Impacts of Hurricane Katrina & Boxing Indian Ocean Tsunami On Ports & Harbors

Facilities Engineering Seminar
American Associate of Port Authorities
January 11-13, 2006

By

John Headland

AAPA

Moffatt & Nichol

Coasts, Oceans, Ports, and Rivers Institute

We learn from history, that we learn nothing from history.”

George Bernard Shaw

Author, Playwright

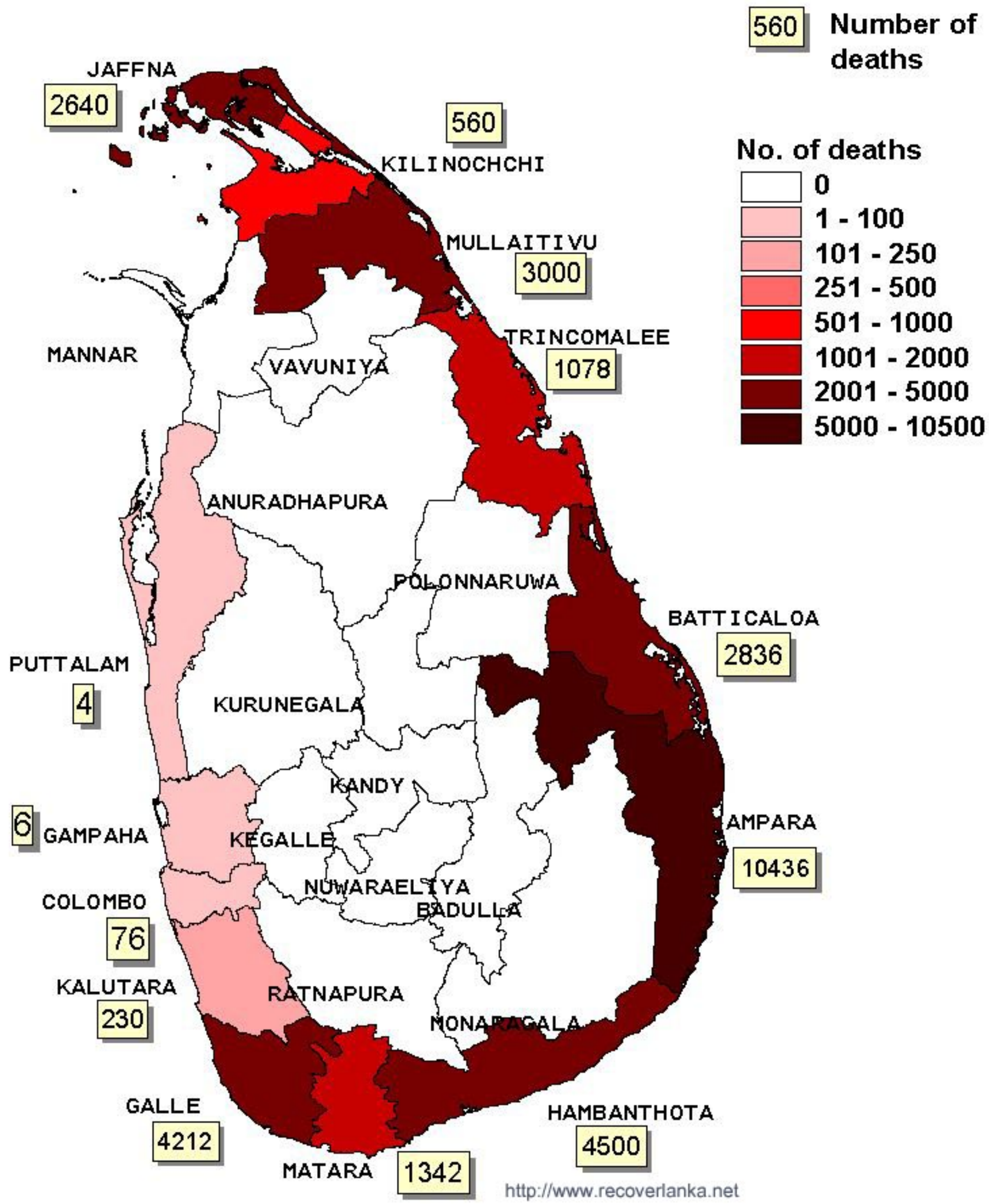

Sri Lanka
Province boundary
National capital
Province capital
Railroad
Road
Sri Jayewardenepura Kotte is the legislative capital.
0 20 40 Kilometers
0 20 40 Miles
Lambert Conformal Conic Projection, SP 09 15N / 06 15N
INDIA
TRINCOMALEE
COLOMBO
GALLE
Tondi
Devipattinam
Rāmanāthapuram
Pāmban Island
Rāmeswaram
Dhanushkodi
ferry
Adam's Bridge
Palk Strait
Palk Bay
Delft Island
Kankesanturai
Point Pedro
Jaffna
Jaffna Peninsula
Elephant Pass
Kilinochchi
Iranamadu Tank
Mullaittivu
Mankulam
Mannar Island
Mannar
NORTH EASTERN
Pulmoddai
Vavuniya
Aruvi Aru
Bay of Bengal
Trincomalee
Mutur
Hammillewa
Yan Oya
Anuradhapura
NORTH CENTRAL
Kalpitiya
Kala Oya
Kaudulla Oya
Gulf of Mannar
Puttalam
Habarane
Polonnaruwa
NORTH WESTERN
Maho
Deduru Oya
Maduru Oya
Batticaloa
Kattankudi
NORTH EASTERN
Chilaw
Kurunegala
Matale
CENTRAL
Mahaweli Ganga
Maduru Oya Reservoir
Kalmunai
Maha Oya
Kandy
Ampara
Gal Oya
Negombo
Kegalla
Victoria Falls Reservoir
Senanayake Samudra
Ganga
Nuwara Eliya
Badulla
Kelani
Sri Jayewardenepura Kotte
Mount Lavinia
Moratuwa
WESTERN
UVA
Monaragala
Pottuvil
Kalu Ganga
Ratnapura
Kirindi Oya
Kalutara
SABARAGAMUWA
Kumana
Kataragama
Laccadive Sea
Walawe Ganga
Ambalangoda
SOUTHERN
Hambantota
Galle
Matara
Dondra Head
INDIAN OCEAN

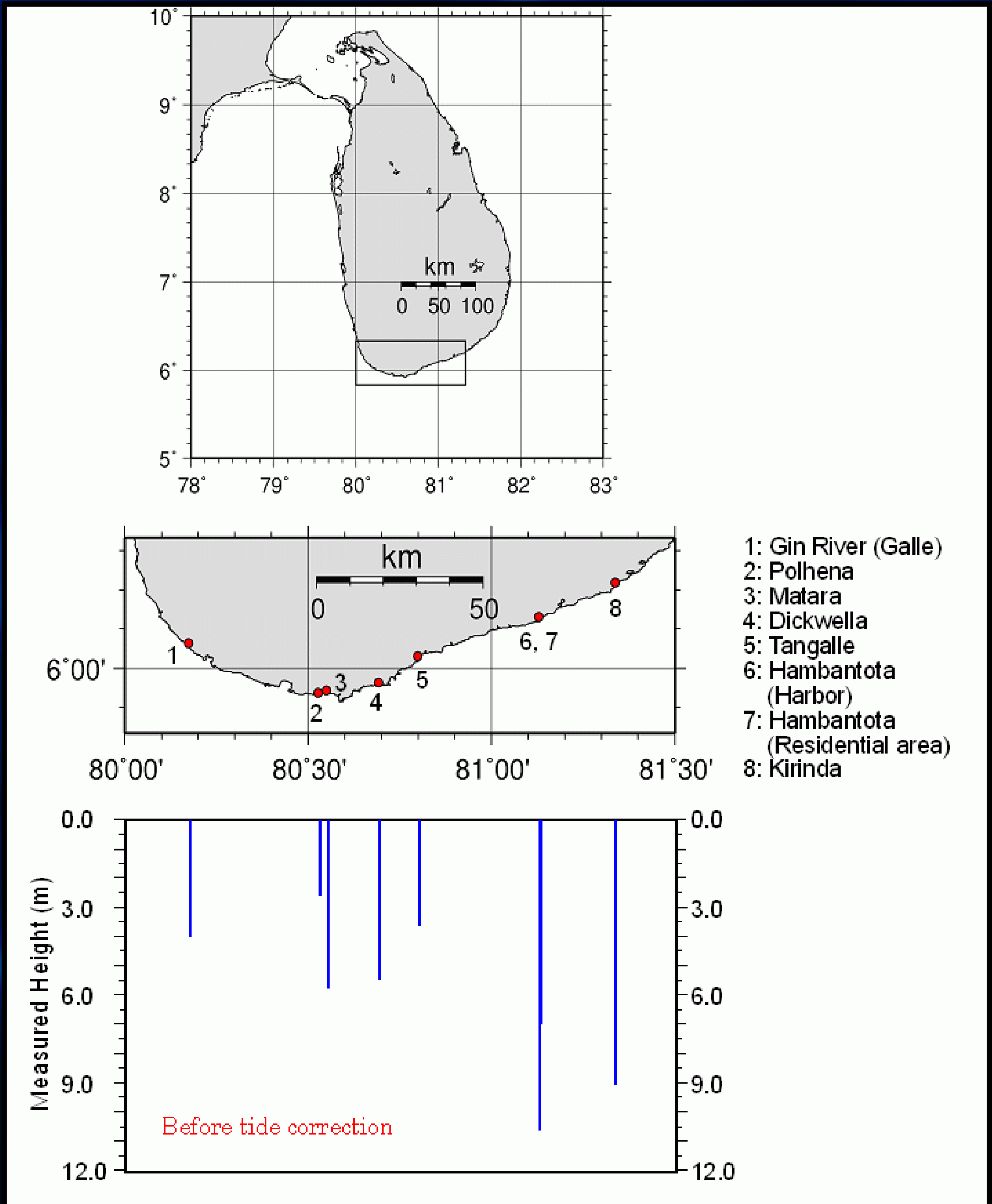
Day 1 #13
Typical Sri Lankan Scene Near Panadura

Tsunami Inundation = 3.3 m

Tsunami 2004 Disaster - Number of Deaths by District

Data from NDMC, 15th January, 2005




10°
9°
8°
7°
6°
5°
78°
79°
80°
81°
82°
83°
km
0 50 100
km
0 50
6°00'
80°00'
80°30'
81°00'
81°30'
1
2
3
4
5
6, 7
8
1: Gin River (Galle)
2: Polhena
3: Matara
4: Dickwella
5: Tangalle
6: Hambantota (Harbor)
7: Hambantota (Residential area)
8: Kirinda
Measured Height (m)
0.0
3.0
6.0
9.0
12.0
Before tide correction

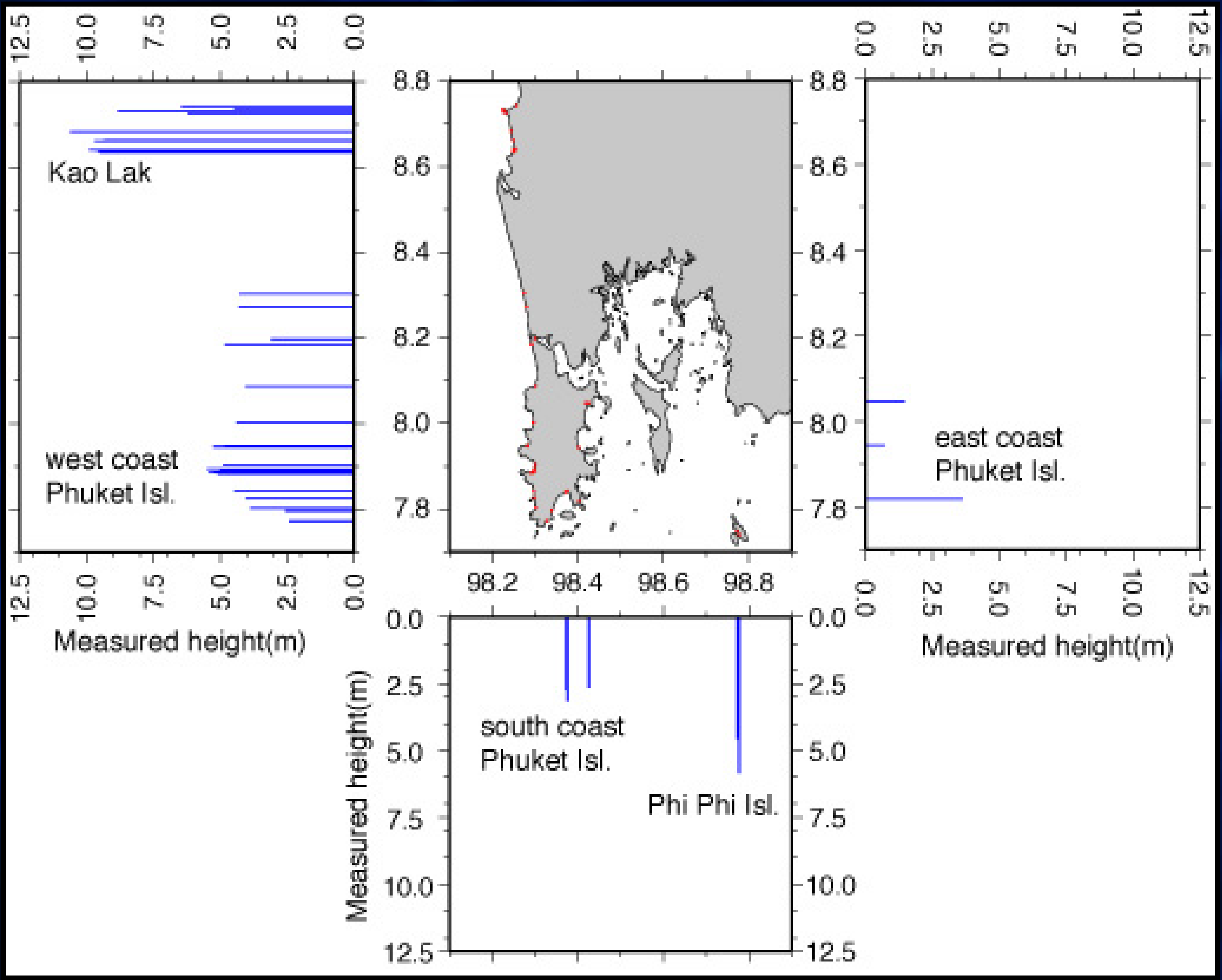

0
0,5
1
km
Hikkaduwa
6°9'36"N
6°9'0"N
6°8'24"N

East Sri Lanka (AP Photo):

