elevated)

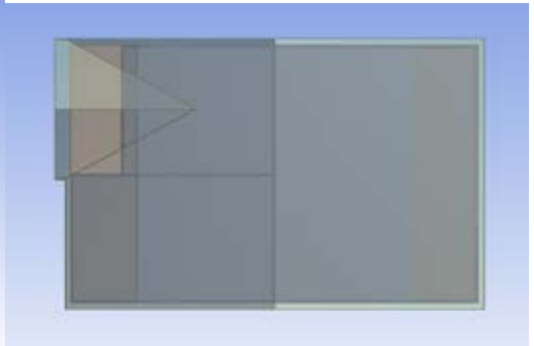


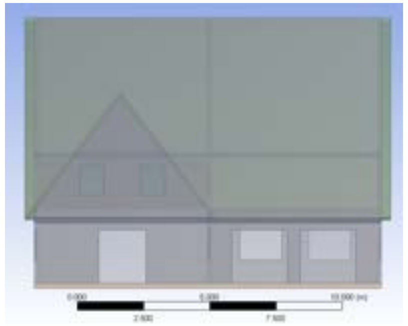
Archetype 6 (2-4m-elevated)

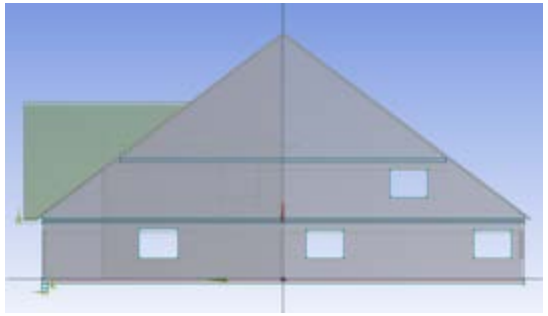
BUILDING ARCHETYPE PHYSICAL DESCRIPTIONS

Archetype 7,8,9: 2-story, medium house (2500- 3500 sqft)

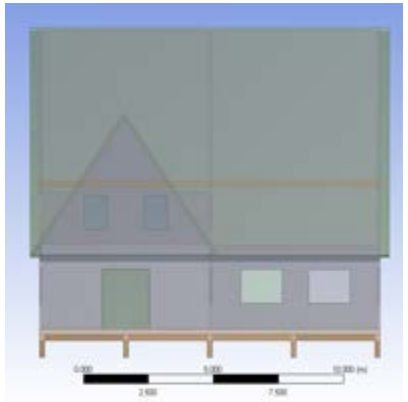


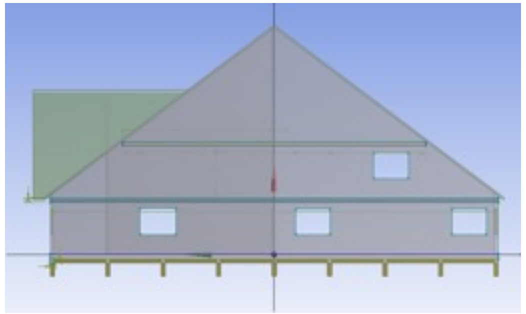




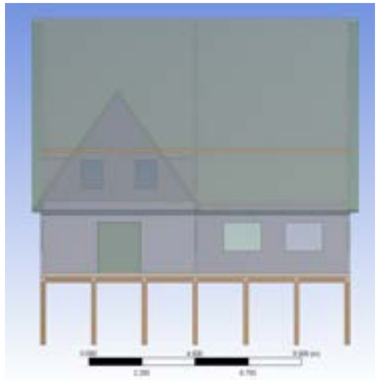


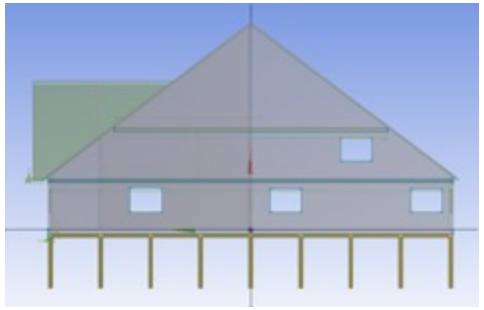
Archetype 7 (slab-on-grade)





