University of Puerto Rico - Mayagüez Campus

Effect of Coastal Inundation on Buildings

Simposium on Management of Coastal Risks

Hotel Verdanza, San Juan November 22, 2019

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COASTAL RESILIENCE CENTER
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Overview

- A few slides from the Coastal Construction Handbook, Chapters on Design and Construction of the Foundation
- A research study on Flood Damage to Buildings, from PhD dissertation of Norberto Nadal under the direction of Raúl Zapata, Ismael Pagán and Ricardo López and the support of Jairo Agudelo.

Unit VII
Design and Construction of the Foundation
(Flood Loads and Conditions, Load Combinations)

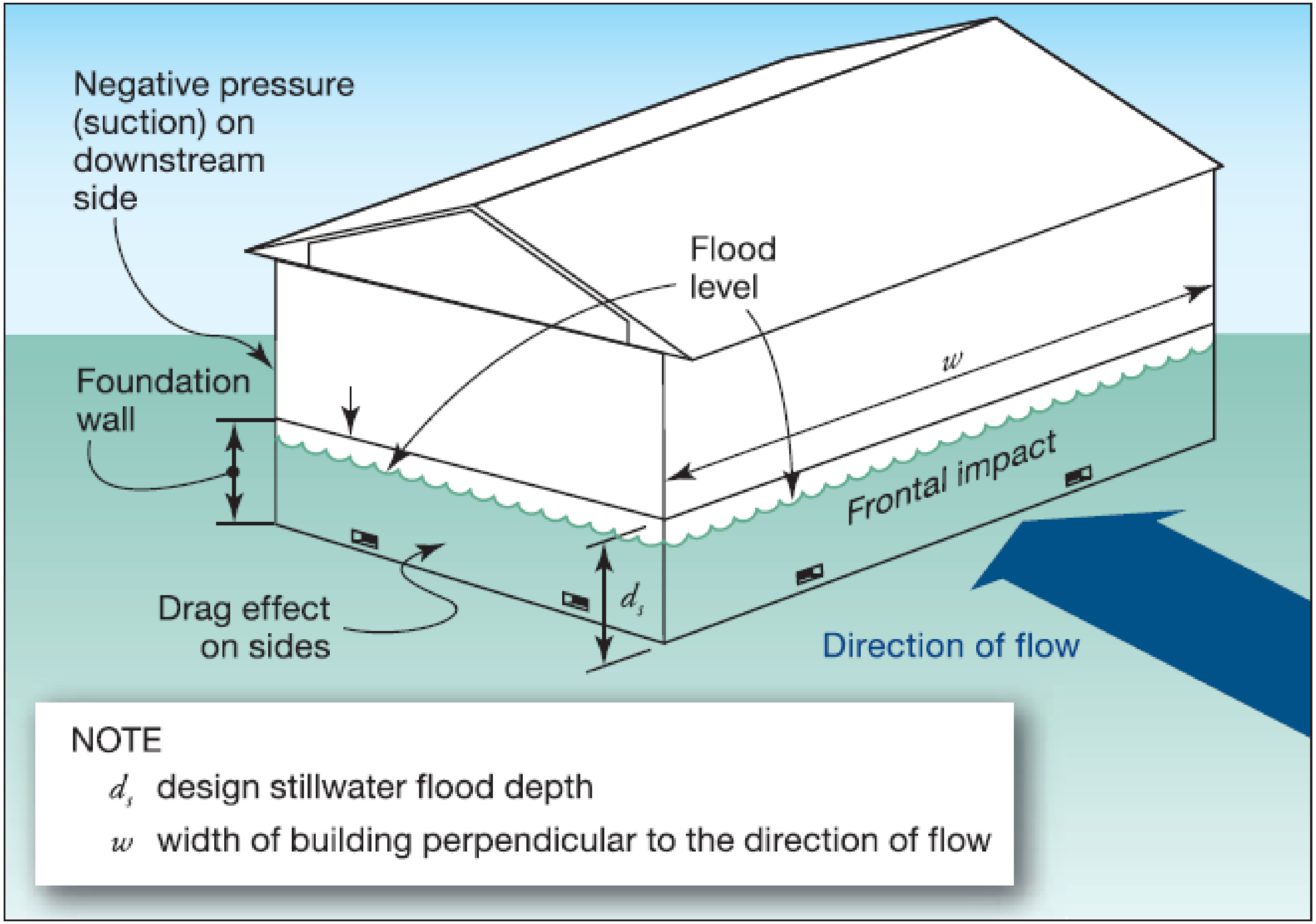
Coastal Construction Manual (FEMA P-55, 2011)
Chapters 8, 9, 10, 13, 14

FEMA EMI Course G0277

FEMA

Building Science Branch

Hydrodynamic Loads on Walls

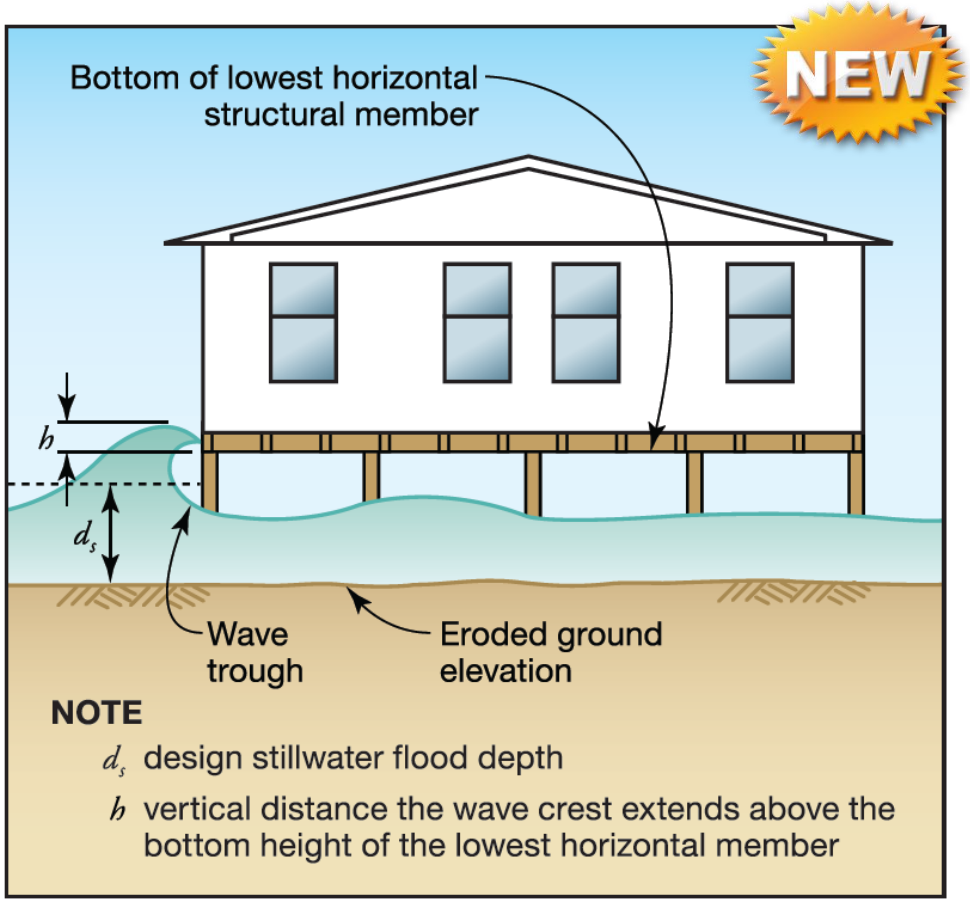


FEMA

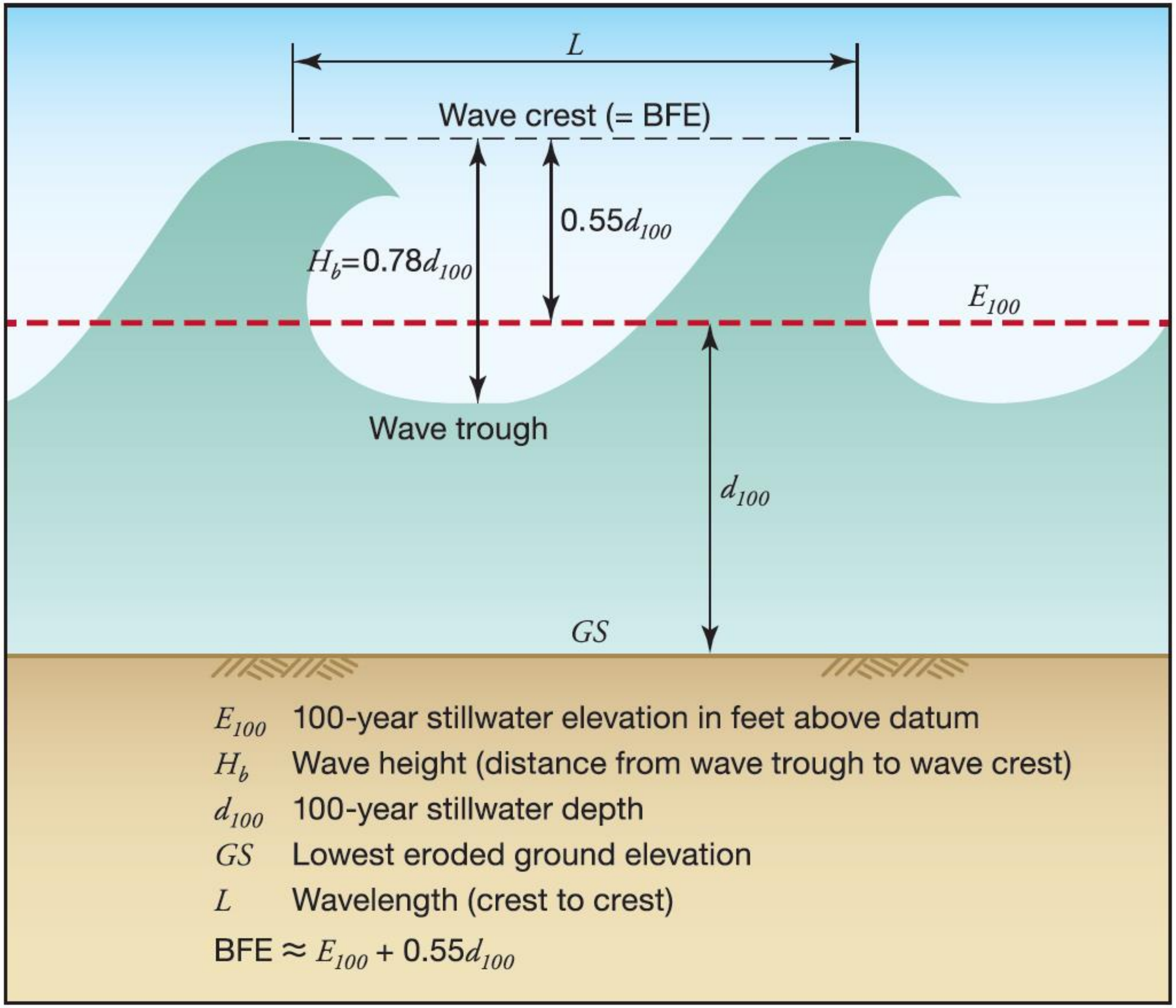
Wave Slam

- Action of wave crests striking elevated portion of a structure
- Introduces lateral and vertical loads on lower portions of elevated structure
- Force can be large; typically results in damaged floor systems

Another reason for using freeboard



Breaking Wave Height (H_b)