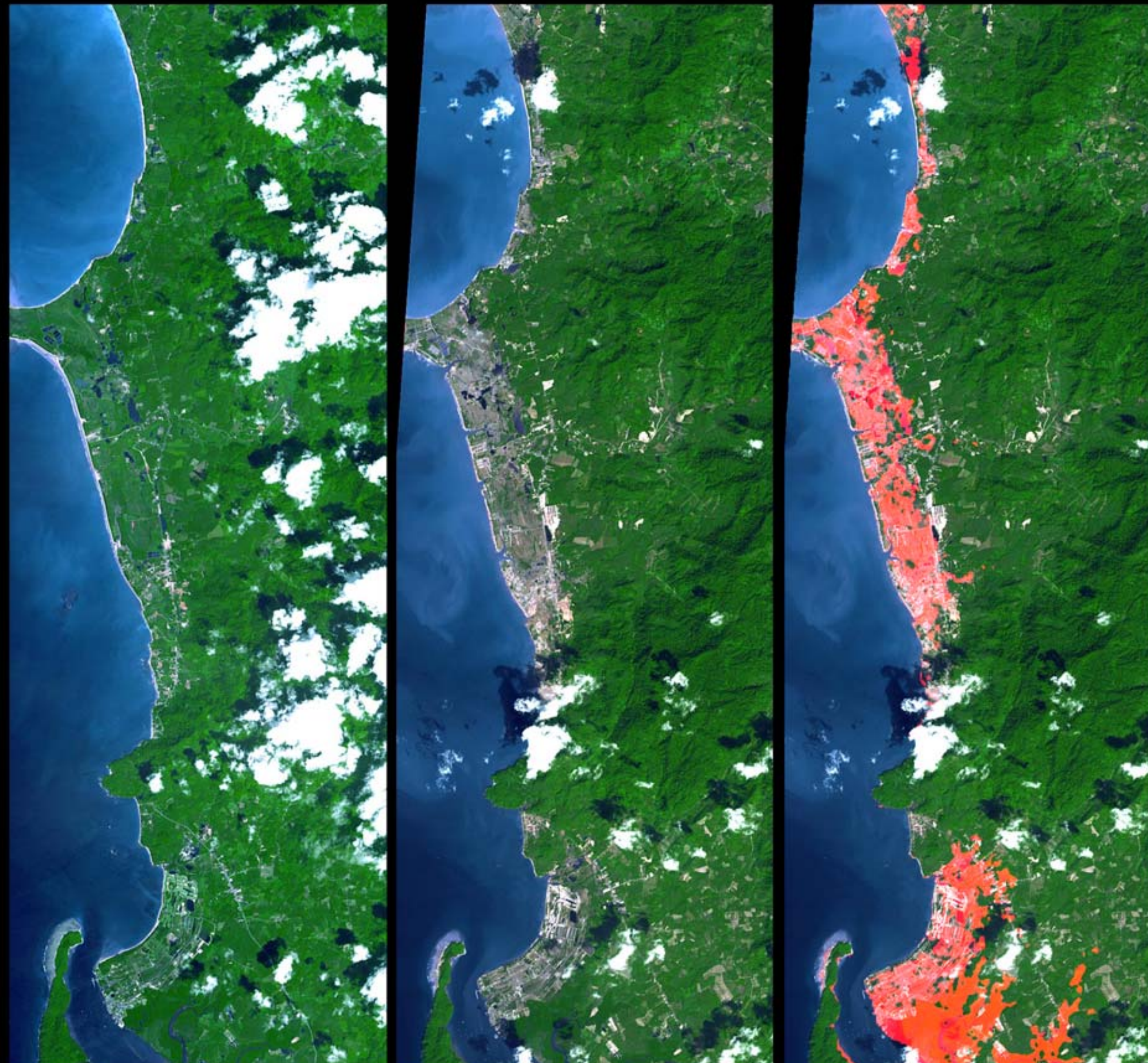
Raging water at beach front properties.


Day 4 #19
Hambantota
Sri Lanka
Runup= 11m

Thailand



Kao Lak
west coast
Phuket Isl.
Measured height(m)
east coast
Phuket Isl.
south coast
Phuket Isl.
Phi Phi Isl.
8.8
8.6
8.4
8.2
8.0
7.8
98.2
98.4
98.6
98.8
0.0
2.5
5.0
7.5
10.0
12.5



Before Tsunami
15 November 2002

After Tsunami
31 December 2004

SRTM Elevations
within 10 m of Sea Level

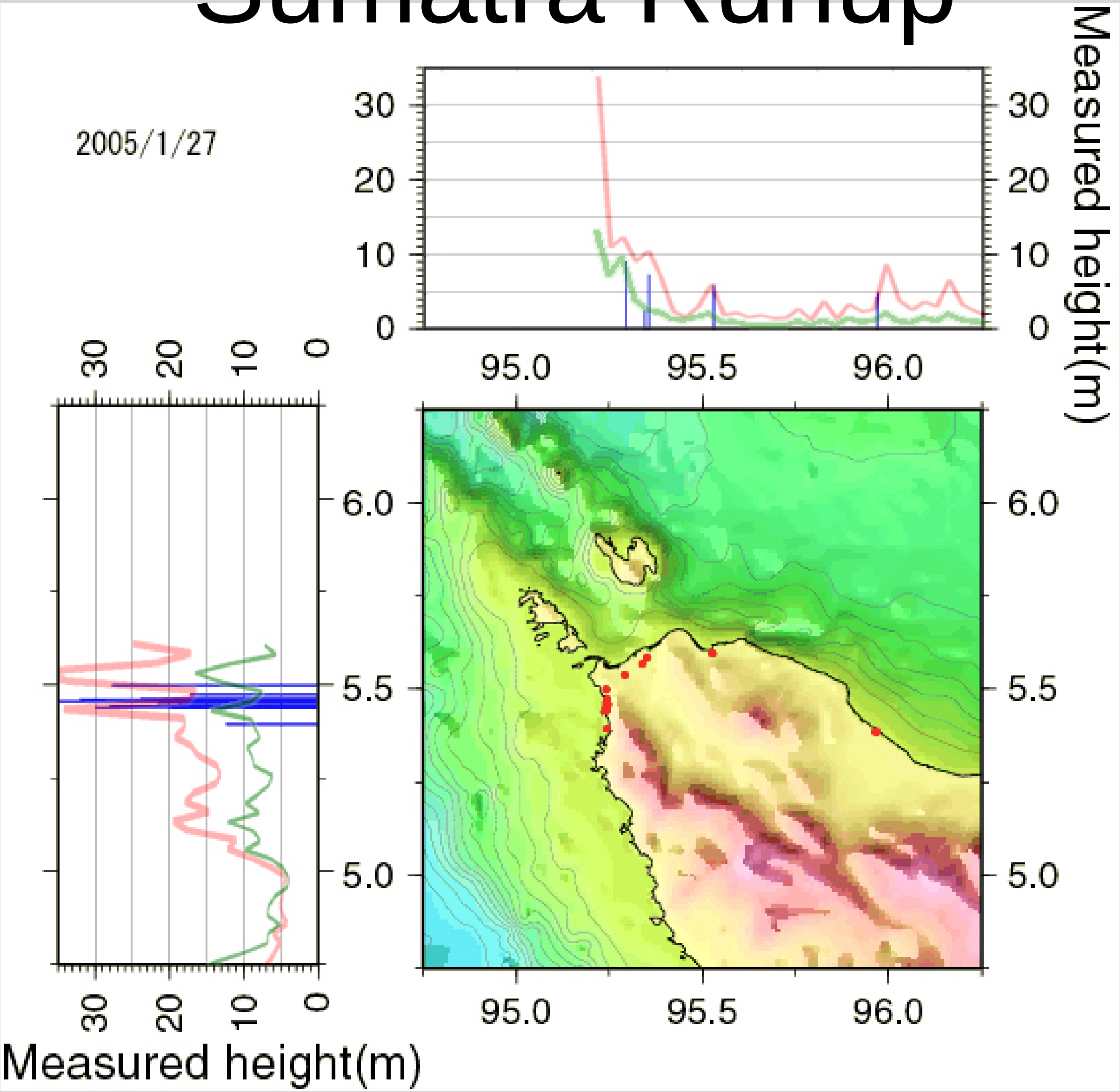
North of Phuket, Thailand

Tsunami: 26 December 2004

ASTER Images with SRTM Elevation Range Mask

5 km

Sumatra Runup

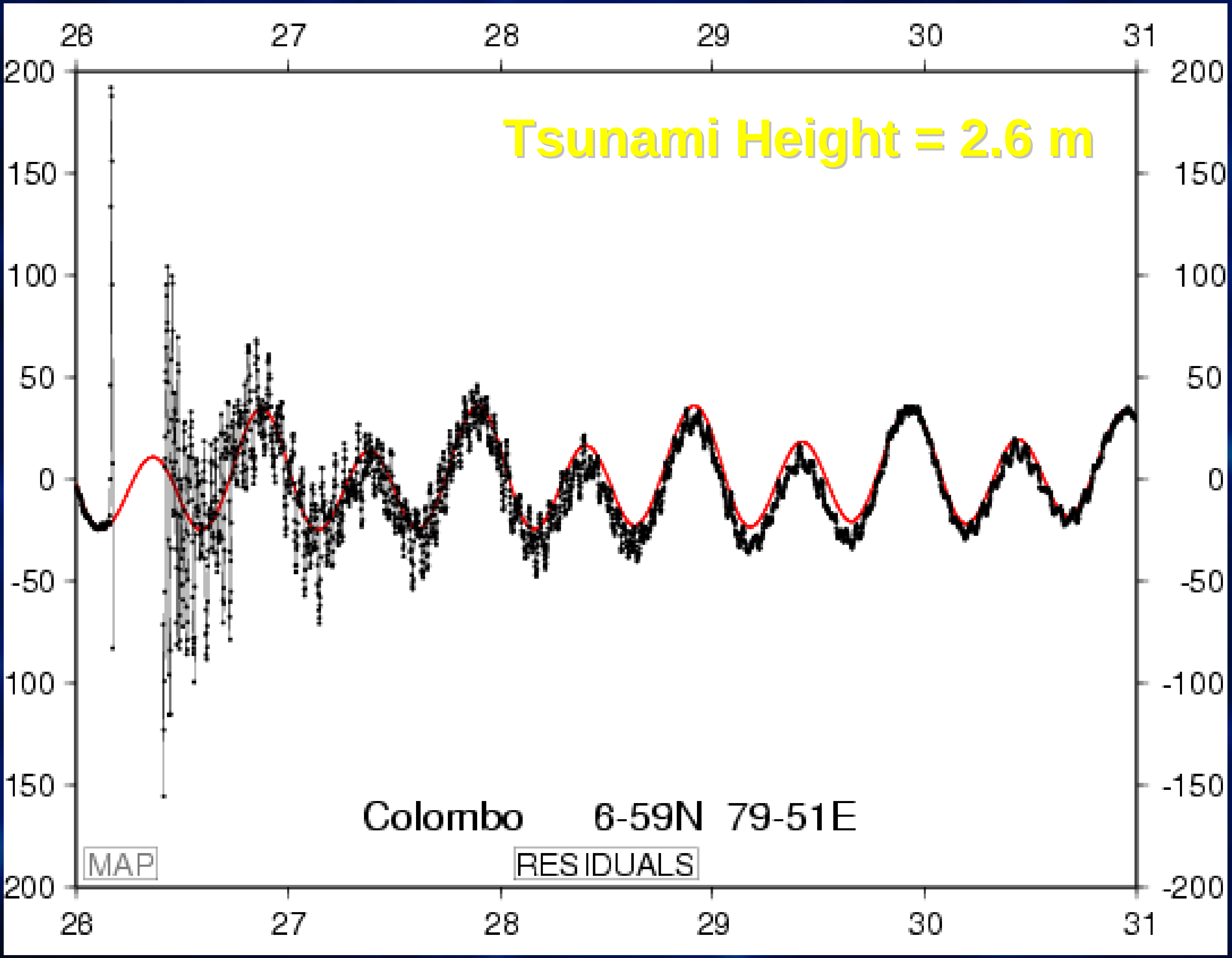


by Philip Liu

Tsunami Impacts On Ports & Harbors

Port of Colombo

- General cargo terminal and 2 container terminals
- 12-15 m draft (Jaya) and 9-11 m draft (SAGT)
- 2 million T.E.U in 2004
- Reinforced concrete deck on piles
- 200 Ha water area, 130 Ha land area