Archetype 8 (0.5-1.5m- elevated)





Archetype 9 (2-4m-elevated)

Year 5 + 6

- Community Building Archetype Mapping: Crystal Beach, Bolivar Peninsula, TX

Year 5 + 6

- Community Building Archetype Mapping: Crystal Beach, Bolivar Peninsula, TX

09-03-2008 Building footprints

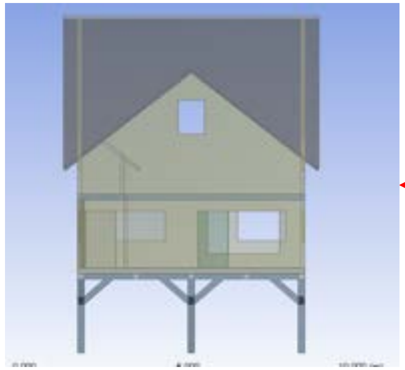
09-03-2008 Before Hurricane

09-14-2008 After Hurricane

Year 5 + 6

- Community Fragility Mapping: M.S. footprint for Crystal Beach, TX

Google Maps
9/3/2008



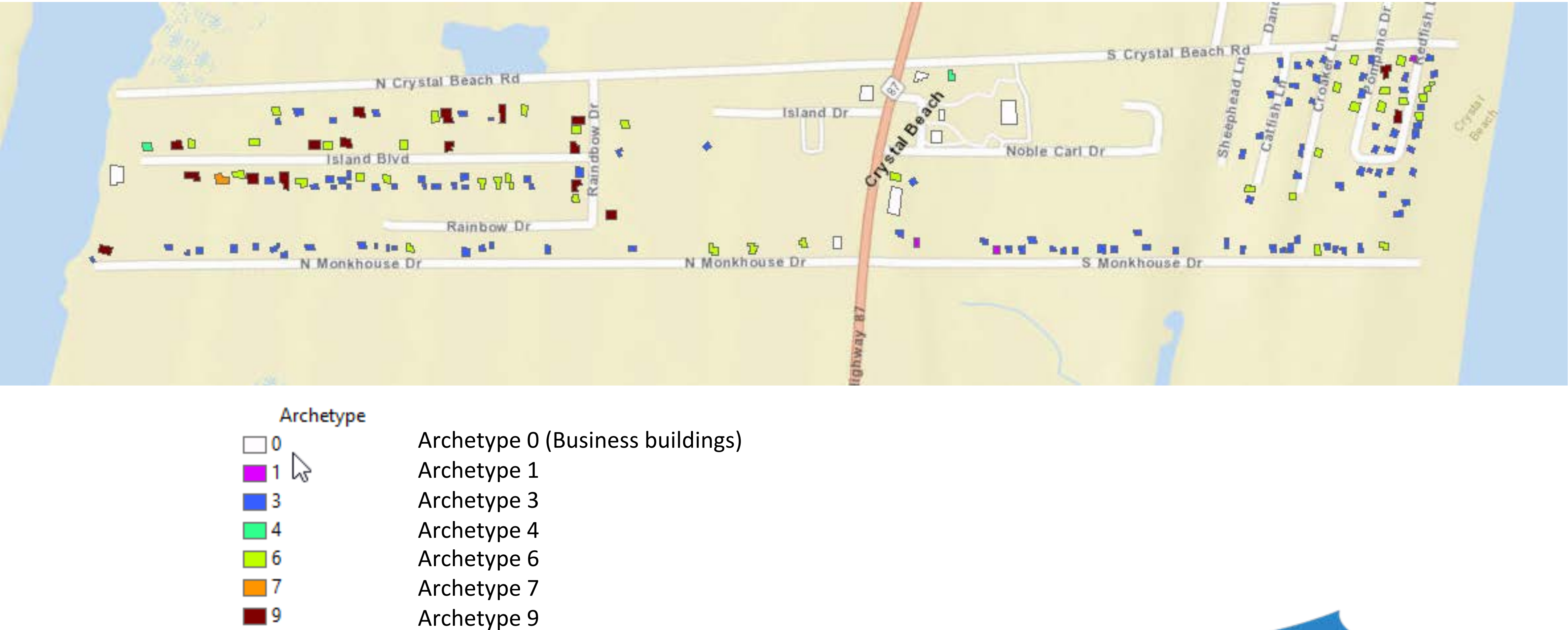
Archetype 3
2000 sqft, 2-4m elevated

Google Street View (9/3/2008)