Determining Design Flood Velocity

Lower and upper bound values: Determine using Equation 8.2

EQUATION 8.2. DESIGN FLOOD VELOCITY

Lower bound $$V = \frac{d_s}{t}$$ (Eq. 8.2a)

Upper bound $$V = (gd_s)^{0.5}$$ (Eq. 8.2b)

where:

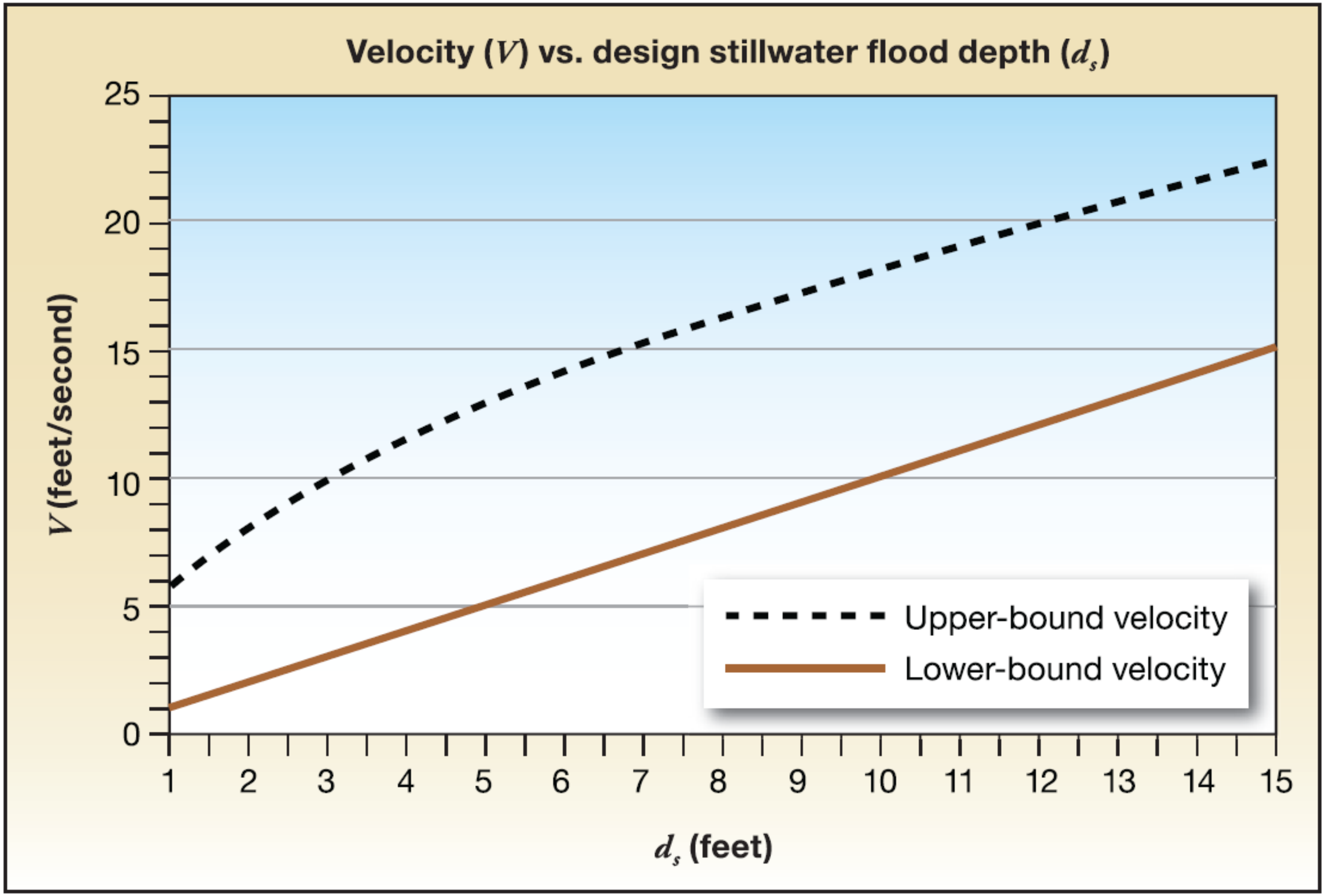
V = design flood velocity (ft/sec)

d_s = design stillwater flood depth (ft)

t = 1 sec

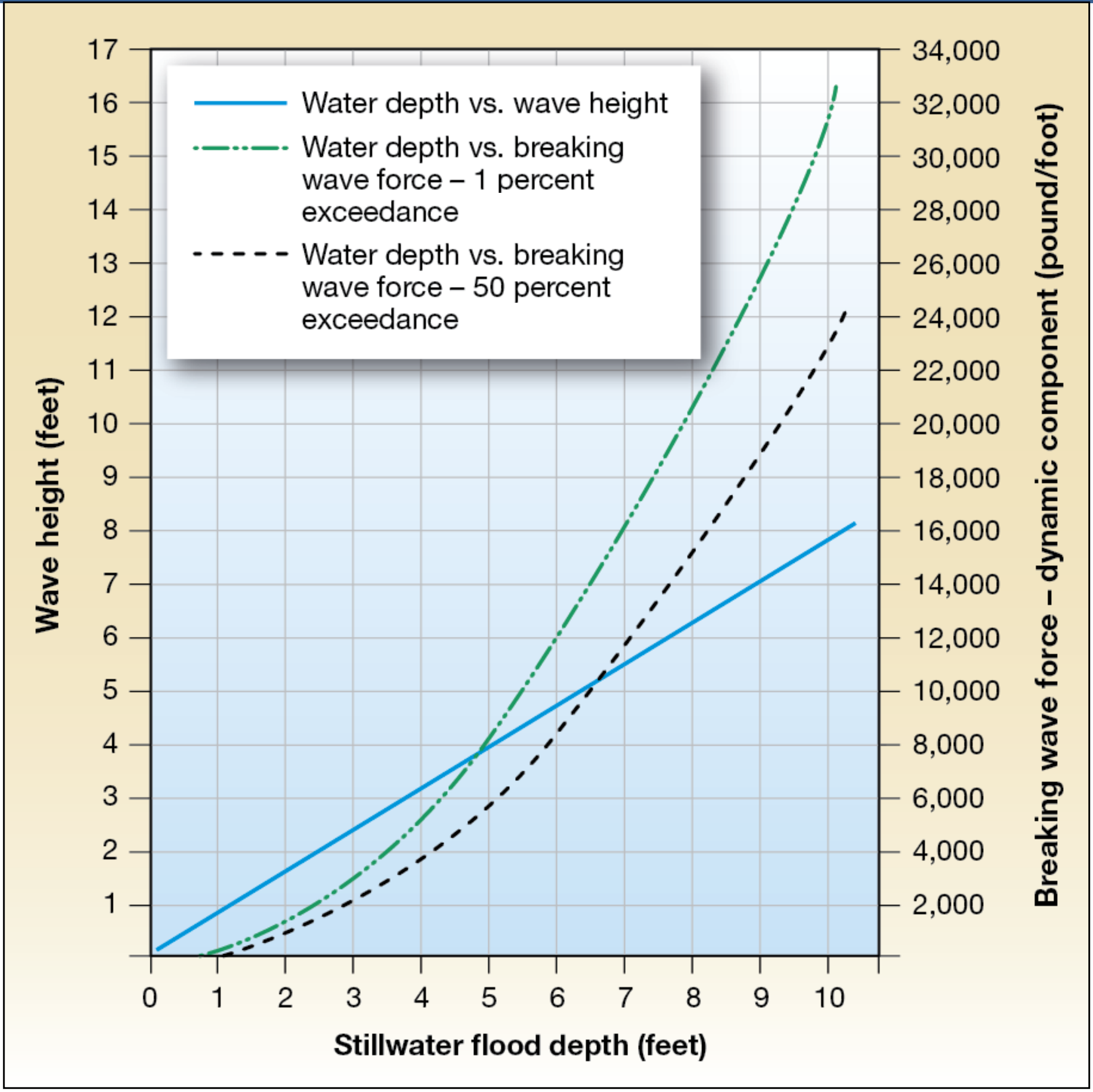
g = gravitational constant (32.2 ft/sec^2)

Velocity vs. Design Stillwater Flood Depth



FEMA

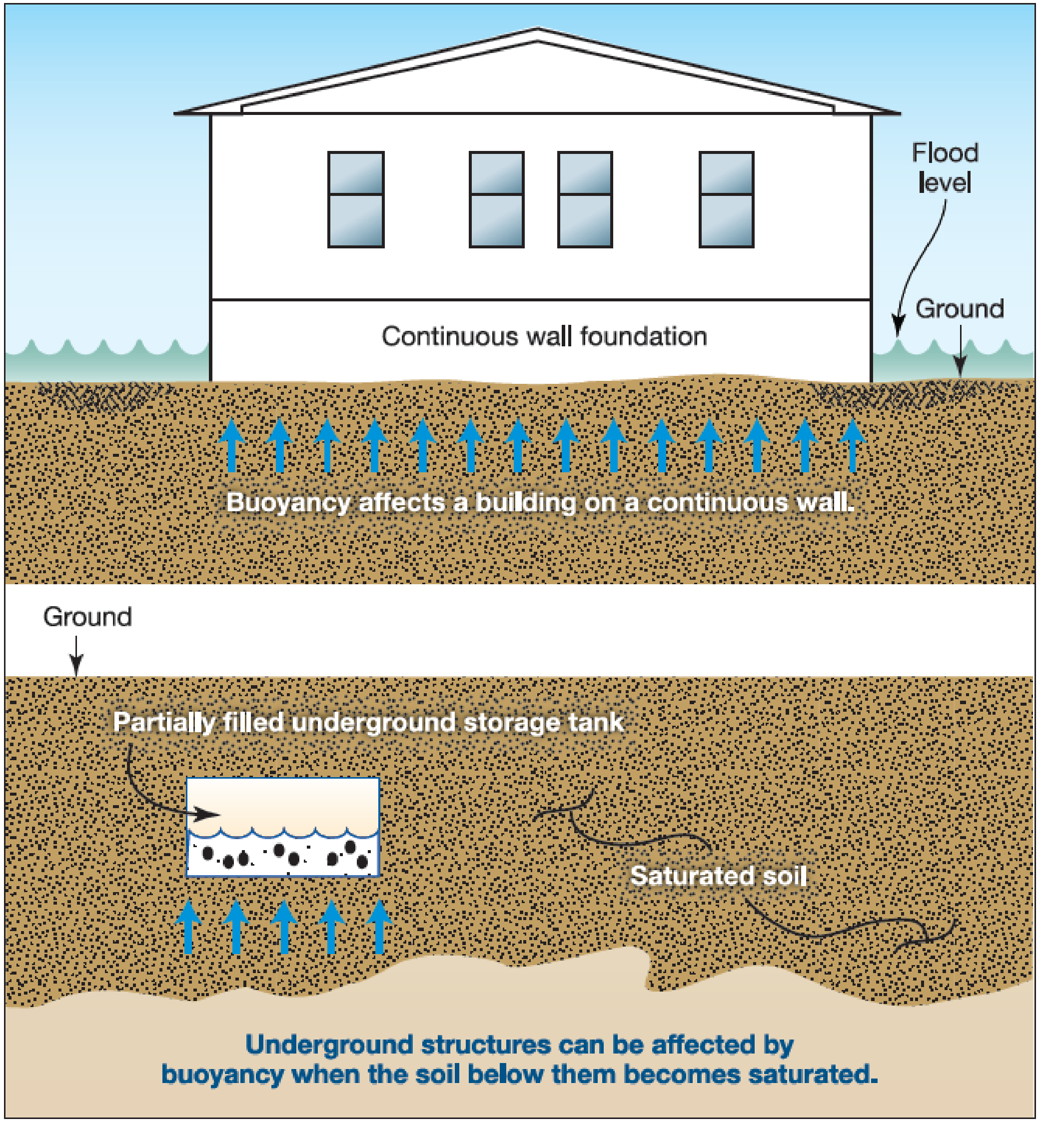
Breaking Wave Heights and Loads on Walls