Tsunami Height = 2.6 m
Colombo 6-59N 79-51E
MAP
RESIDUALS
26
27
28
29
30
31
200
150
100
50
0
-50
-100
-150
-200


Day 2 # 5 Port of Colombo
Sri Lanka
No Discernable Damage

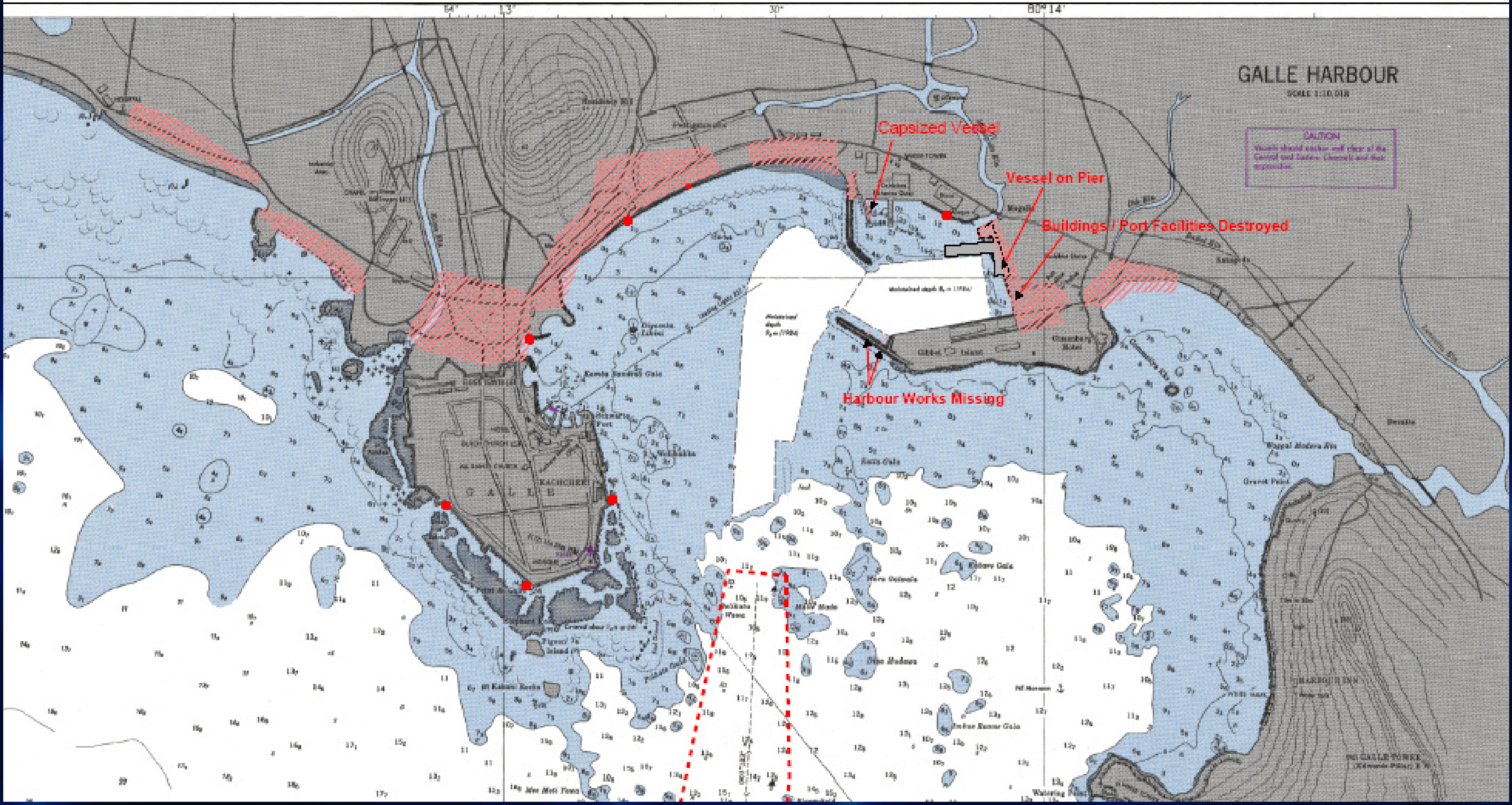
Day 2 # 37 Port of Colombo
Sri Lanka
A Ship Lost Control In This Entrance During the Tsunami

Galle Harbour, Sri Lanka

Tsunami Height= 5.3 m

Tsunami Damaged Areas

● Unknown Obstructions / Wrecked Vessels

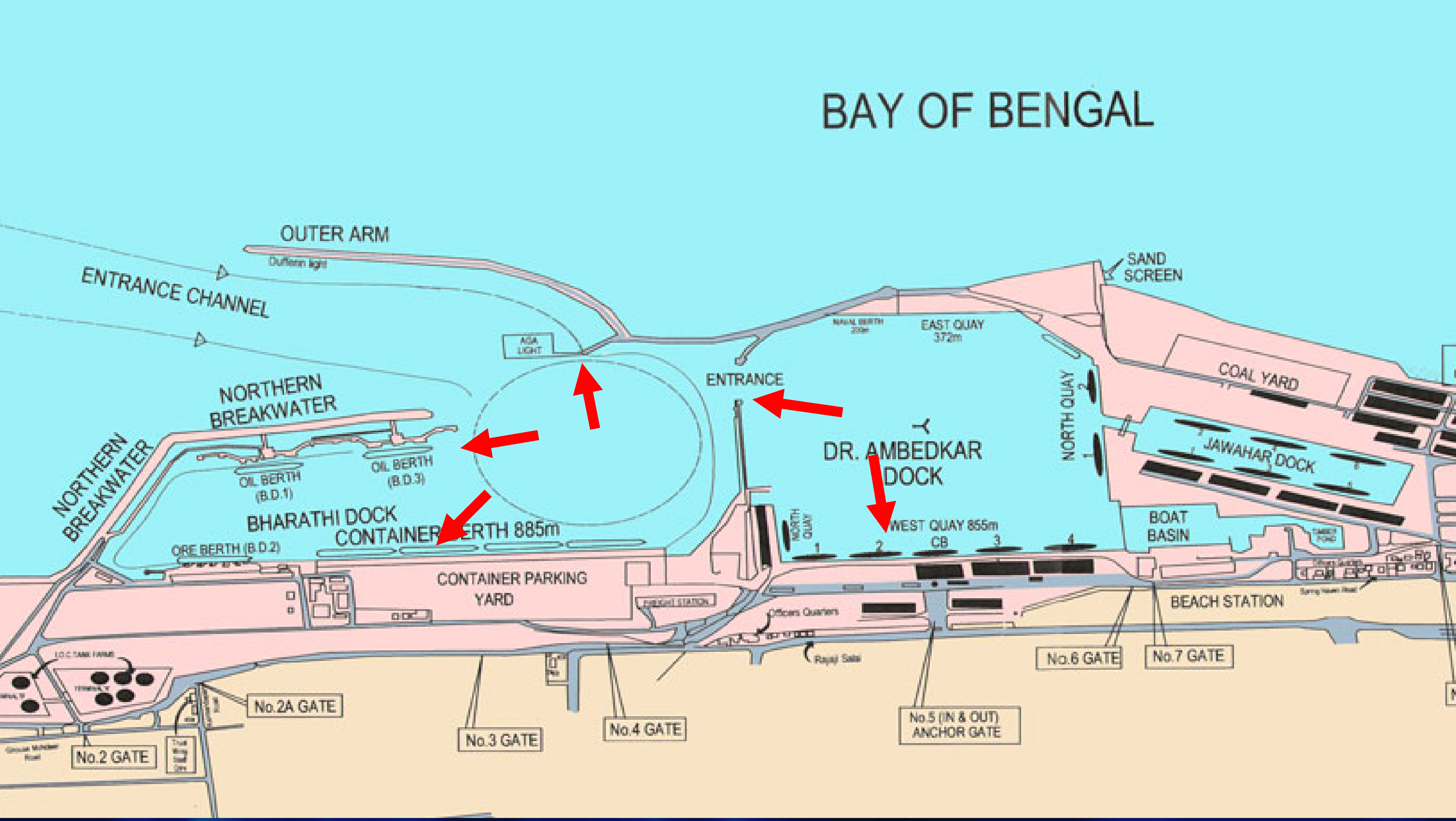



Day 1 #100
Sri Lanka Port of Galle
2m Sedimentation During Tsunami

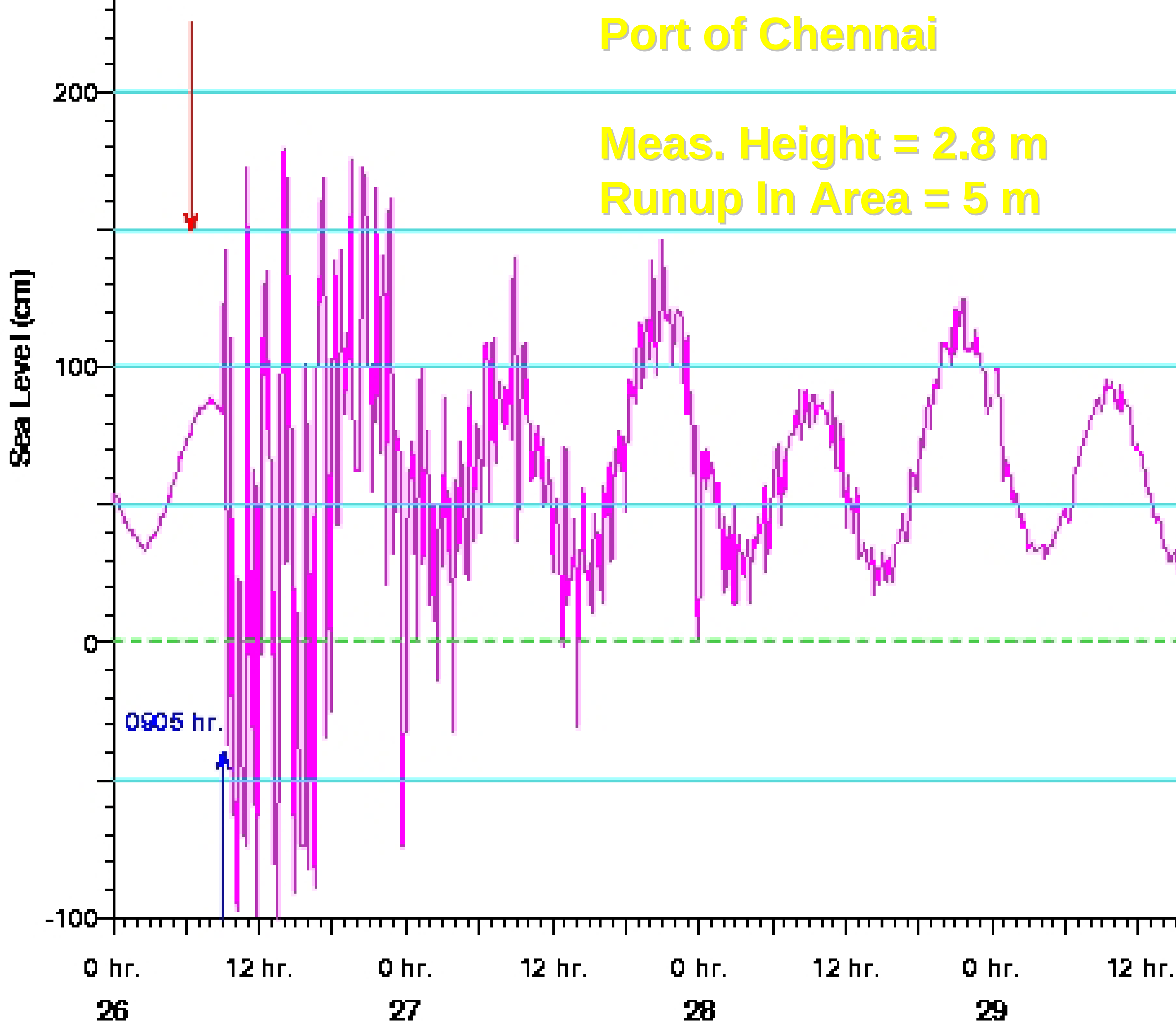

Day 1 #108
Sri Lanka Port of Galle
Warehouse Damage


Day 1 # 115
Sri Lanka Port of Galle
Dredge Grounded On Wharf
Tsunami Height= 5.3 m

Bhutan
Bangladesh
India
Macau
Myanmar (Burma)
Laos
Paracel Islands
Thailand
Bay of Bengal
Cambodia
Vietnam
Sri Lanka
Thailand
Areas Visited
Malaysia
Sumatra
Singapore
Earthquake Epicenter
(3.316 deg, 95.854 deg)
Indonesia
Maldives
British Indian Ocean Territory



Port of Chennai



Port of Chennai
Meas. Height = 2.8 m
Runup In Area = 5 m
Sea Level (cm)
200
100
0
-100
0905 hr.
0 hr.
12 hr.
0 hr.
12 hr.
0 hr.
12 hr.
0 hr.
12 hr.
26
27
28
29