Draw footprint

Year 5 + 6

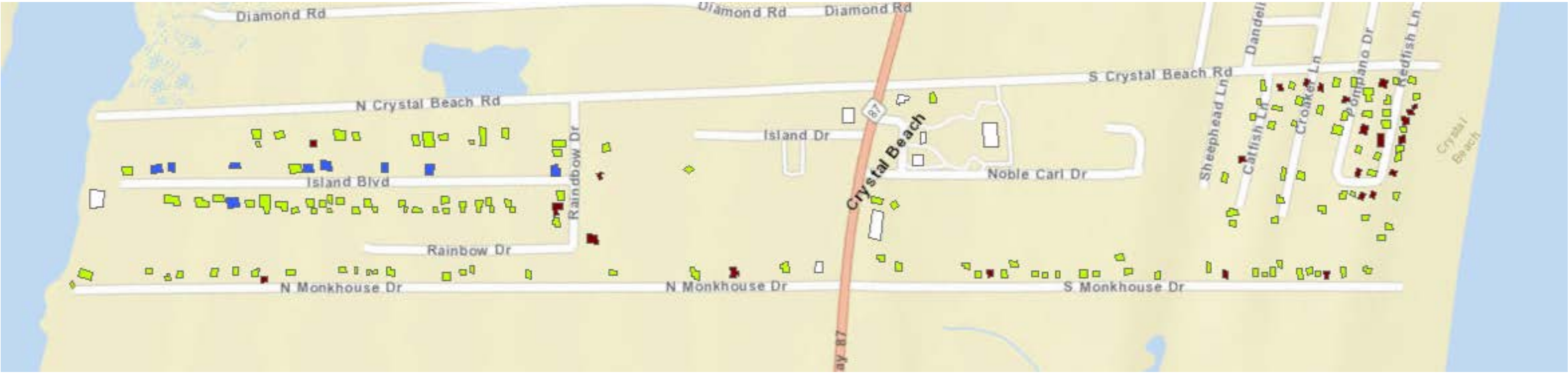
- Building archetype layout for Crystal Beach, Bolivar Peninsular, TX (174 buildings)



Archetype 0 (Business buildings)
Archetype 1
Archetype 3
Archetype 4
Archetype 6
Archetype 7
Archetype 9

Year 5 + 6

Matching score for building archetype to community



Matching evaluation:

- Building area
- Building elevation
- Building cover material (brick, wood)
- Building foundation (slab on grade, crawlspace, elevated)