FEMA

Vertical (Buoyant) Hydrostatic Force

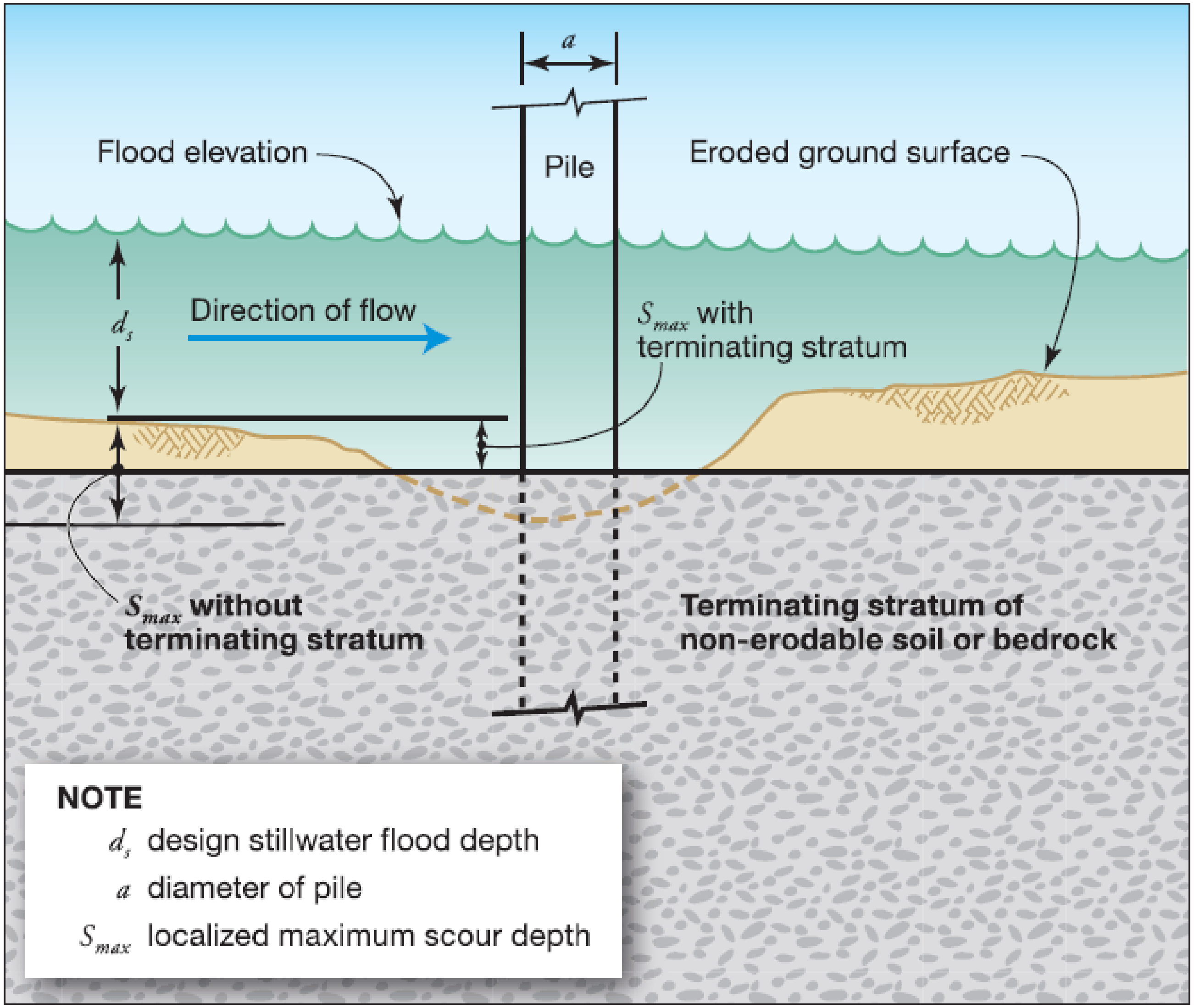
Always present when there is water



Localized Scour

Hurricane Ike, 2008, Bolivar Peninsula, TX

Localized Scour



FEMA

Localized Scour at Single Vertical Pile

EQUATION 8.10. LOCALIZED SCOUR AROUND A SINGLE VERTICAL PILE

$$S_{\text{max}} = 2.0a \qquad \text{(Eq. 8.10)}$$

where:

S_{max} = maximum localized scour depth (ft)

a = diameter of a round foundation element or the maximum diagonal cross-section dimension for a rectangular element

Hurricane Ivan, 2004

Flood Damage to Buildings:
Riverine and Coastal Zones

A Project Sponsored by the Insurance Commissioner Office of Puerto Rico

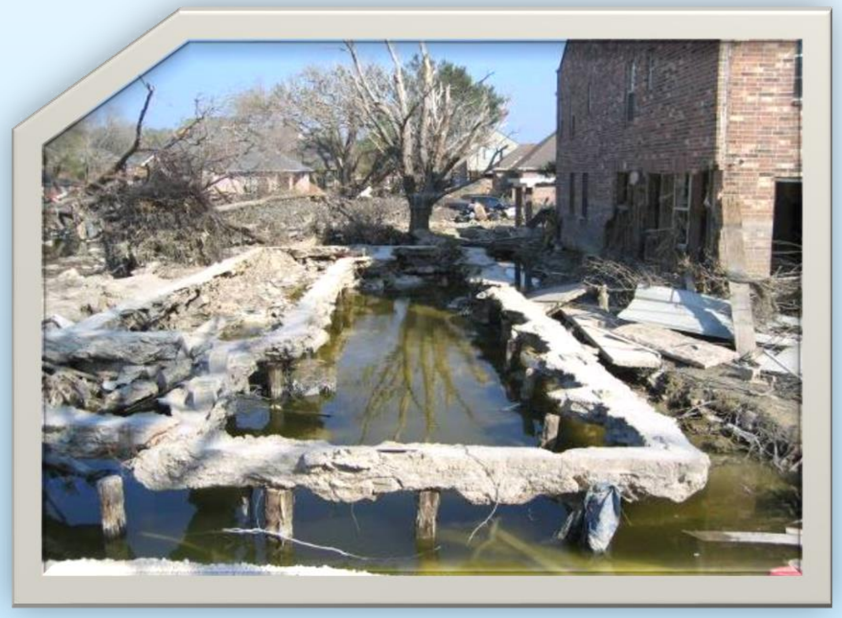
Participants in the Project

Ismael Pagán-Trinidad, Raúl Zapata, and Ricardo López: Co-PI's
Norberto Nadal, Jairo Agudelo, Víctor González: Grad. Students

Introduction

- Flooding events can be categorized into several types:
  - **riverine floods**
  - **coastal floods** - storm surges, tsunamis
  - urban floods – improper drainage
  - dam/levee failures

- Flood actions can cause direct damage to buildings and even structural failure.

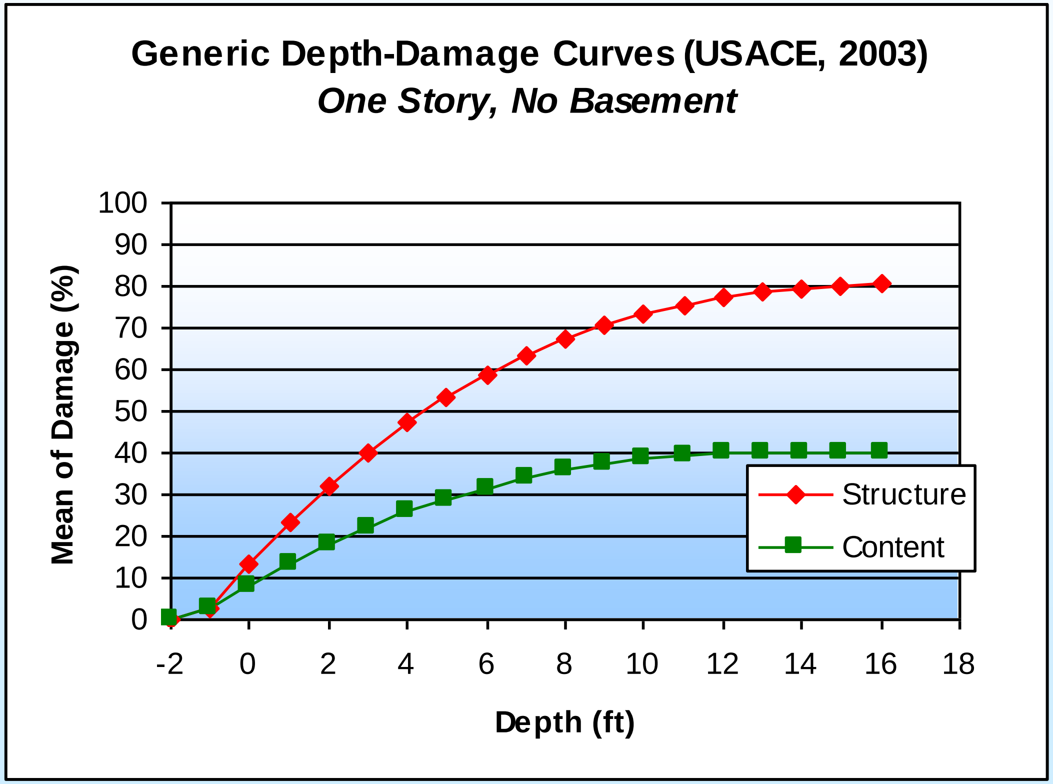


Problem Definition

- Traditional methodologies do not consider the direct effects of flooding hydrodynamics and source of hazard.