Container Berth- Port of Chennai

Container Berth- Mooring Lines Parted

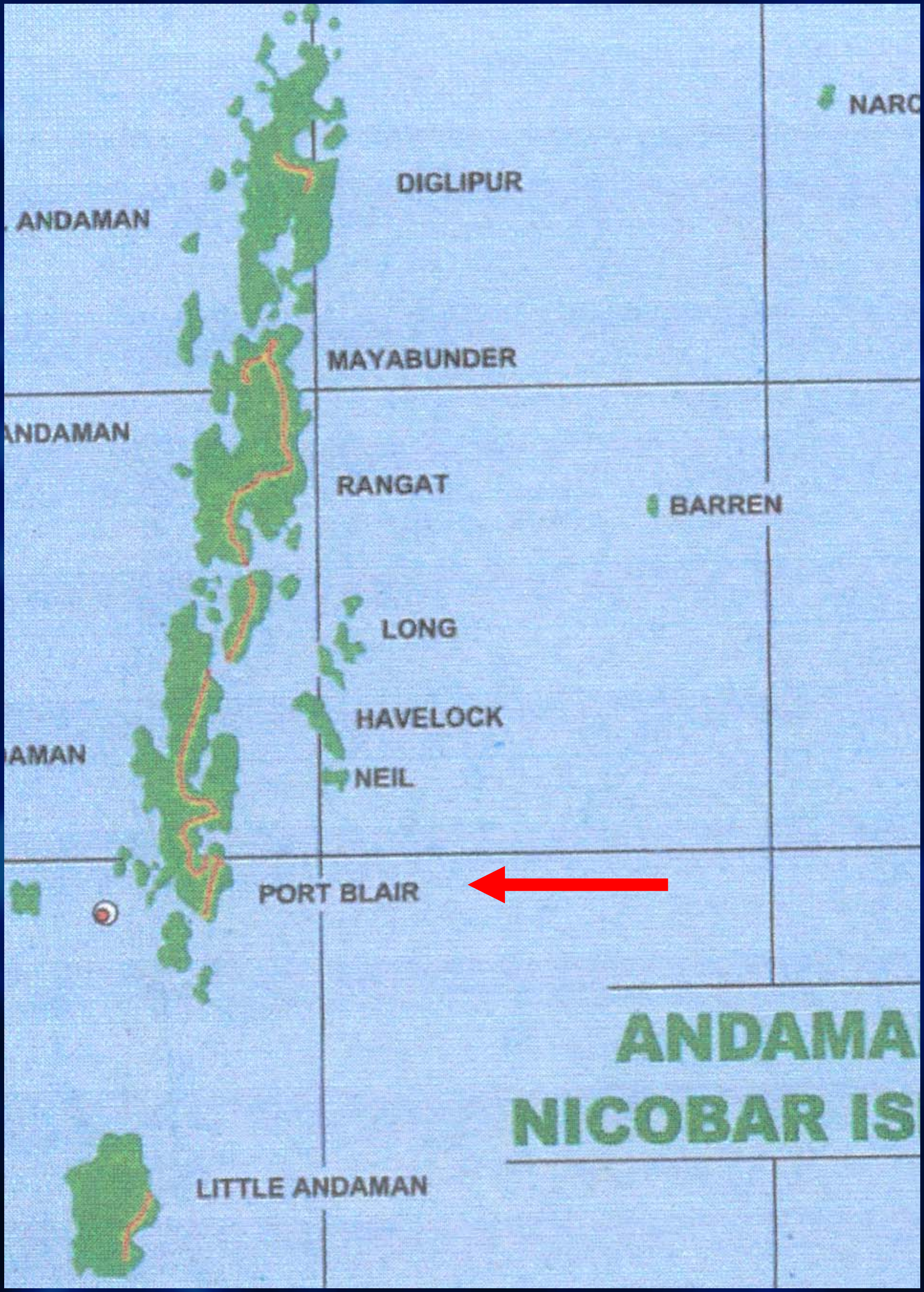
Second Ship Being Drawn Out of Entrance Will Knock Out Mooring Dolphin

Inner Harbor Berth

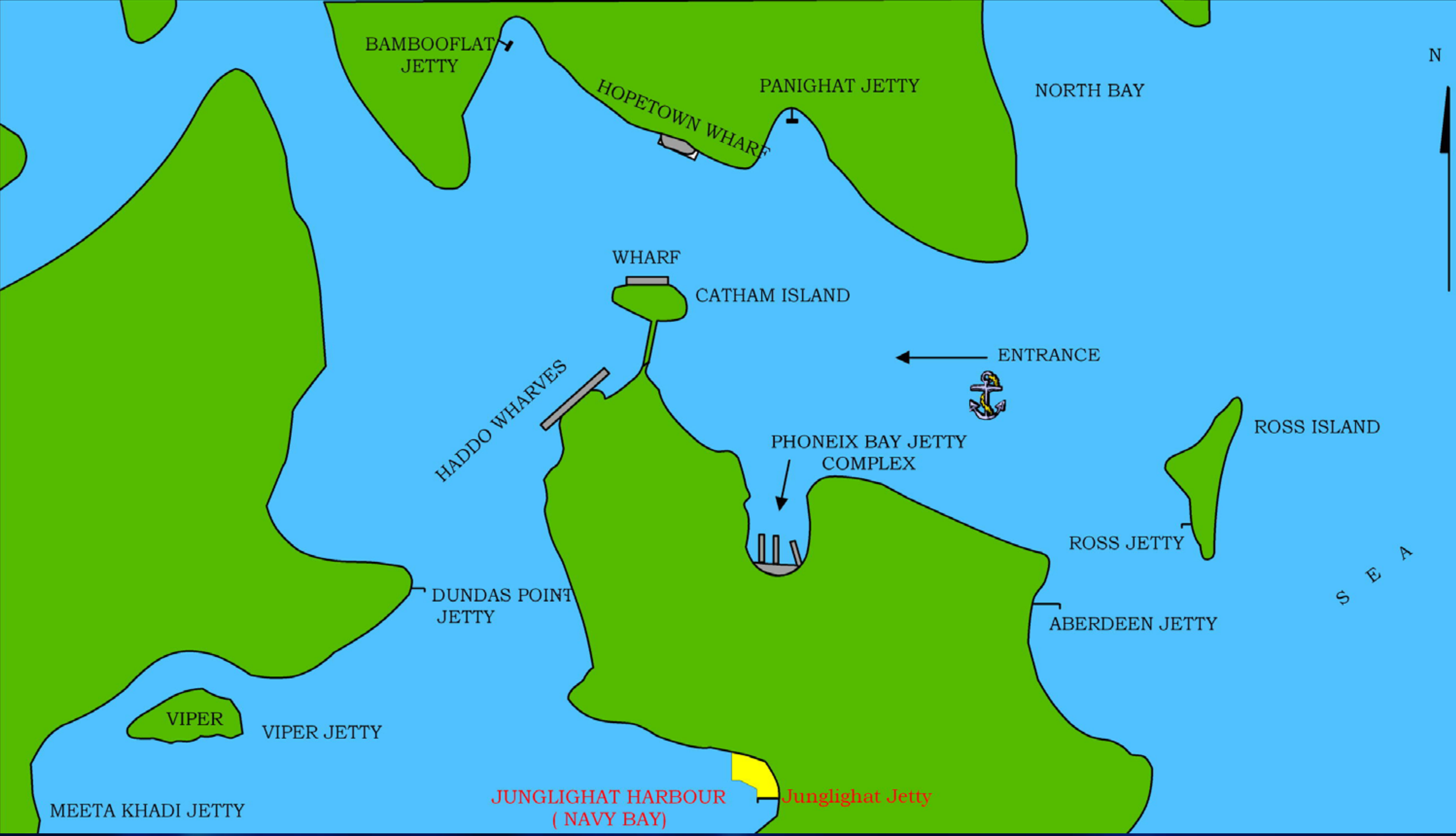
ABG Keshava hitting a Shore Crane

Crew on Board ABG Keshava using the Crane as gang way

Hoppers destroyed by ABG Keshava



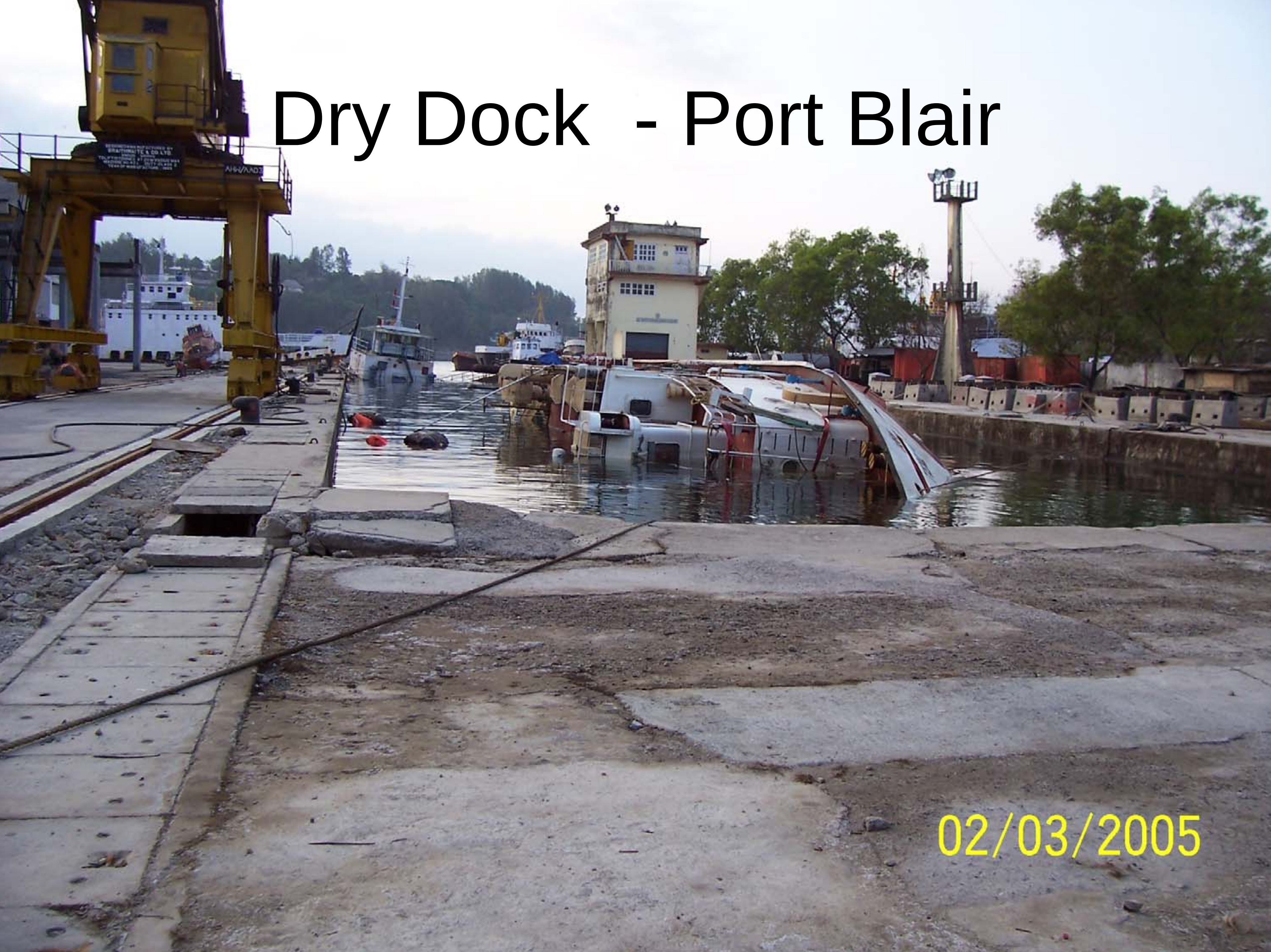
NARC
DIGLIPUR
ANDAMAN
MAYABUNDER
ANDAMAN
RANGAT
BARREN
LONG
HAVELOCK
AMAN
NEIL
PORT BLAIR
ANDAMA
NICOBAR IS
LITTLE ANDAMAN