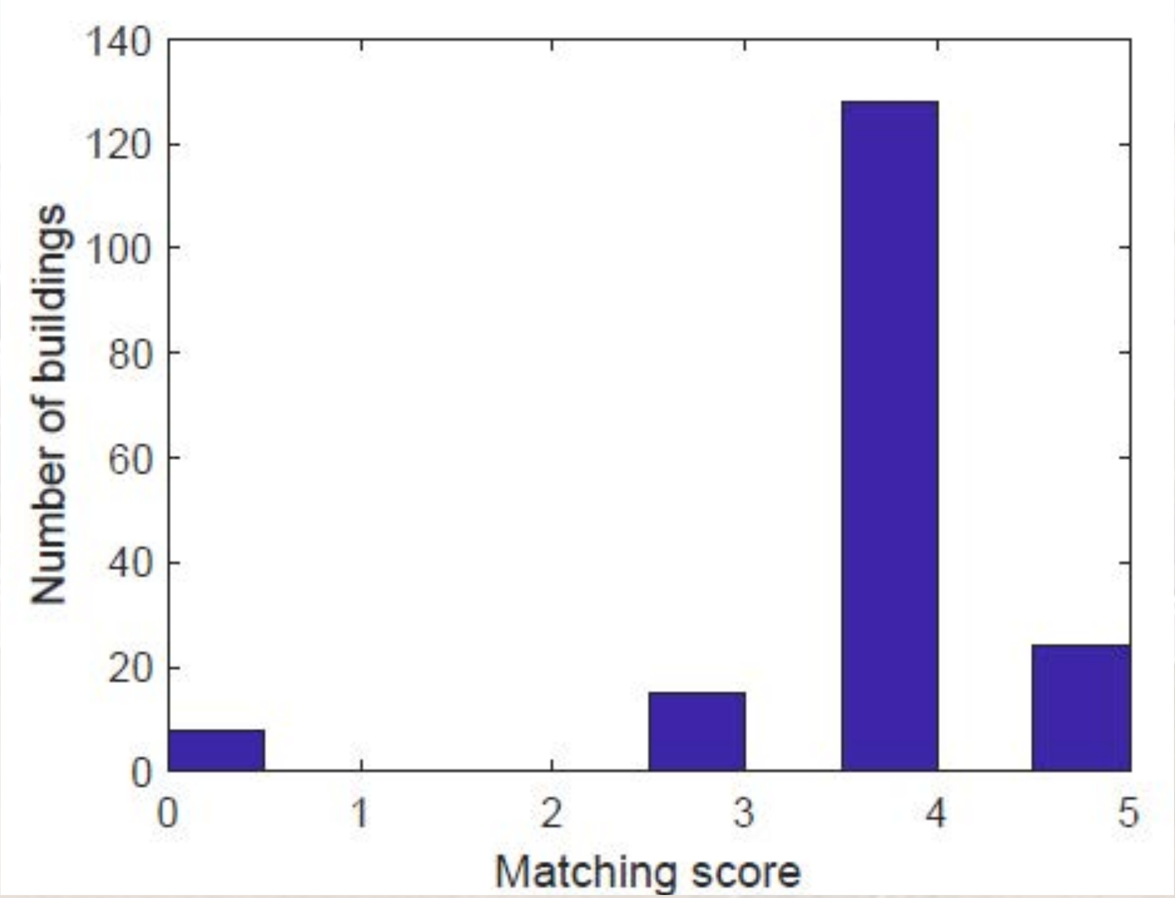
0= not assigned,

1= poor match

5= excellent match

Year 5 + 6

Matching level of building archetype to community



Matching evaluation:

- Building area
- Building elevation
- Building cover material (brick, wood)
- Building foundation (slab on grade, crawlspace, elevated)

0= not assigned
1= poor match
5= excellent match

Overall building archetype comments:
- Number of mapped buildings: 174
- Most buildings were elevated **8-9ft** above the ground level

End User Transition

People and Agencies involved in the End-User Transition

- Chris Jones, Jones Consulting, ASCE 7; ASCE 24
- Bill Coulbourne, AECOM, ASCE 7; FEMA P55 Coastal Construction Manual
- FEMA, Deputy Assistant Administrator for Mitigation
- FEMA, Acting Branch Chief, Actuarial and Catastrophic Modeling Branch
- FEMA, Actuarial and Catastrophic Modeling Branch
- FEMA, Risk Management, Engineering Resources Branch
- FEMA, Coastal Program Specialist
- Jordan Burns, NIYAMIT, Inc., Risk Analysis Lead
- Doug Bausch, NIYAMIT, Inc., Risk Analysis Program Manager
- NPPD Section Chief, infrastructure Development and Recovery
- USACE-Galveston District, Hurricane Flood Risk Reduction Design Branch
- USACE-ERDC, Coastal Hydraulics Laboratory

End User Transition

Recent and Planned meetings

- 2019.06 Hazus Working Group meeting*, FEMA HQ, Washington DC
- 2019.10 ASCE 7-22 Chapter 5 Flood Load Subcommittee meeting, Baltimore, MD
- 2020.03 USACE-Galveston District office meeting, Galveston TX
- 2020.05 Hazus Risk Assessment Symposium, Washington DC
- 2021.06 NHERI Summit (joint session: HAZUS-MH, IN-CORE, SimCenter)