Flood Damage Estimation: Current Approach

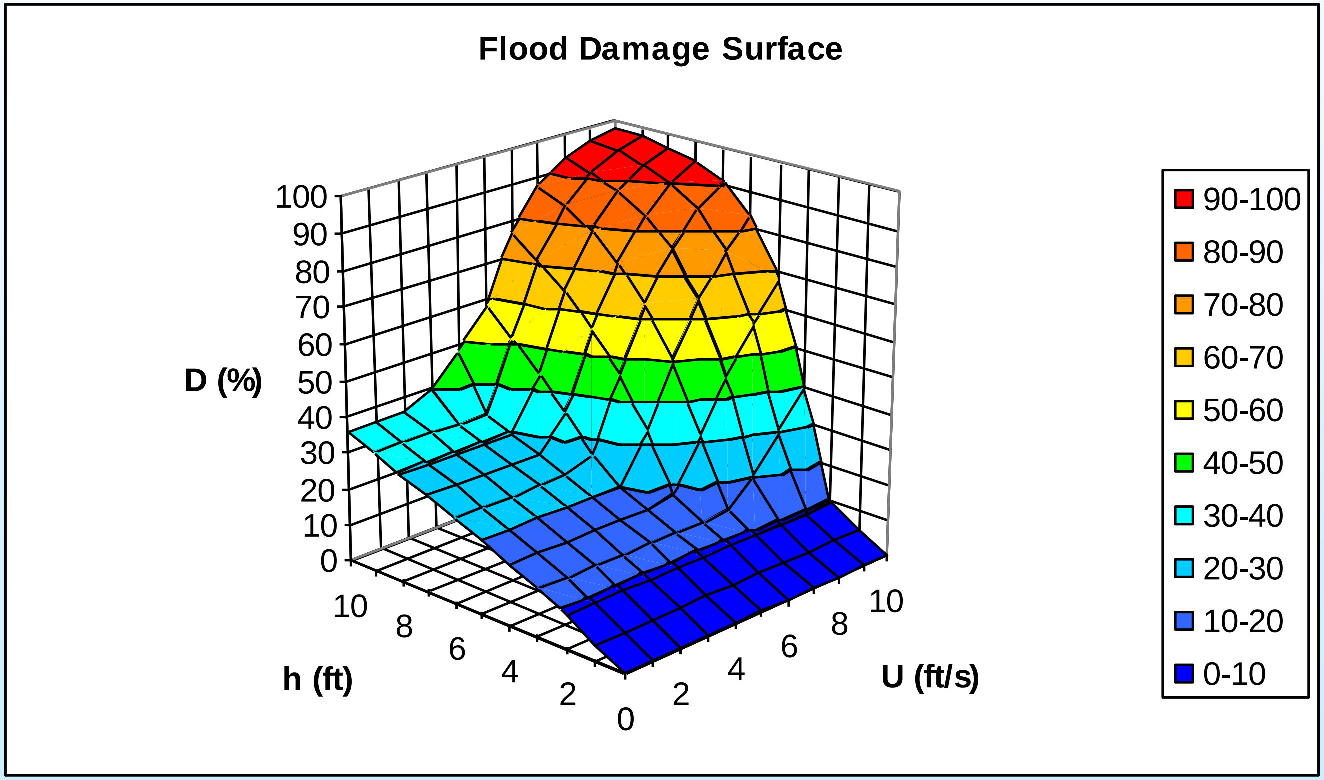
- Example of *traditional* depth-damage curves



$$Building\ Damage = f\left(Floodwater\ Depth\right)$$

Flood Damage Estimation: Studied Approach

- 3-Dimensional Surface: Depth-Velocity-Damage



$$Building\ Damage = f\left(Floodwater\ Depth,\ Floodwater\ Velocity\right)$$

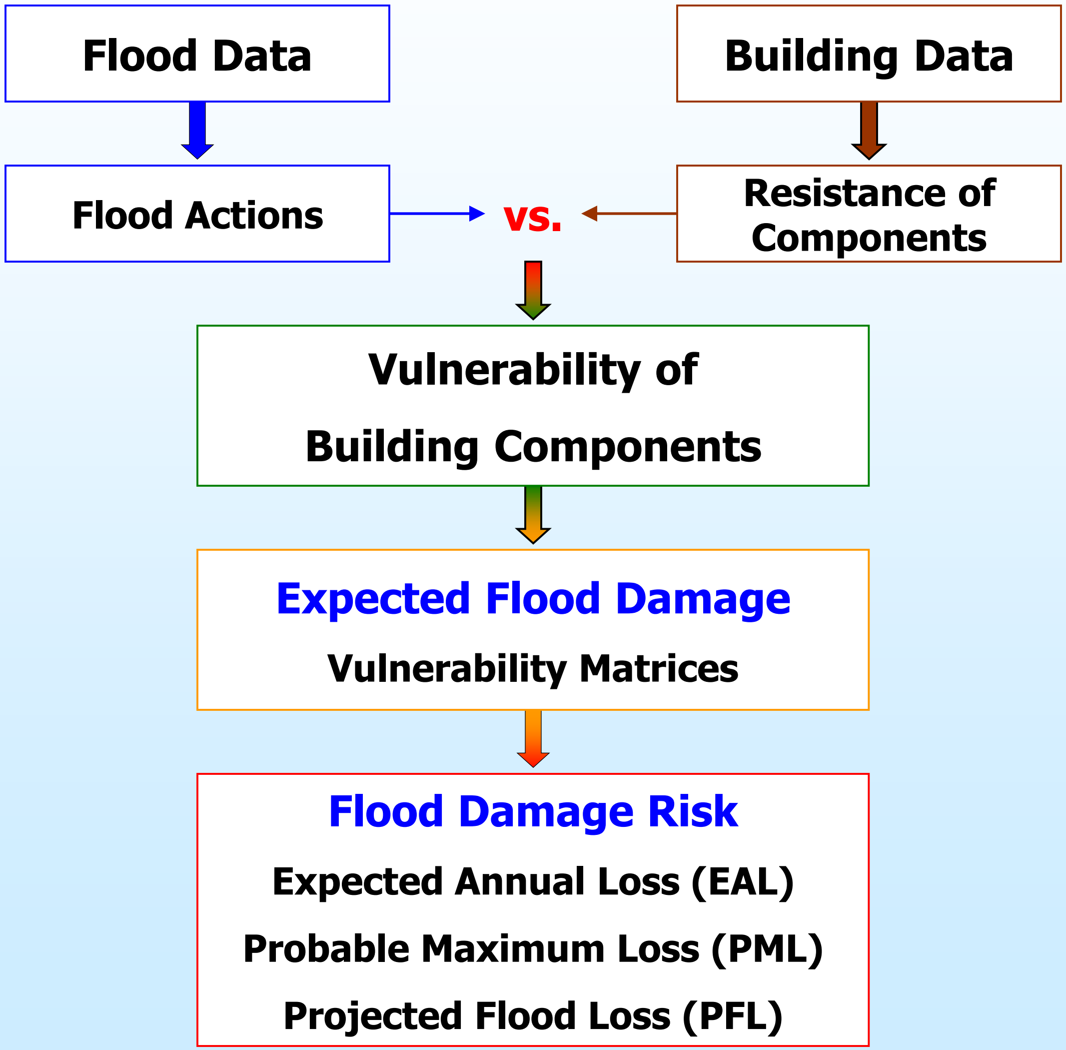
Objectives

- **Evaluate the direct impact of floodwater actions** on buildings: hydrostatic and hydrodynamic forces, waves, debris impacts, and local soil scour.

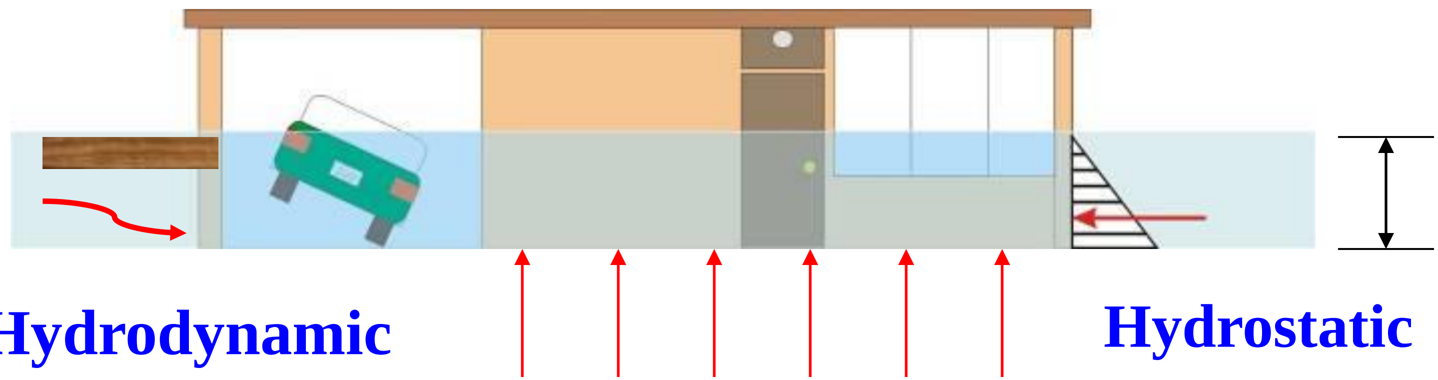
- Determine the **resistance of individual building components**, including: reinforced-concrete frame, concrete-block walls, doors, and windows.

- Assess **the vulnerability and flood damage risk** of buildings.
  - **EAL** – Expected Annual Loss
  - **PML** – Probable Maximum Loss
  - **PFL** – Projected Flood Loss

Conceptual Model



Riverine Floods – Flood Forces



Debris

$$\overline{F}_I = \frac{wU}{g\,t}$$

Hydrodynamic Force

$$F_D = \int 0.5 C_d \rho U^2 dA$$

Buoyancy

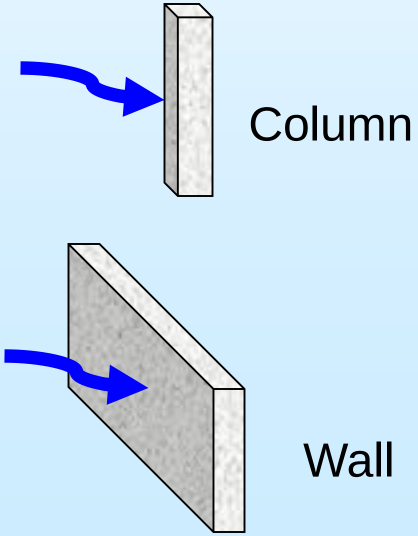
$$F_B = \int \gamma\, h\, dA$$

Hydrostatic Force

$$F_S = \int \gamma\, h\, dA$$

Storm Surges

- Case 1: **Surging Flood:** *Hydrodynamic* (equal water level on both sides of the external walls)
- Case 2: **Breaking Waves:** *Hydrodynamic* **+** *Breaking Waves* (equal water level on both sides of the elements)



Storm Surges – Flood Forces

- ***Surging Flood*** (high-velocity currents)

$$F_S = \frac{1}{2} C_d \rho_S U^2 h b$$

- The velocity of the surge varies from (FEMA, 2000):

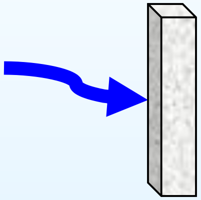
$$\frac{h}{t} \le U \le \sqrt{gh} \quad where\ t = 1\ s$$

Storm Surges – Flood Forces *(cont.)*

- ***Breaking Waves*** on columns (FEMA, 2000)

$$F_W = 0.5 C_d \rho_S g D_c H_W^2$$

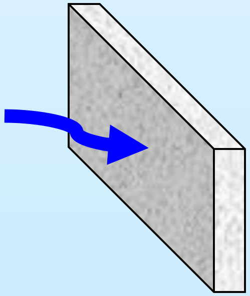
$$H_W \approx 0.78\, h$$



- ***Breaking Waves*** on walls (FEMA, 2000)

$$F_{W_{+s}} = (1.1\, C_p + 2.41) \rho_S g h^2 b$$

$$F_W = (1.1 C_p + 1.91) \rho_S g h^2 b$$



$$H_W \approx 1.2\, h$$

Tsunamis

- Case 1: **Turbulent Bore:** *Hydrostatic* **+** *Hydrodynamic (*dry space inside the building)

- Case 2: **Tsunami Waves:** *Hydrostatic* **+** *Hydrodynamic* **+** *Breaking Waves* (dry space inside the building)

Tsunamis – Flood Forces

- ***Turbulent Bores*** (Broken Waves)

  The forces induced by turbulent bores are modeled as those from extreme-velocity currents (Arnason, 2005).