Port Blair- Tsunami Height of 3m

Flood Damage To Utilities – Container Wharf

Dry Dock - Port Blair



Junglighat Harbor Pier



Pheonix Bay Drydock

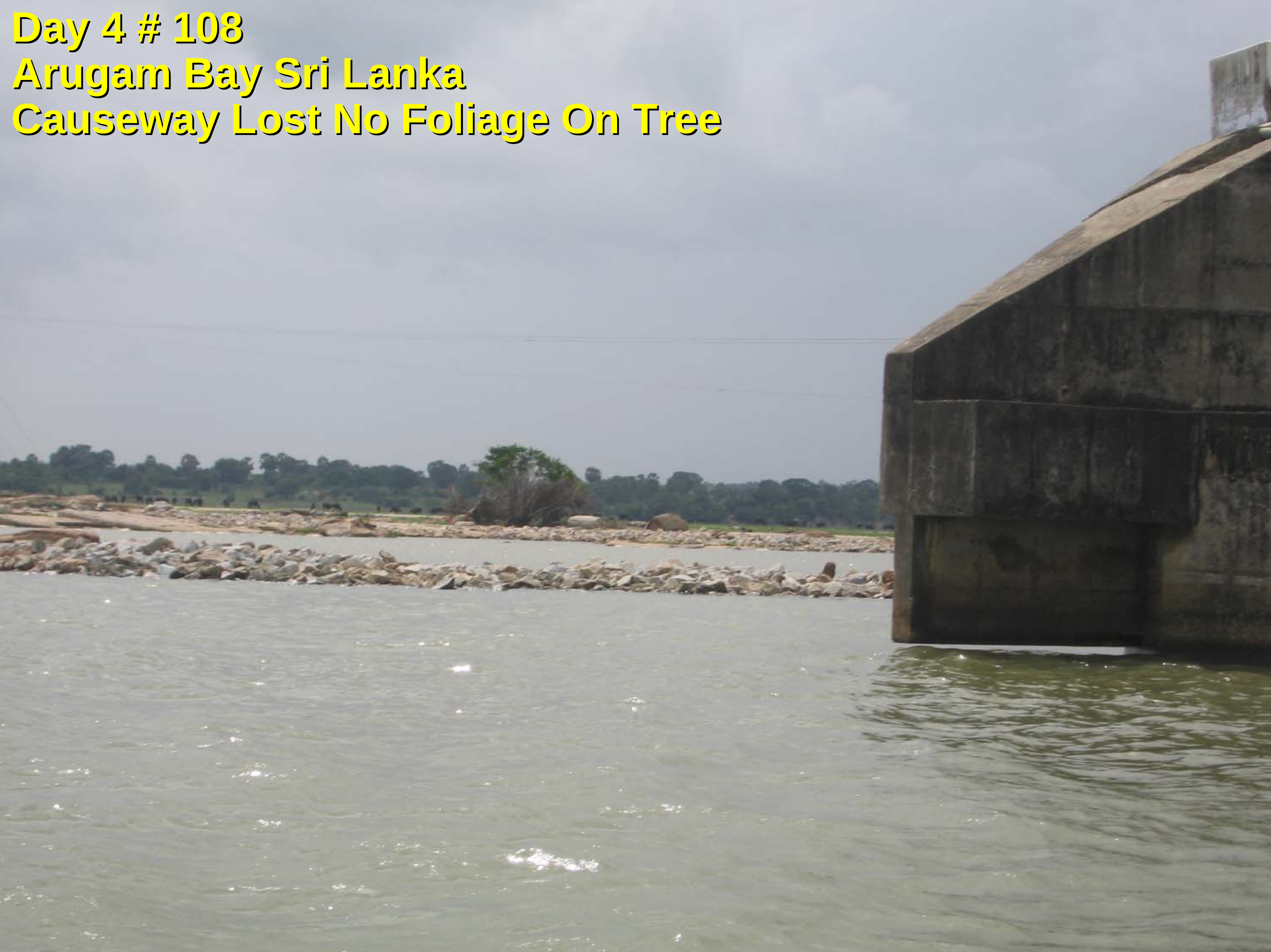
Roads, Bridges & Railroad


Day 1#34
Kosgoda
Sri Lanka


Day 1 #49
Ambalangoda
Sri Lanka
Tsunami Runup= 4.7 m


Day 4 #105
Arugam Bay
Sri Lanka

Day 4 # 108
Arugam Bay Sri Lanka
Causeway Lost No Foliage On Tree



Coastal Structures


Day 3 # 11
Moratuwa
Sri Lanka
Runup= 4.4 m


Day 1 # 102
Galle Seawall
Sri Lanka

Day 3 # 141

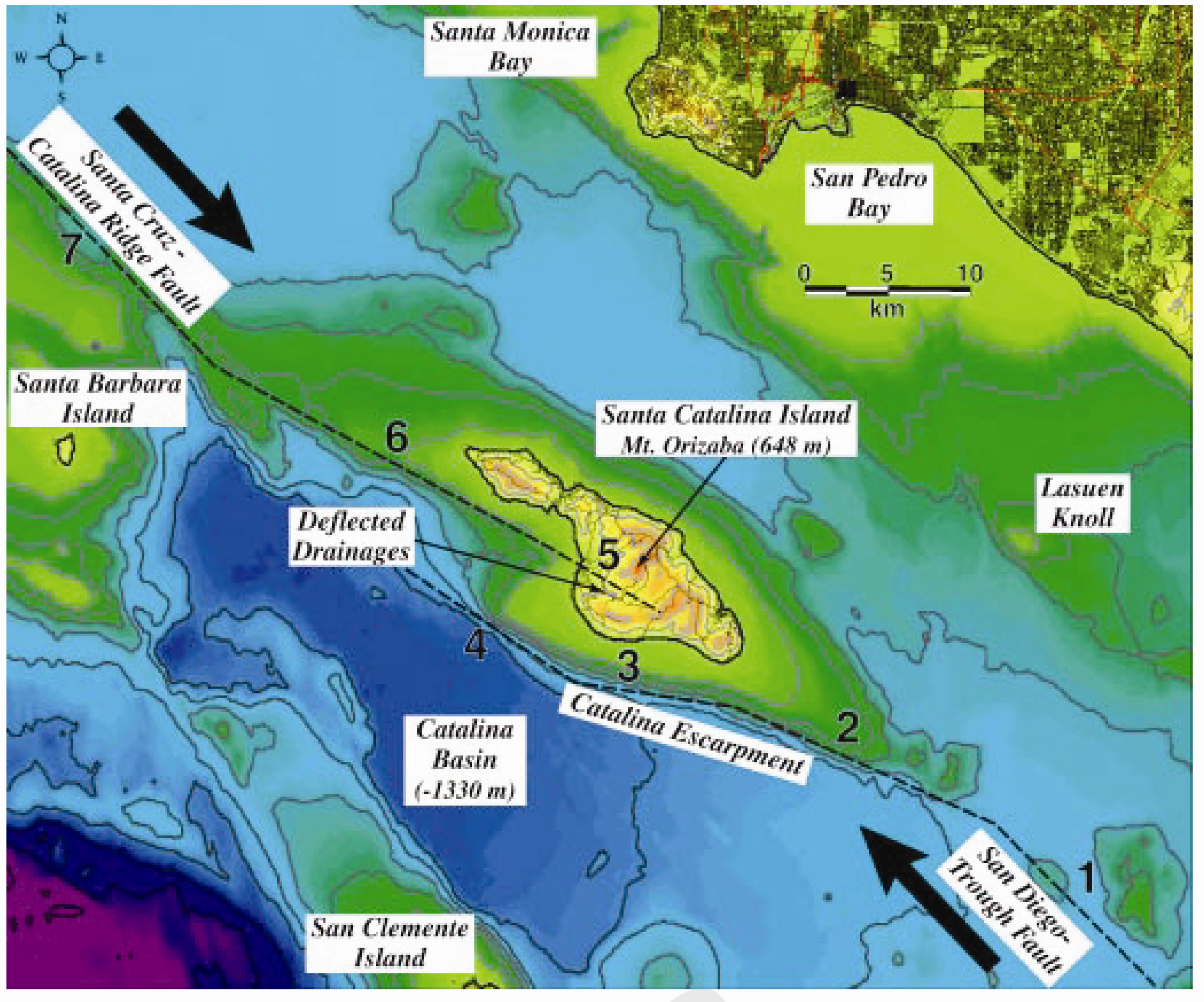
Hikkaduwa Fishing Harbor - Sri Lanka

Backside Breakwater Damage

Tsunami Inundation = 4.73 m

Locally Generated Tsunami propagation Into Ports of Long Beach and Los Angeles

Tsunami Source Locations



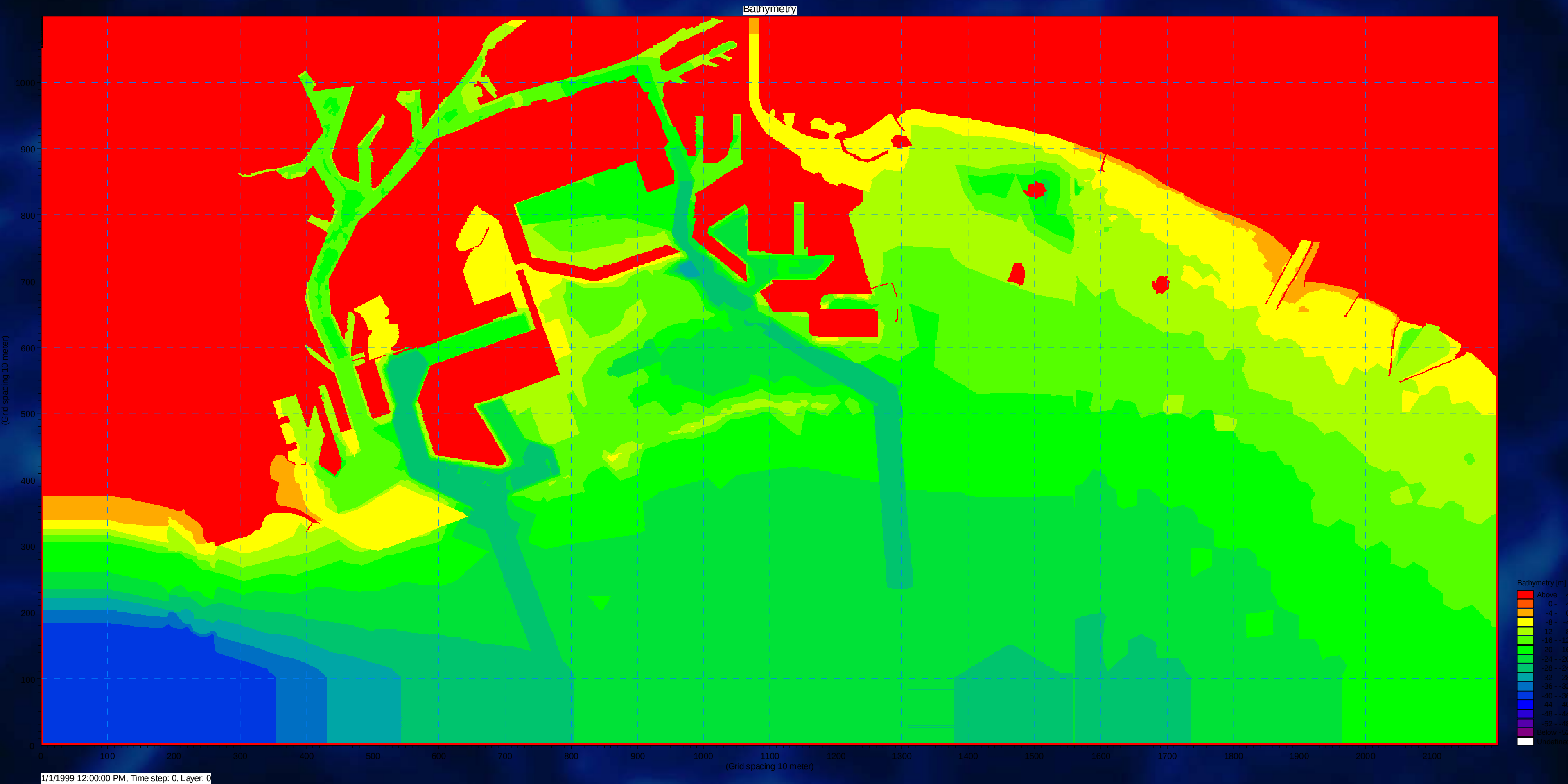
Catalina Source Characteristics

Segments*	Length (km)	Fault Area (km^2)	Max. Slip (m)	Ave. Slip (m)	Magnitude (M_W)	Max. Uplift (m)	Recurrence** (yrs)
1–7	165#	2317	6.4	4.46	7.63	2.17	4,500
1–4	86.5	1225	5.0	4.39	7.44	2.17	4,400
5–7	78.0	1092	6.4	4.54	7.41	1.43	4,500
1–4	86.5	1225	3.6	2.61	7.29	1.30	2,600
2–4	64.6	918.2	3.6	1.50	7.04	0.71	1,500
5–7	78.0	1092	6.4	2.61	7.25	1.39	2,600
5–6	48.3	676.4	2.0	1.92	7.02	0.46	1,900

* See Table 2 for segment parameters; #Includes 25-km overlap of two fault sections.