*collaboration is part of FEMA/HAZUS work plan

Summary of Proposed Year 6 Activities

Activity 1 Description: In-person meeting with FEMA HAZUS transition team. Purpose of this meeting is to outline specific objectives and milestones; data availability; and plan for sustained engagement and transition.
Activity 2 Description: Topology and data for HAZUS hindcast. Work to be conducted jointly by OSU and CSU to build a hindcast model for the Texas coast near Galveston, impacted by Hurricane Ike. Focus will be on single family and multi-family residential structures. Hazard data for wave and surge will be selected for Hurricane Ike.
Activity 3 Description: Validation and uncertainty quantification. Work to be conducted jointly by OSU and CSU for hindcast validation and to quantify uncertainty of this approach due to hazard input as well as building portfolio description.

Interim Products

Peer reviewed papers

1. Do, T, JW van de Lindt, DT Cox (2019) "Hurricane Surge-Wave Building Fragility Methodology for Use in Damage, Loss, and Resilience Analysis," *J. Structural Engineering*, 146(1), 04019177, doi.org: 10.1061/(ASCE)ST.1943-541X.0002472.
2. Tomiczek, T, A Wyman, H Park, DT Cox (2019) "Modified Goda Equations to Predict Pressure Distribution and Horizontal Forces for Design of Elevated Coastal Structures," *J. Waterway Port Coastal and Ocean Engineering*, 145, 6, doi.org: 10.1061/(ASCE)WW.1943-5460.0000527.
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.
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.

Conference Proceedings

6. Do, T., van de Lindt, J.W., Cox, D.T. (2018) "Physic-Based Component Fragility Model for Near-Coast Residential Wood Building Subjected to Hurricane Wave and Surge" Engineering Mechanics Institute Conference 2018, Cambridge MA (abstract only).
7. 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. (abstract only).
8. 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. (abstract only).

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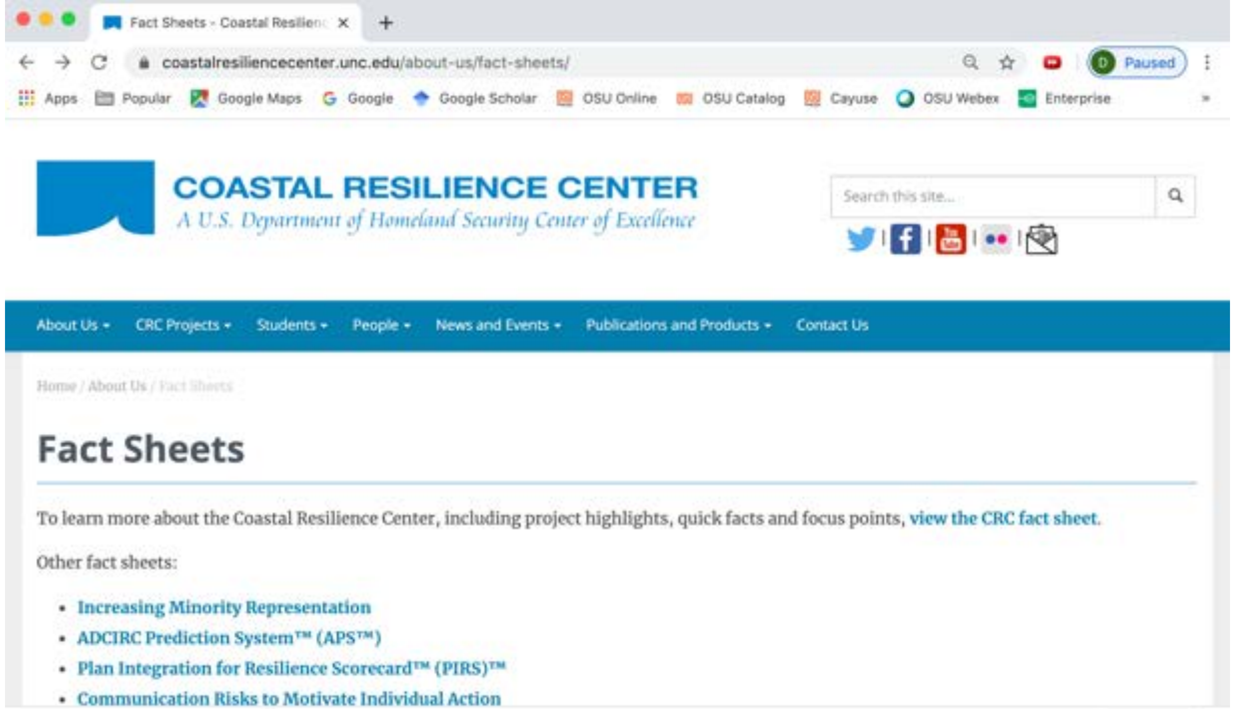
Interim Products