$$F_T = \frac{1}{2} C_d \rho_S h U^2 b$$

$$\sqrt{gh} \le U \le 2\sqrt{gh}$$

- ***Breaking Waves*** – modeled as in the storm surge case

Special Cases

- **Debris Impact Forces:** considered in areas of potential debris flow hazard and where high velocity flows are likely
- **Buoyancy:** only a concern for lightweight buildings (i.e., wood, metal sheets) or improperly anchored buildings
- **Local Soil Scour:** considered whenever high velocity flows are likely

Visit to New Orleans, Louisiana, after Hurricane Katrina (NSF-CMS Grant No. 0553986)

Building Divisions for Damage Estimation

- Division 1: ***Reinforced-Concrete Frame***
- Division 2: ***Concrete-Block Walls***
- Division 3: ***Doors*** (single, double)
- Division 4: ***Windows***
- Division 5: ***Utilities & Finishes***

Estimated Flood Damage (EFD)

$$EFD = \int (D)\, d(BV)$$

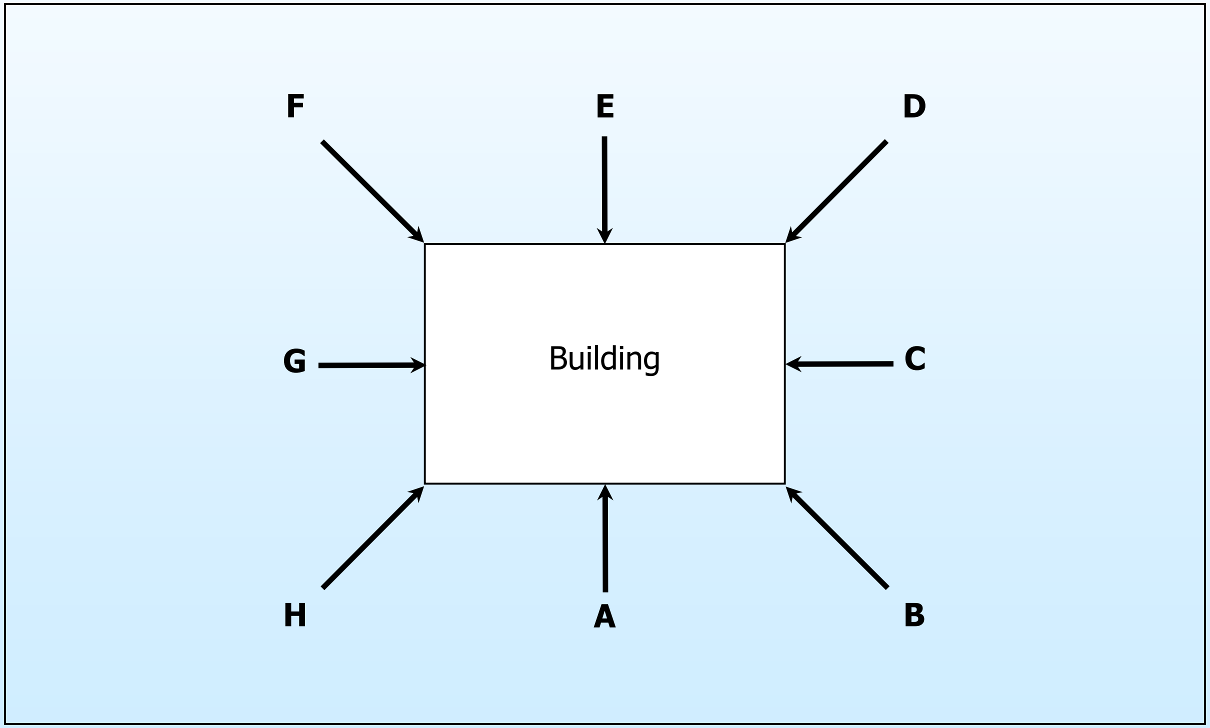
$$EFD = \sum_{i=1}^{5} \left(Damage\ to\ Building\ Division_i \times Percentage\ of\ Building\ Value \right)$$

Building Division	**Percentage of Building Value*** *residential (commercial)*
Concrete Frame	35% (35%)
Block Walls	10% (5%)
Doors	5% (5%)
Windows	5% (5%)
Utilities & Finishes	45% (50%)

Values for average buildings in Puerto Rico, based on: Botero and Lluch, 2005; Botero, 2004.

Estimated Flood Damage *(cont.)*

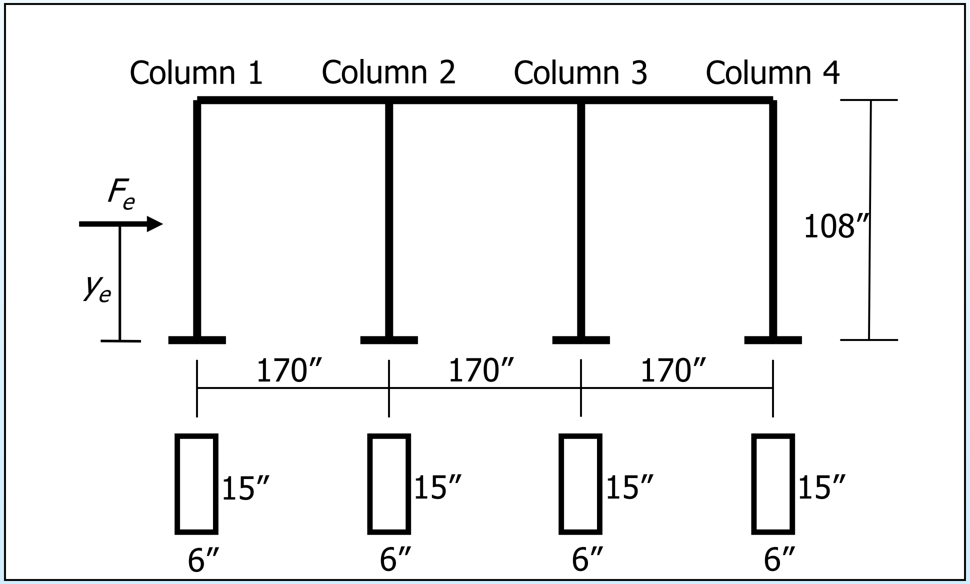
- Floodwater Flow Direction



$$Damage\ to\ Building\ Division = f\left(Approach\ Angle\right)$$

Estimated Flood Damage *(cont.)*

- Division 1: ***Reinforced-Concrete Frame***

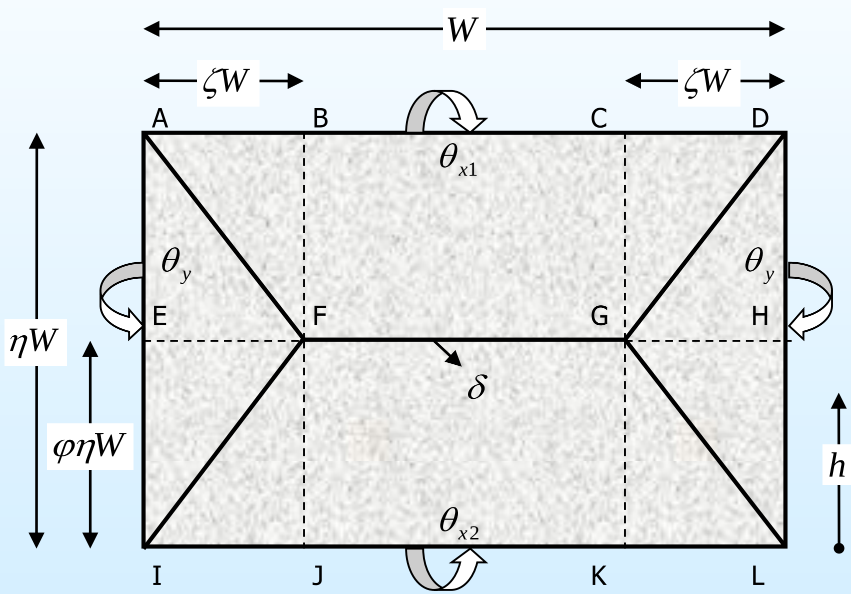


* shear force
* bending moment

$$\% \, Damage\, Div_1 = \frac{Number\ of\ \ Failed\ Columns}{Total\ Number\ of\ \ Columns}$$

Yield Line Analysis

- Division 2: ***Concrete-Block Walls***

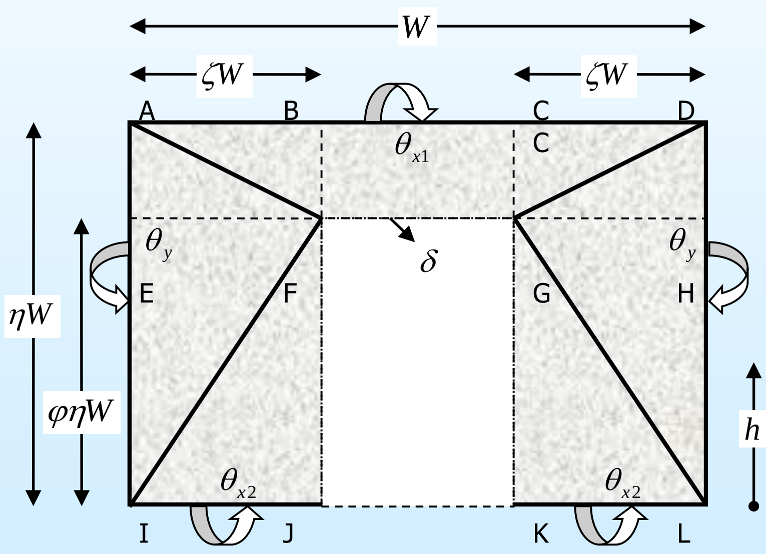


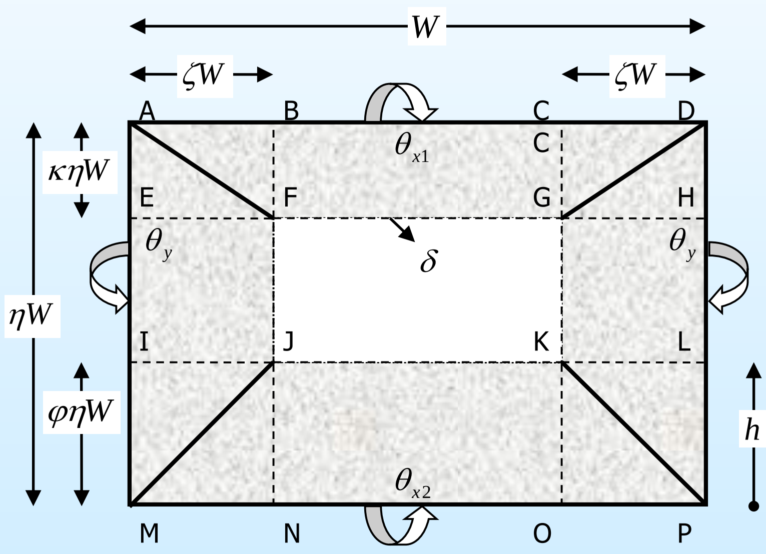
- walls without openings
- walls with openings:
  - doors
  - windows

$$\%\ Damage\, Div_2 = \frac{Plan\ Area\ of\ \ Failed\ Walls}{Total\ Plan\ Area\ of\ \ Walls}$$