** Recurrence time (approximate upper bound) assumes 1 mm/yr average slip rate.

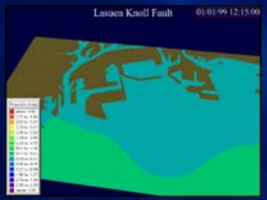
Numerical Model Setup



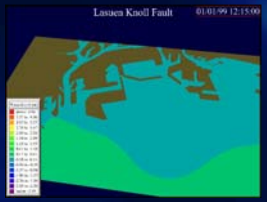
Bathymetry

Animated Results

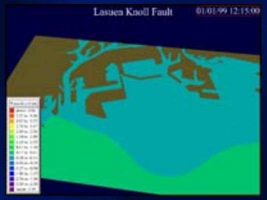
Lasuen Knoll Earthquake

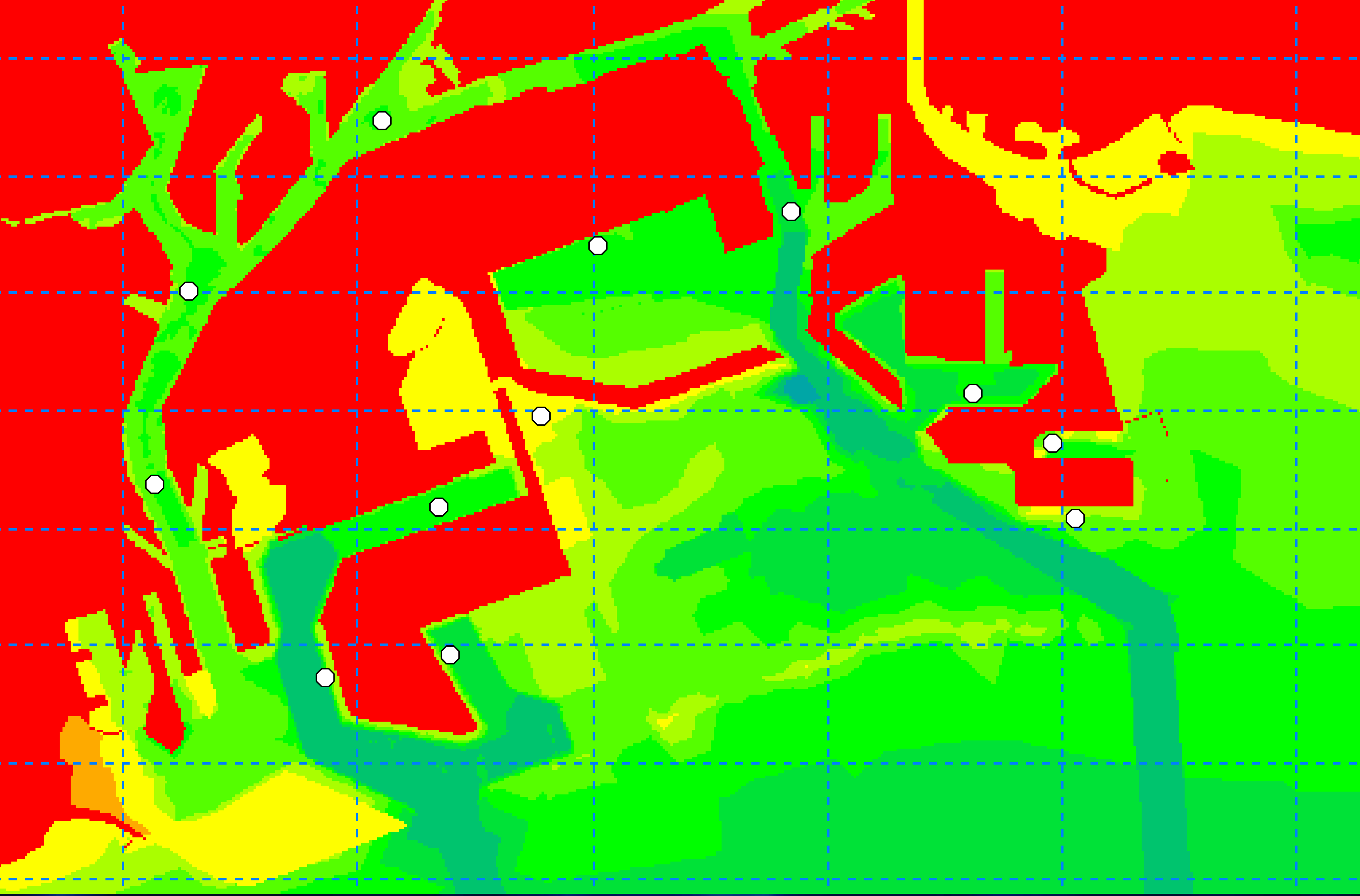


Palos Verdes, No Breakwater

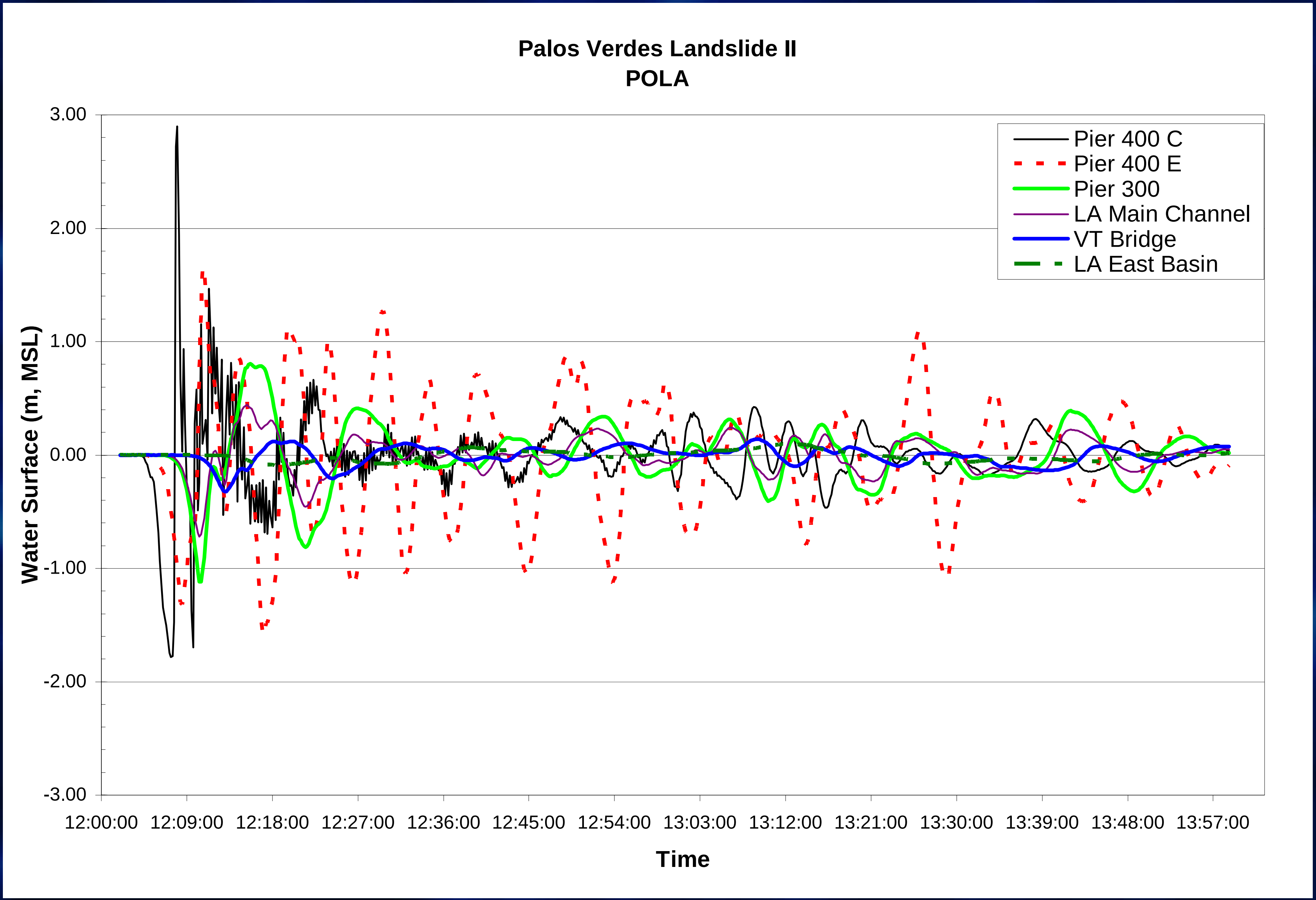


Catalina 7 Segment Earthquake

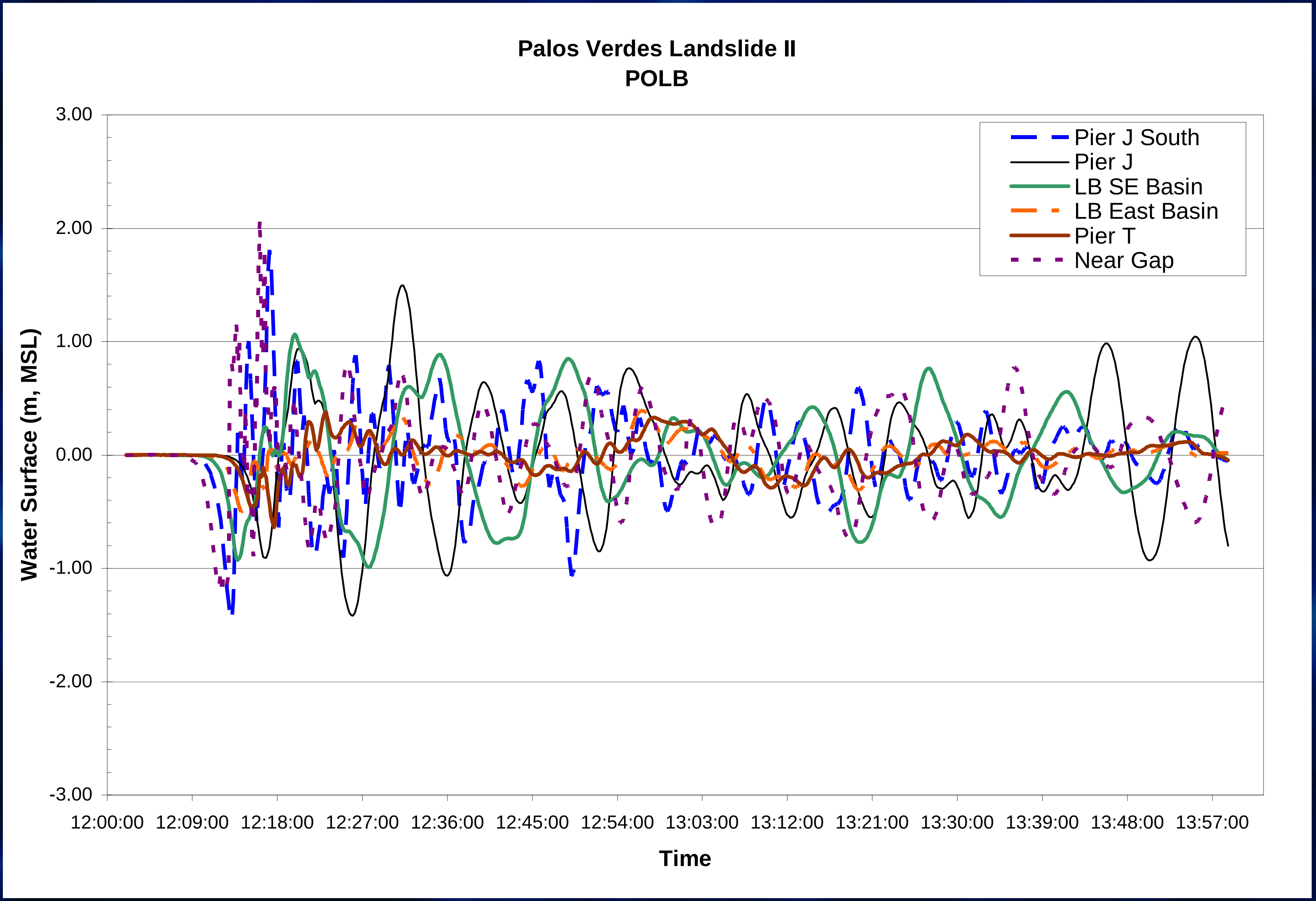




Gage Locations

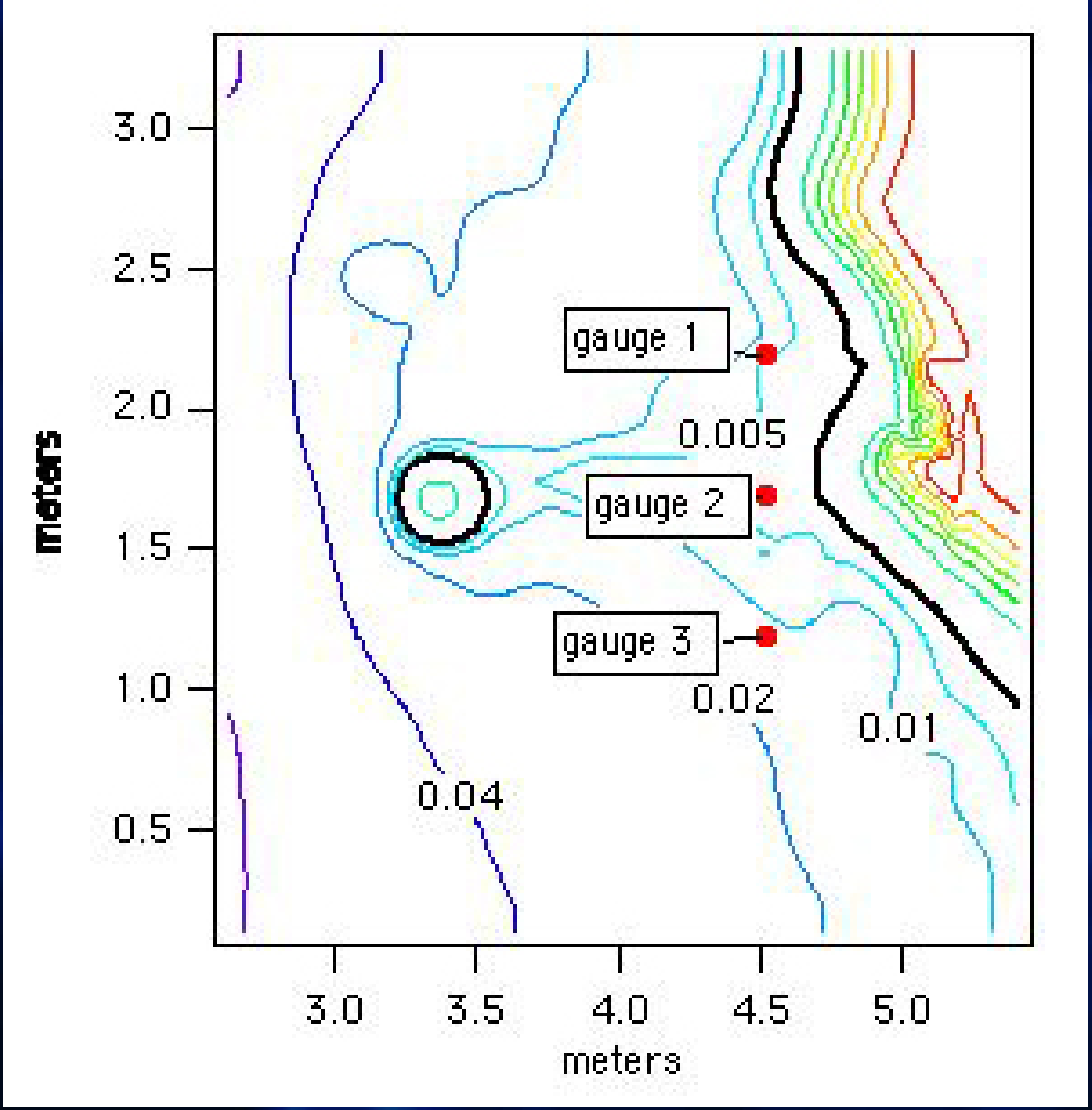


Palos Verdes Landslide II
POLA
Water Surface (m, MSL)
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
12:00:00
12:09:00
12:18:00
12:27:00
12:36:00
12:45:00
12:54:00
13:03:00
13:12:00
13:21:00
13:30:00
13:39:00
13:48:00
13:57:00
Time
Pier 400 C
Pier 400 E
Pier 300
LA Main Channel
VT Bridge
LA East Basin