CRC Fact Sheets



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COASTAL INFRASTRUCTURE RESILIENCE

Improving Damage and Loss Estimation

Project title: *Experimental and Numerical Study to Improve Damage and Loss Estimation due to Overland Wave and Surge Hazards on Near-Coast Structures*
Researchers: Dr. Dan Cox, Oregon State University (PI); Dr. John van de Lindt, Colorado State University (co-PI)

As coastal infrastructure owners, city planners and emergency managers seek to mitigate damage, risk to property and structure loss during overland wave hazards (from hurricanes and tsunamis), it is necessary to update federal standards to include a broader range of building types, storm conditions and potential for resulting damages. Effective decision-support tools such FEMA's HAZUS-MH (flood loss estimation model that covers a geographic region) rely on multi-hazard fragility curves - a statistical representation of the chances a hazard event exceeds a certain level of structure performance and suffers damage or loss.

Researchers are developing computer models to predict the fluid pressures caused by waves on doors, windows and other components of buildings. Combined with the structure's limit states, probabilities of failure (fragility curves) are generated and then combined to form system-level damage models.

Companion hydraulic laboratory tests are used to parameterize and validate these models providing confidence that they can be used to provide accurate predictions of damage over a wide range of wave hazard conditions.

Researchers will work with end users in FEMA's HAZUS team to improve federal damage and loss estimation. Results can also be used for improvement of and retrofits to residential and commercial structures.

FAST FACTS

- Researchers have developed fragility curves to predict building damage from storms.
- Findings could help improve structural retrofits funded through FEMA hazard mitigation grants.
- OSU hosts engineering students from the University of Puerto Rico-Mayagüez annually through a CRC program.

Fig. 1
Model structures during hydraulic laboratory test at OSU.

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Thanks, Josh!

Workforce Development: SUMREX Students from UPRM

2016
- Kevin Cueto – PhD at UPRM
- Diego Delgado – MS in Coastal Engrg (UC, Spain)

2017
- Hector Colon – UG at UPRM, Civil Engineering
- Peter Rivera – GS at UPRM, Coastal Engineering and Science

2018
- Jorge Santiago – GS at U. Florida, Wind Hazards Engineering
- Bryan Avecedo – UG at UPRM, Civil Engineering

2019
- Robert Lewis – UG at UPRM
- Ihan-Jarek T. Acevedo – UG at UPRM

2020
- Currently recruiting for "*Engineering with Nature: The Role of Mangroves in Coastal Disaster Mitigation*"

Workforce Development: US Naval Facilities Engineering Command (NAVFAC)

2016
- William Short – OSU MSc '16; USN
- Ben Hunter – OSU MSc '16 ; USN

2018
- Jason Burke – OSU MSc '18; USN
- Matt Karny – OSU MSc '18; USN

Workforce Development: Coastal Research and Education

2018 • Dr. Tori Tomiczek Johnson – Assistant Professor, USNA

2019 • Dr. Hyoungsu Park – Assistant Professor, Univ. Hawaii

2019 • Dr. Trung Do – Visiting Assistant Professor, Univ. of Louisiana Lafayette

UNIVERSITY OF LOUISIANA LAFAYETTE

UNIVERSITY of HAWAI'I

USNA
UNITED STATES NAVAL ACADEMY

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2020.03.09

RECINTO UNIVERSITARIO DE MAYAGUEZ

CAAM

UNIVERSIDAD DE PUERTO RICO

Thank you!

Daniel Cox
Oregon State University

John van de Lindt
Colorado State University