Yield Line Analysis *(cont.)*

- Yield line patterns: ***with openings*** *(doors & windows)*

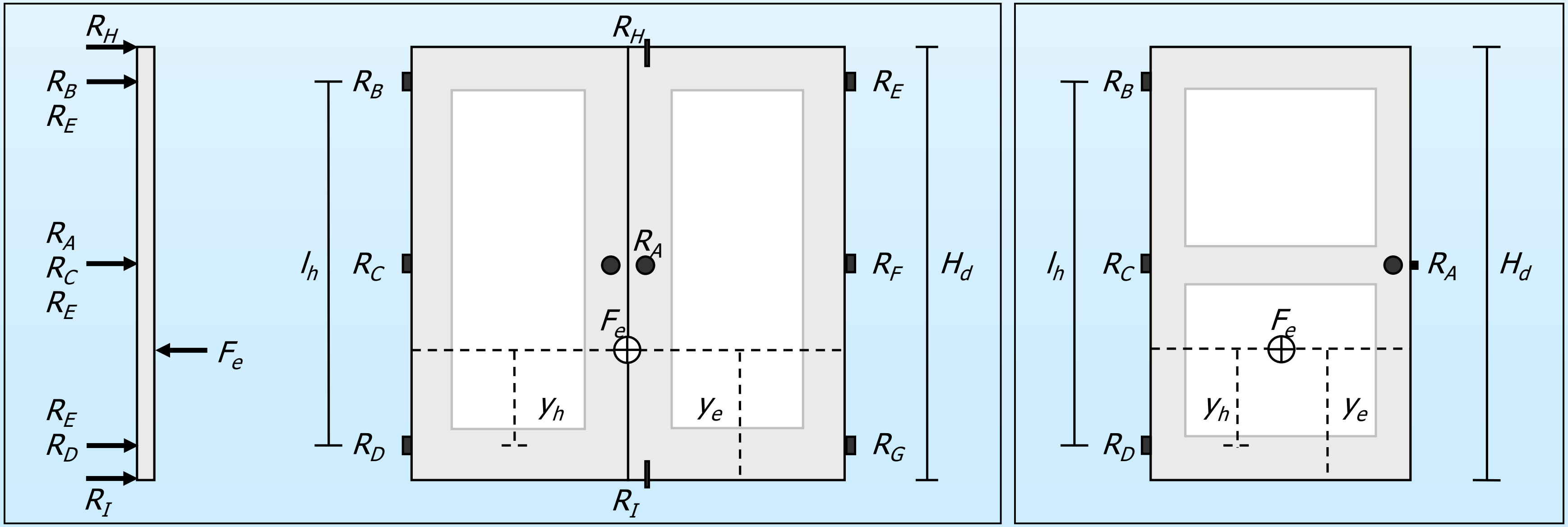




Estimated Flood Damage *(cont.)*

- Division 3: ***Doors*** (single, double)

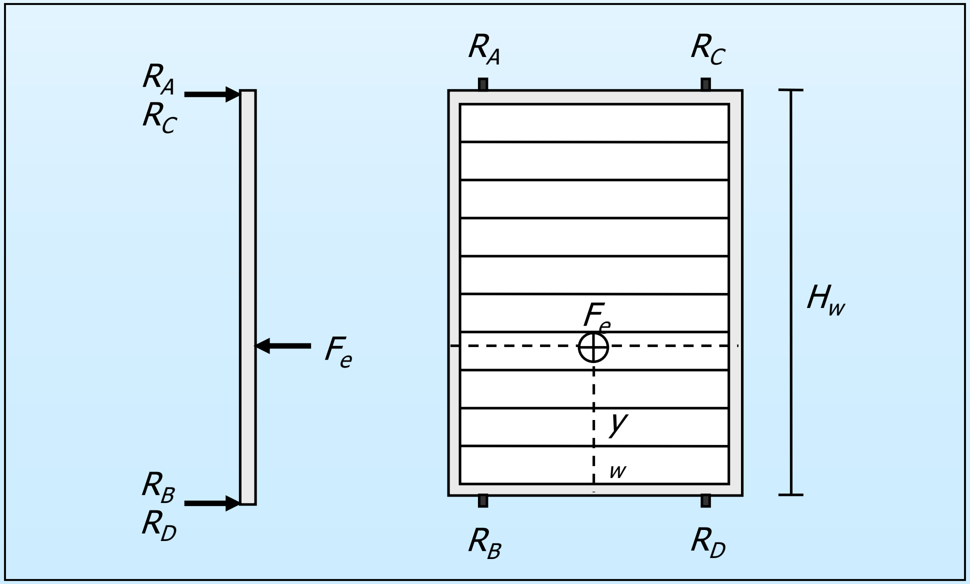
$$\% \, Damage \, Div_3 = \frac{Number \; of \; Failed \; Doors}{Total \; Number \; of \; Doors}$$



Estimated Flood Damage *(cont.)*

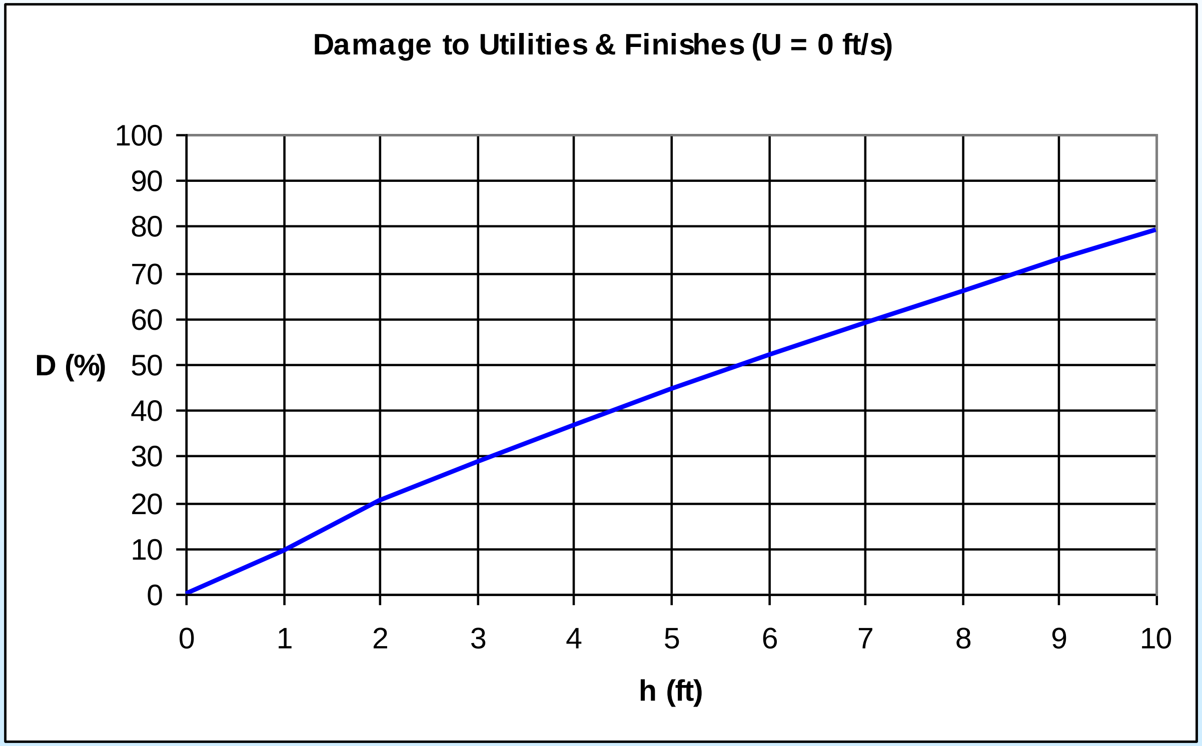
- Division 4: ***Windows***

$$\%\ Damage\ Div_4 = \frac{Number\ of\ Failed\ Windows}{Total\ Number\ of\ Windows}$$



Estimated Flood Damage *(cont.)*

- Division 5: ***Utilities & Finishes***



$$\%\ Damage\, Div_5 = f\left(floodwater\ depth\right)$$

Monte Carlo Simulation

- ***Generation of Synthetic Data*** – 10,000 buildings

  Based on the structural and geometric data obtained from 28 typical residential buildings in Puerto Rico.

Variable	PDF	Description
width of unsupported wall panels, W (ft)	uniform	$\in = [5, 20] \Rightarrow e_b = 5 + \chi(20-5)$
height of unsupported wall panels, H (ft)	discreet	$P(H=8)=0.20,\ P(H=9)=0.65,$ $P(H=10)=0.05,\ P(H=11)=0.05,$ $P(H=12)=0.05$
thickness of concrete-block walls, t_w (ft)	discreet	$P(t_w = 0.5) = 1.0$
compressive strength of concrete, f'_c (psi)	discreet	$P(f'_c = 3000) = 1.0$

Example of building data (concrete-block walls) and the corresponding PDFs

Flood Damage Risk

$$Risk = f\left(Hazard, Exposure, Vulnerability\right)$$

- ***Hazard*** = flood event including its exceedance probability
  - riverine flood, storm surge, tsunami*
  - T_R = 10, 50, 100, 500, (1000) years
  - P (X≥x) 10%, 2%, 1%, 0.2%, 0.1% annually
- ***Exposure*** = buildings that are located at the affected area
  - location: in/out of flood-prone zone
  - floodwater depth and velocity
- ***Vulnerability*** = lack of resistance of the buildings to flood actions
  - building materials
  - structural integrity

Flood Damage Risk *(cont.)*

Indexes

Expected Annual Loss (EAL)

Average value of annual flood damages over the lifespan of a building (FEMA, 1986).

Expected value of the annual damage considering all possible floods (Maidment, 1999).

Probable Maximum Loss (PML)

Risk Management:

Defined based on an annual exceedance probability.

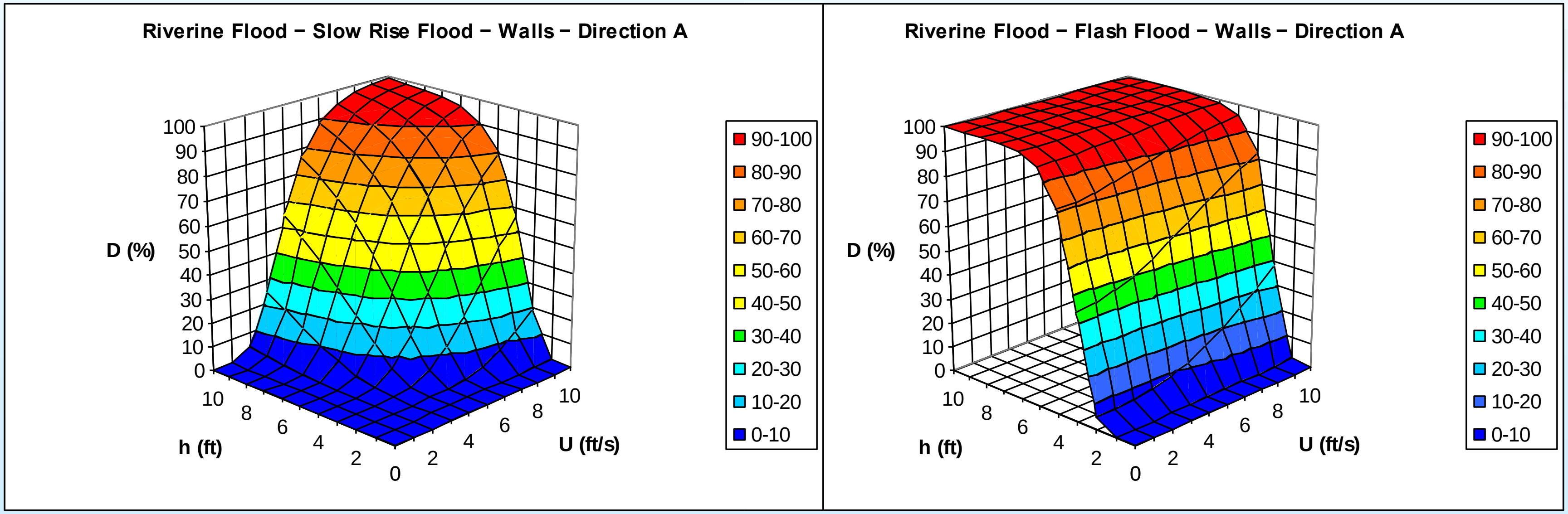
(i.e., T_R = 200-yr, 500-yr)

Insurance Industry:

Amount that no claim is likely to exceed. Protect against high losses and assure survival.