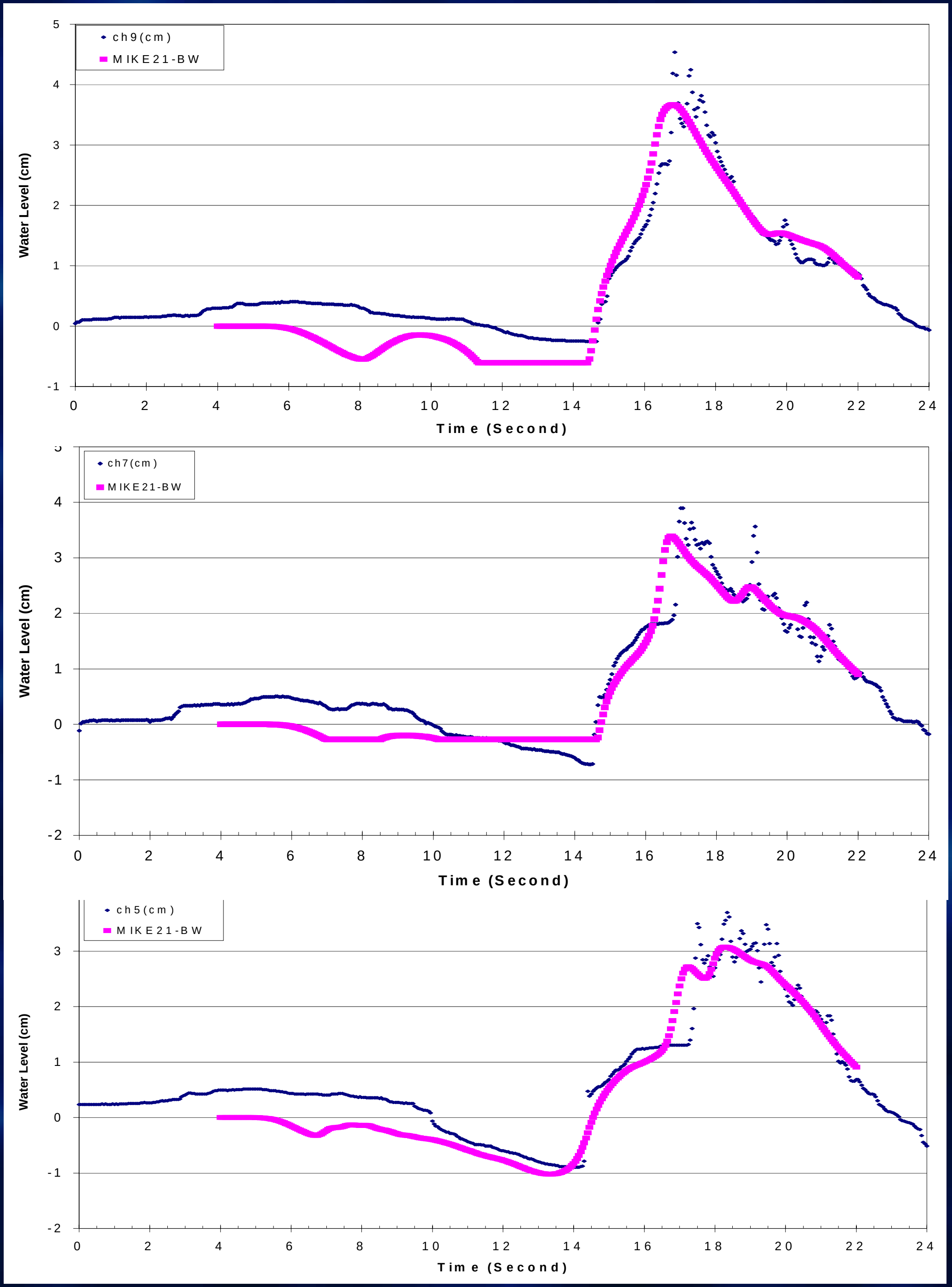
Palos Verdes Landslide II
POLB
Pier J South
Pier J
LB SE Basin
LB East Basin
Pier T
Near Gap
Water Surface (m, MSL)
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
12:00:00
12:09:00
12:18:00
12:27:00
12:36:00
12:45:00
12:54:00
13:03:00
13:12:00
13:21:00
13:30:00
13:39:00
13:48:00
13:57:00
Time

Okushiri Tsunami 1993



Okushiri Tsunami

Comparison between Physical Model Results and Numerical Model Results



CONCLUSIONS-TSUNAMI

- Risks Can Be Quantified and Managed
- Port of Chennai Survived 3-5 m Tsunami, Back In Operation Within Days
- Moorings Vulnerable to Water Level Rise
- Tsunami Currents Important (Scour, Navigation)
- Manageable Risk of Ship Impact Damages
- Properly Built Ports Can Survive
- Utility Systems Vulnerable

Priorities

1. Education
2. Warning System (Communications & Measurements)
3. Inundation Mapping
4. Evacuation Planning
5. Better Zoning/Building Practices

ASCE/COPRI Post Katrina Damage Assessment Trip

Post-Disaster Assessment Teams

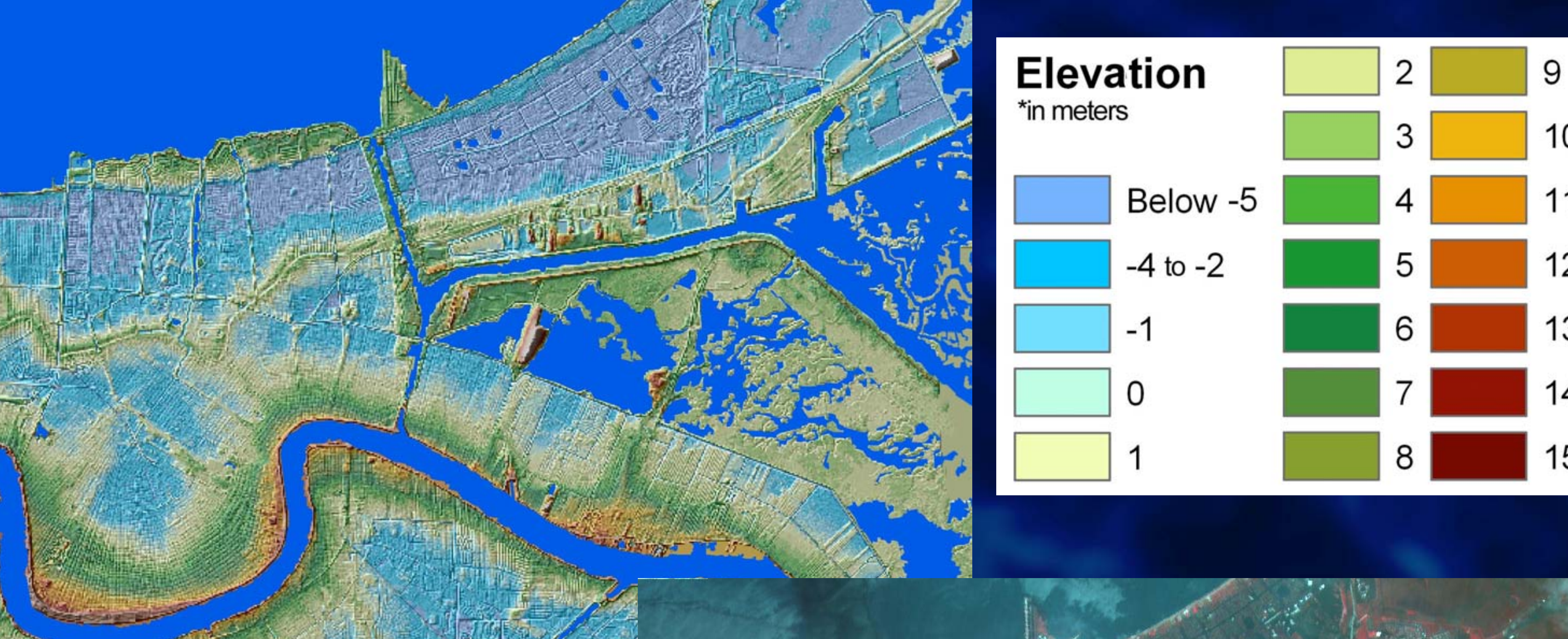
- Overall
  - New Orleans (T. Dalrymple)
  - Mississippi Ports (S. Curtis)
  - Louisiana Ports (N. Pansic)
  - Alabama/Mississippi Shoreline Areas (S. Douglass)

New Orleans Team

- ASCE- COPRI
  - T. Dalrymple, Johns Hopkins University
  - J. Battjes, TU Delft, The Netherlands
  - S. Tanaka, Public Works Research Institute, Japan
  - J. Headland, Moffatt & Nichol

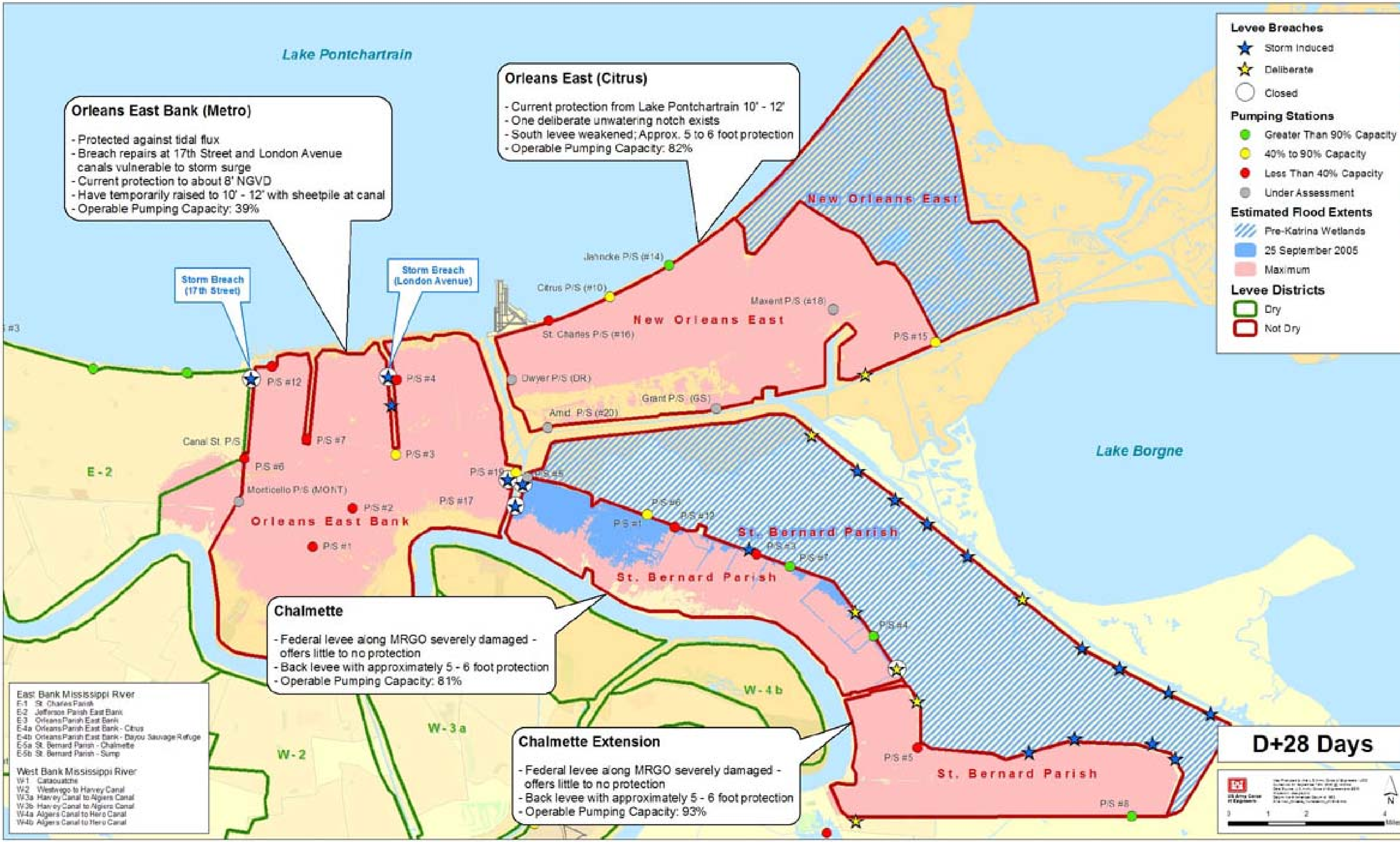
Mission

- Collect perishable data and observations;
- Gain on-site understanding; and
- Pass along observations and lessons.