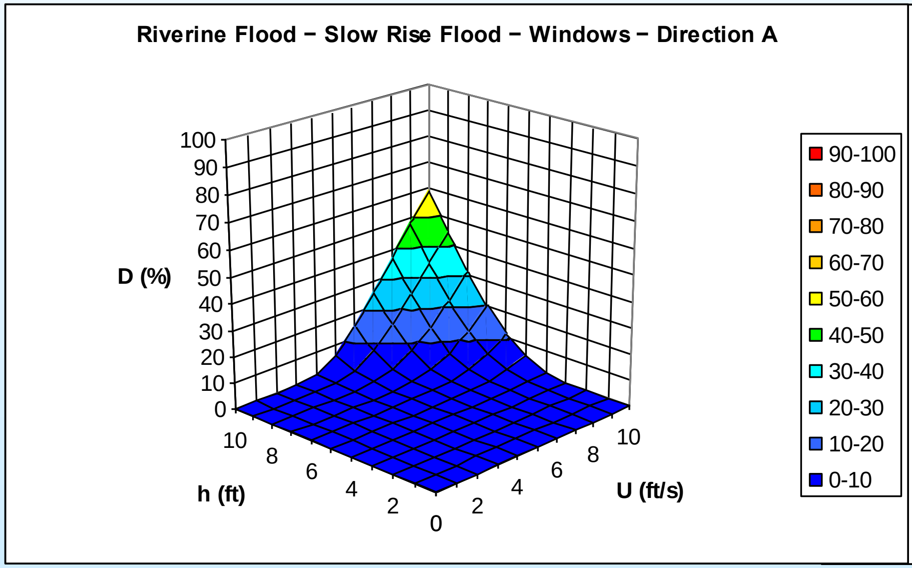
Results of the Current Study *(cont.)*

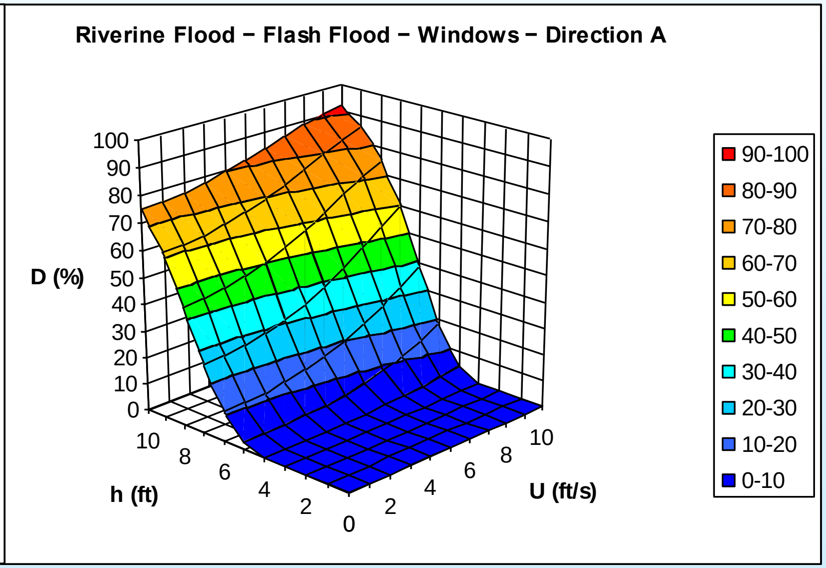
- Concrete-Block Walls: **Slow Rise Flood** vs. **Flash Flood**



Results of the Current Study *(cont.)*

- Windows: **Slow Rise Flood** vs. **Flash Flood**

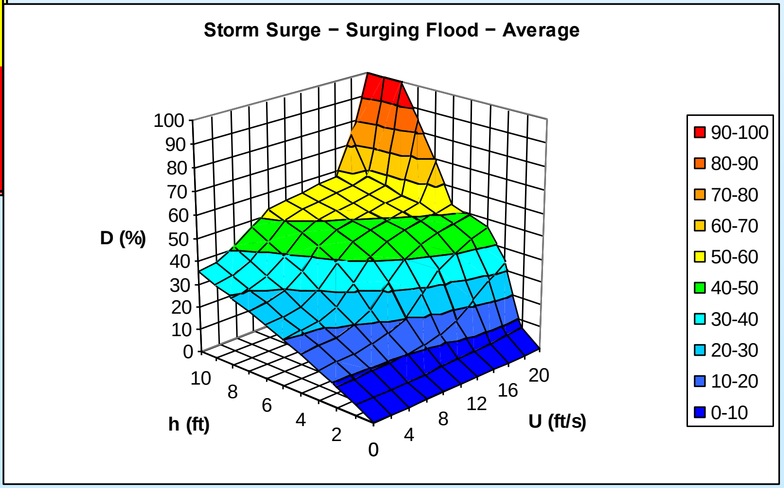




Results of the Current Study *(cont.)*

- EFD - Storm Surges: ***Surging Flood***

h	**U** (ft/s)										
(ft)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0	0	0	0	0	0	0	0	0	0	0
1	4.3	4.3	4.3	4.3	4.3	4.5	4.7	5.1	5.5	5.9	6.5
2	9.1	9.1	9.4	9.5	10.1	11.1	12.5	15.9	22.0	28.1	33.3
3	13.0	13.5	13.6	14.6	16.5	19.8	28.1	35.3	40.3	43.8	46.3
4	16.6	17.2	17.5	19.9	23.5	33.3	40.0	44.1	46.6	48.3	49.7
5	20.0	20.6	21.3	25.3	32.7	41.4	45.6	47.7	49.1	50.4	51.6
6	23.3	23.9	25.5	30.4	39.2	45.7	48.3	49.7	50.9	52.1	69.4
7	26.5	27.2	29.6	35.1	43.8	48.2	49.9	51.0	52.3	53.6	85.6
8	29.6	30.3	33.4	39.3	47.3	50.5	51.8	52.9	54.1	55.5	100
9	32.7	33.4	37.2	43.3	50.1	52.5	53.6	54.7	55.9	57.3	100
10	35.7	36.4	41.0	47.1	52.4	54.4	55.3	56.3	57.5	74.9	100

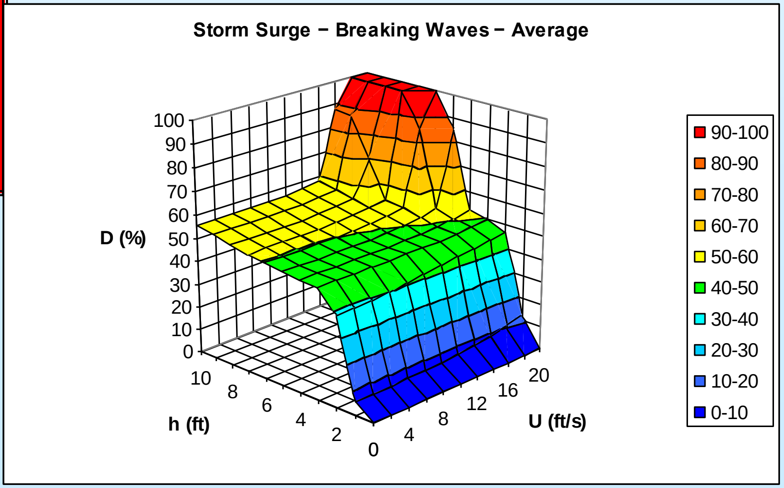


EFD=estimated flood damage

Results of the Current Study *(cont.)*

- EFD - Storm Surges: ***Breaking Waves***

h (ft)	**U** (ft/s)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0	0	0	0	0	0	0	0	0	0	0
1	5.6	5.6	5.7	5.9	6.1	6.4	6.9	7.5	8.8	10.7	12.9
2	38.4	38.6	39.1	39.8	40.7	41.7	42.7	43.7	44.6	45.5	46.3
3	47.6	47.7	47.7	47.7	47.8	47.9	48.0	48.2	48.5	49.0	49.7
4	48.1	48.1	48.1	48.1	48.1	48.2	48.4	48.8	49.4	50.2	51.1
5	48.7	48.7	48.7	48.7	48.8	49.0	49.4	50.1	51.0	52.0	85.5
6	49.9	49.9	49.9	49.9	50.0	50.3	50.9	51.7	52.8	85.6	100
7	50.8	50.8	50.8	50.8	50.9	51.3	52.0	53.0	54.2	100	100
8	52.3	52.3	52.3	52.3	52.5	52.9	53.7	54.7	70.2	100	100
9	54.0	54.0	54.0	54.0	54.1	54.5	55.3	56.3	87.1	100	100
10	55.7	55.7	55.7	55.7	55.8	56.2	56.9	57.9	87.8	100	100

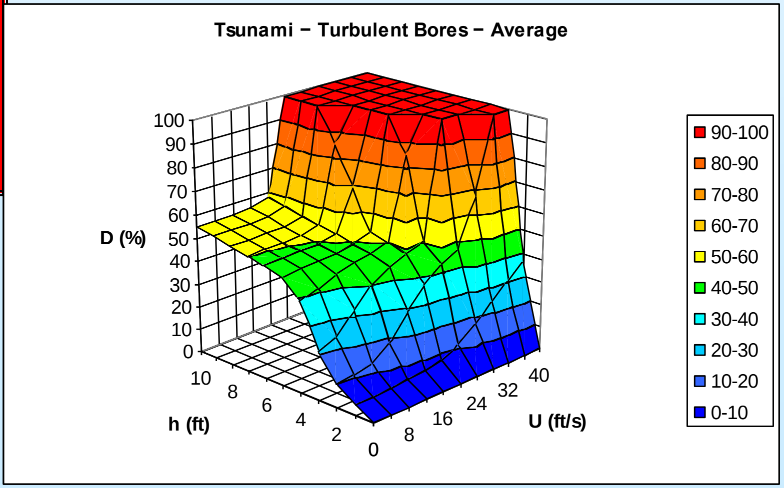


EFD=estimated flood damage

Results of the Current Study *(cont.)*

- EFD - Tsunamis: ***Turbulent Bores***

h (ft)	**U** (ft/s)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0	0	0	0	0	0	0	0	0	0	0
1	4.3	4.3	4.6	5.3	6.1	7.2	11.3	17.6	24.3	30.8	36.5
2	10.1	10.6	12.4	18.4	29.0	37.5	43.4	47.4	67.4	100	100
3	20.9	24.0	32.4	40.5	45.1	48.0	50.3	100	100	100	100
4	39.2	41.3	44.7	46.9	48.3	50.1	85.4	100	100	100	100
5	46.7	47.2	48.0	48.5	49.7	51.7	100	100	100	100	100
6	49.0	49.1	49.3	49.7	51.2	69.4	100	100	100	100	100
7	50.1	50.2	50.3	50.8	52.5	85.7	100	100	100	100	100
8	51.7	51.8	51.9	52.5	54.3	100	100	100	100	100	100
9	53.4	53.4	53.6	54.2	56.0	100	100	100	100	100	100
10	55.1	55.1	55.2	55.7	57.6	100	100	100	100	100	100

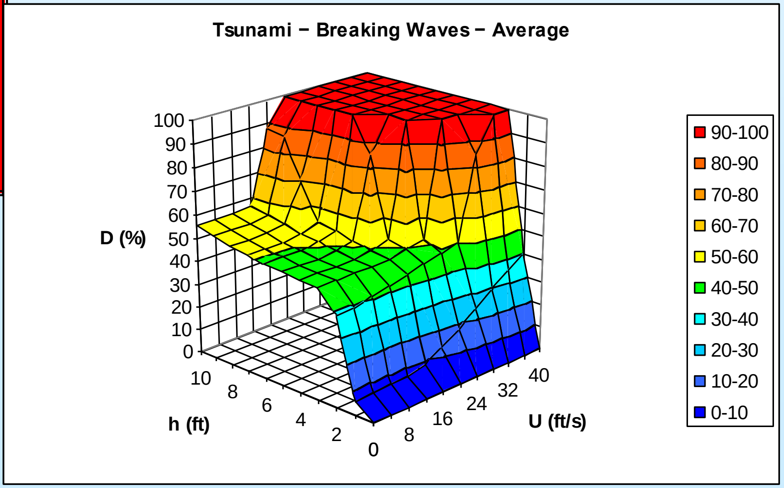


EFD=estimated flood damage

Results of the Current Study *(cont.)*

- EFD - Tsunamis: ***Tsunami Waves***

h (ft)	**U** (ft/s)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0	0	0	0	0	0	0	0	0	0	0
1	6.0	6.1	6.4	7.0	8.8	12.9	18.2	24.0	29.8	35.1	39.6
2	38.4	39.1	40.7	42.7	44.6	46.3	48.1	49.9	85.3	100	100
3	47.6	47.7	47.8	48.0	48.5	49.7	51.3	100	100	100	100
4	48.1	48.1	48.1	48.4	49.4	51.1	100	100	100	100	100
5	48.6	48.6	48.7	49.3	50.8	85.5	100	100	100	100	100
6	49.6	49.6	49.6	50.5	52.4	100	100	100	100	100	100
7	50.4	50.4	50.5	51.6	53.7	100	100	100	100	100	100
8	51.9	51.9	52.1	53.3	70.1	100	100	100	100	100	100
9	53.6	53.6	53.8	55.0	86.9	100	100	100	100	100	100
10	55.4	55.4	55.5	56.6	87.7	100	100	100	100	100	100

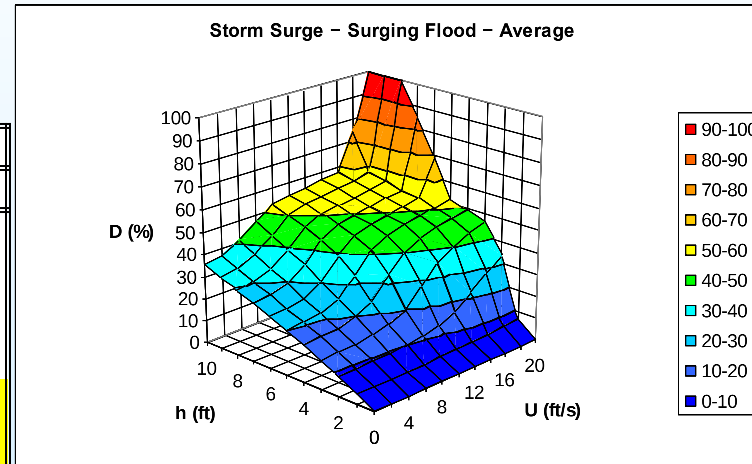


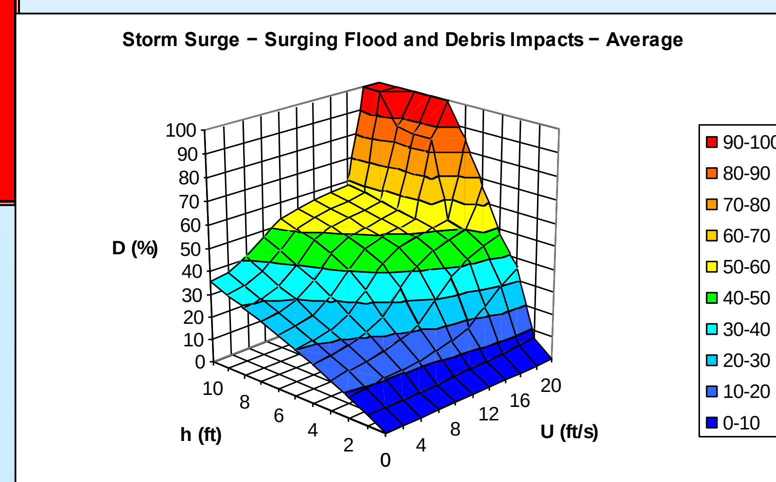
EFD=estimated flood damage

Results of the Current Study *(cont.)*

- EFD - Special Cases: ***Surging Flood*** + ***Debris Impacts***

h (ft)	U (ft/s)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0	0	0	0	0	0	0	0	0	0	0
1	4.3	4.3	4.3	4.3	4.3	4.5	4.7	5.1	5.5	5.9	6.5
2	9.1	9.5	10.5	11.0	11.6	12.7	14.2	17.6	23.7	29.8	35.0
3	13.0	13.9	14.7	16.0	18.0	21.4	29.8	37.0	42.0	45.4	47.8
4	16.6	17.4	18.4	21.3	25.0	34.9	41.7	45.8	48.2	49.8	67.5
5	20.0	20.8	22.1	26.6	34.1	43.0	47.2	49.3	50.6	51.7	85.3
6	23.3	24.0	26.1	31.4	40.4	47.1	49.8	51.1	52.2	85.3	100
7	26.5	27.2	30.0	35.9	44.9	49.4	51.2	52.3	53.5	85.5	100
8	29.6	30.3	33.7	39.9	48.2	51.5	52.9	54.1	55.3	86.3	100
9	32.7	33.4	37.4	43.7	50.7	53.3	54.6	55.7	57.0	100	100
10	35.7	36.4	41.1	47.3	52.9	55.0	56.2	57.3	58.5	100	100



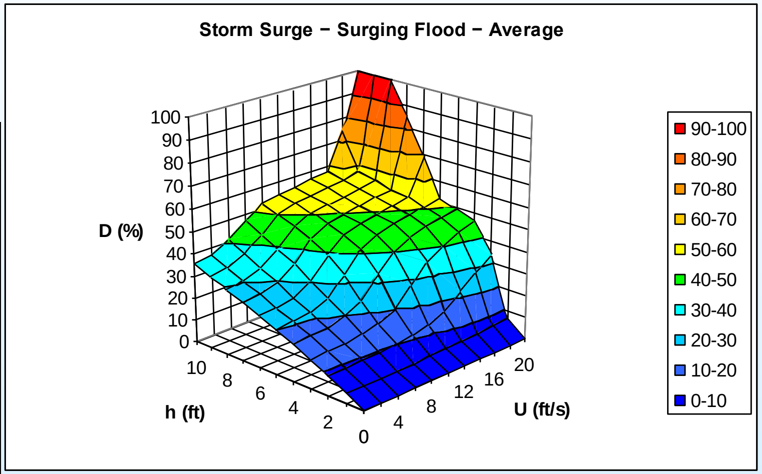


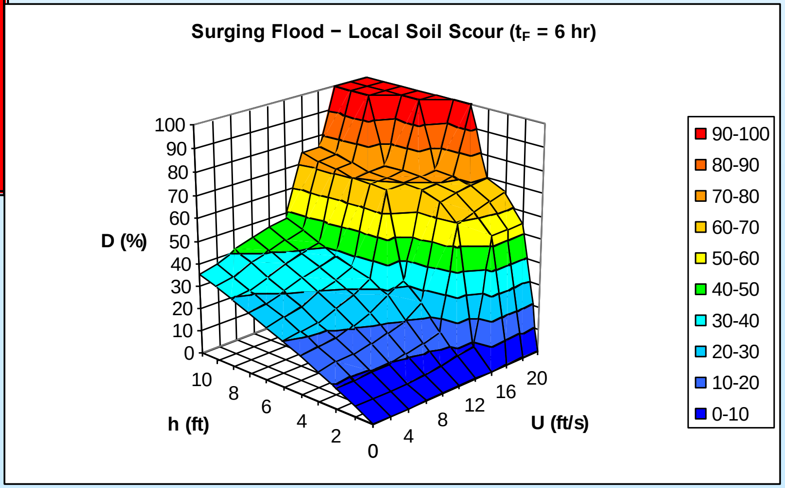
EFD=estimated flood damage

Results of the Current Study *(cont.)*

- EFD - Special Cases: ***Surging Flood*** + ***Local Soil Scour***

h (ft)	U (ft/s)										
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	0	0	0	0	0	0	0	0	0	0	0
1	4.3	4.3	4.3	4.3	4.7	5.7	6.9	8.0	54.0	54.2	54.5
2	9.1	9.1	9.6	9.8	10.8	12.6	14.8	59.2	62.0	64.2	66.0
3	13.0	14.1	14.1	15.3	17.3	20.3	25.3	66.7	68.2	69.2	69.8
4	16.6	17.8	18.1	20.6	23.4	28.2	31.7	69.2	69.9	70.4	100
5	20.0	21.3	21.9	25.4	28.4	32.7	69.3	70.0	70.4	70.7	100
6	23.3	24.6	26.2	29.7	32.4	35.6	69.8	70.2	70.6	100	100
7	26.5	27.8	30.4	33.6	36.0	37.8	70.0	70.4	70.9	100	100
8	29.6	30.9	34.0	37.2	39.4	41.2	71.4	71.9	100	100	100
9	32.7	34.0	37.5	40.7	42.6	44.4	73.1	73.7	100	100	100
10	35.7	37.1	41.0	44.0	45.8	47.6	74.8	75.3	100	100	100





EFD=estimated flood damage

Application Example *(cont.)*

- Storm Surge – ***Flood Damage Risk***

	Surging Floods	*Breaking Waves*
EAL	2.16%	4.87%
PML_{500}	33.2%	51.6%
PFL_{10}	14.5%	31.8%
PFL_{30}	24.2%	47.0%
PFL_{50}	25.9%	49.1%

- Tsunamis

PML_{MOM}	100%	100%

Reference

- **Building Damage Due to Riverine and Coastal Floods**
- Journal of Water Resources Planning and Management
- May 2010
- Authors: Nadal, Pagán-Trinidad, Zapata, López, and Agudelo

Acknowledgments

This study has been possible thanks to the sponsorship of :

- Puerto Rico Insurance Commissioner Office – through a contract with the University of Puerto Rico at Mayagüez
- Alliance for the Graduate Education and the Professoriate (AGEP) – through an NSF-sponsored fellowship (NSF Grant No. HRD9817642)
- This project served for the PhD thesis of Dr. Norberto Nadal.

Acknowledgement

- **Acknowledgement:** “This material is based upon work supported by the U.S. Department of Homeland Security under Grant Award Number 2015-ST-061-ND0001-01.”
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