Elevation
*in meters
Below -5
-4 to -2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

New Orleans Vulnerabilities

Current as of 25 Sep 05 - 1430hrs



ADCIC HINDCAST

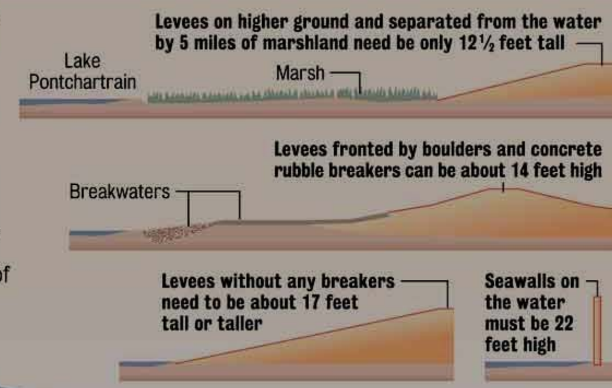
Hassan Mashriqui LSU Contact cemash@lsu.edu

BARRIERS OF EARTH AND CONCRETE

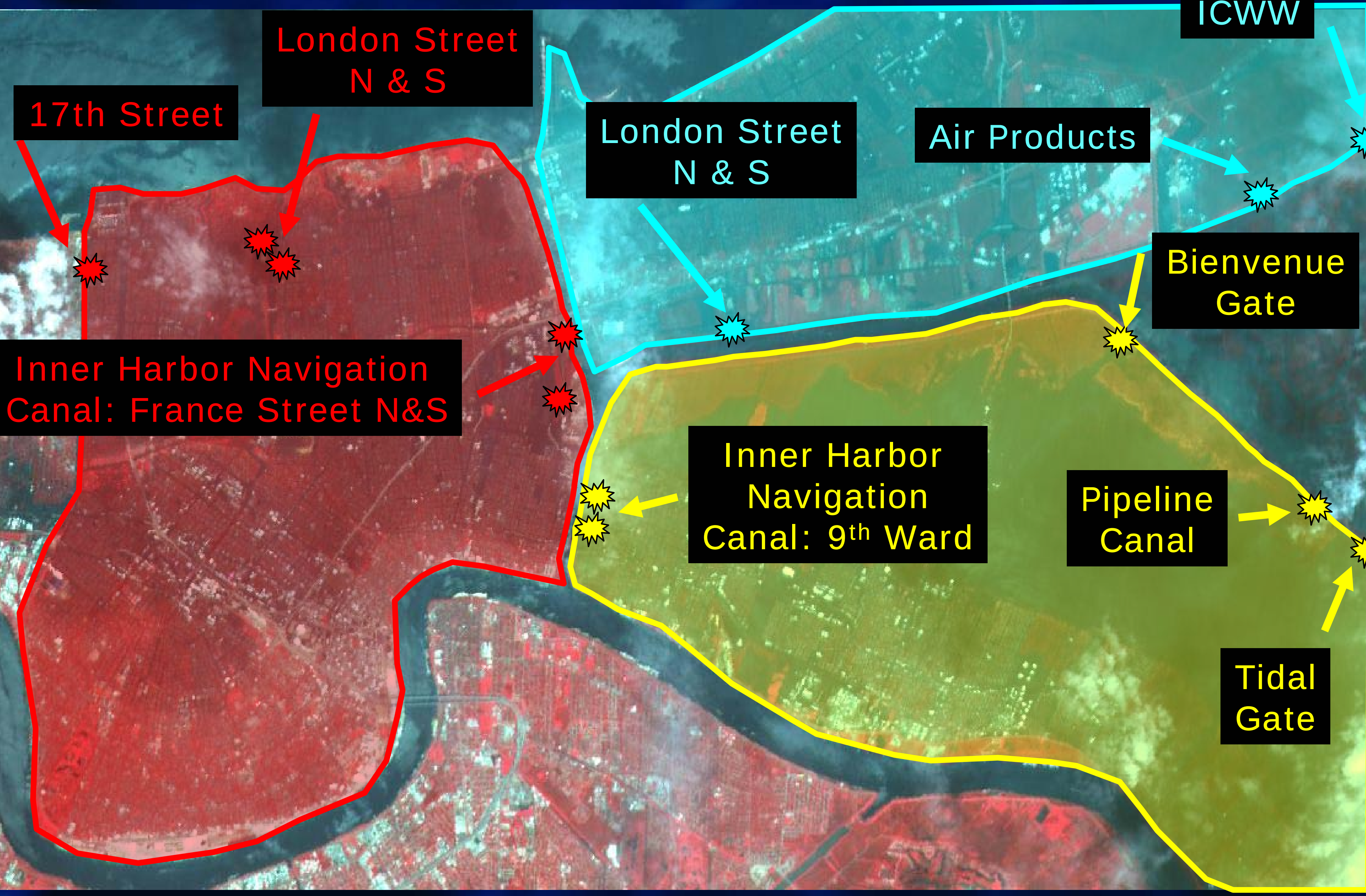
Levees and floodwalls that protect against flooding from both the Mississippi River and hurricanes are built by the Army Corps of Engineers and are maintained by local levee districts. The corps and the local districts share the construction cost of hurricane levees, while the Mississippi River levees are a federal project. Local levee districts also build and maintain nonfederal, lower-elevation levees with construction money from each district's share of property taxes and state financing.

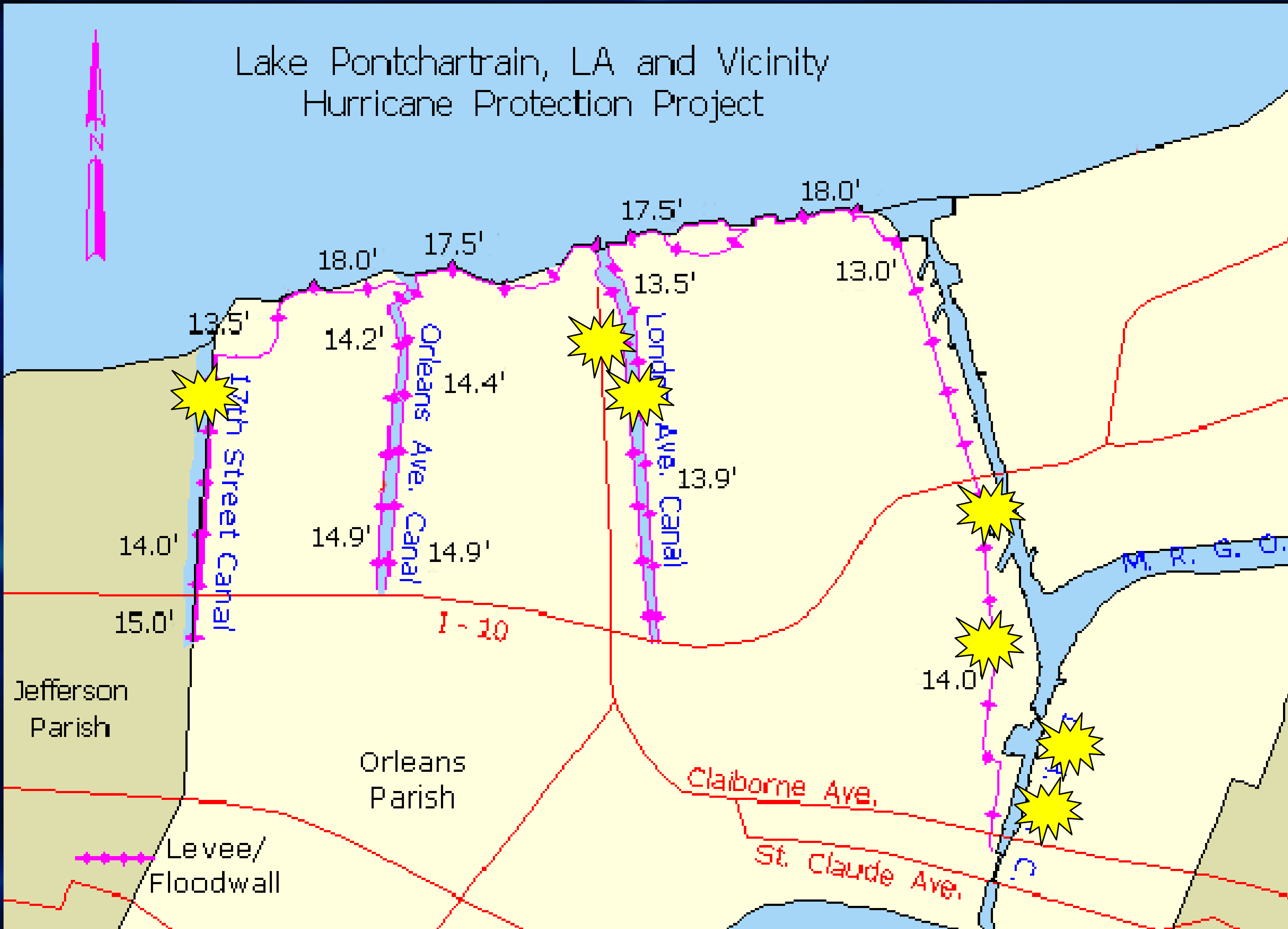
HEIGHT ISN'T EVERYTHING

Different factors permit Lake Pontchartrain levees of varying elevations to withstand an 11½-foot storm surge plus several feet of waves:



Note: The height and shape of a levee is based on the roughness of the area over which waves pass to reach the structure, and the slope of the structure.

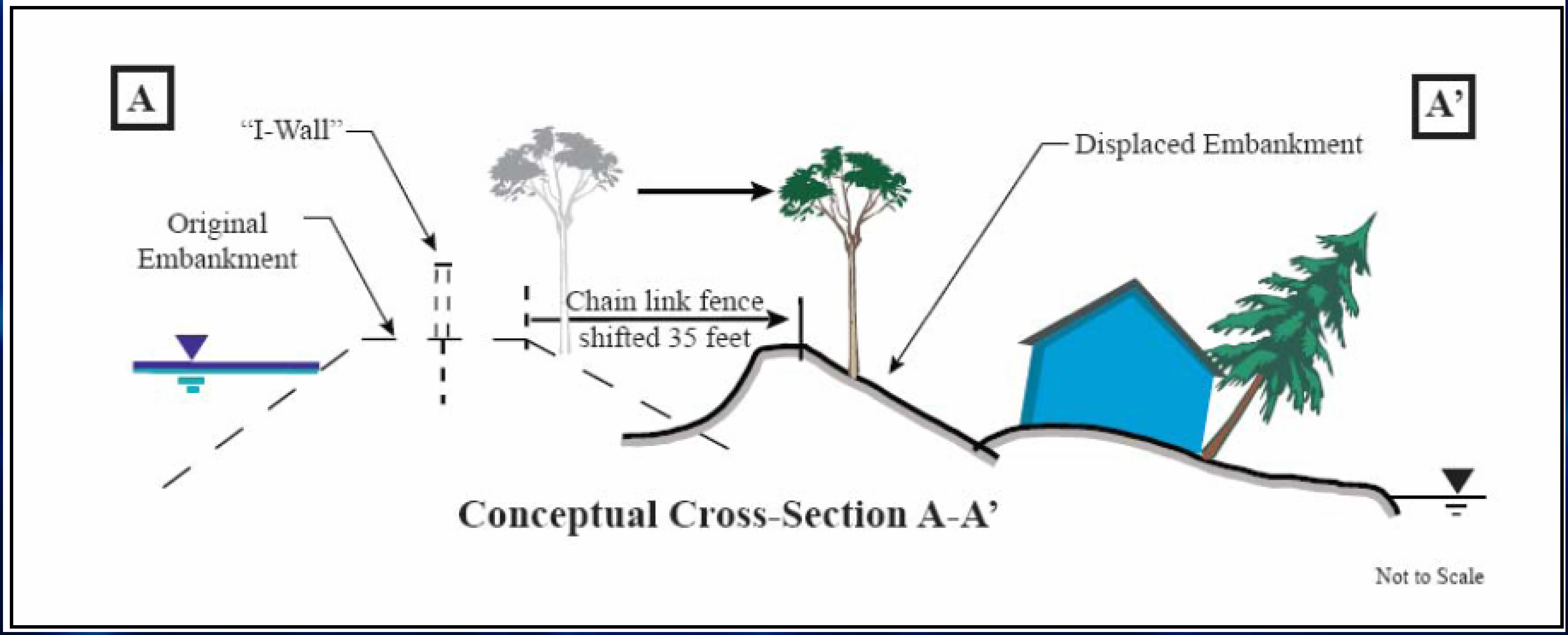

London Street N & S
17th Street
London Street N & S
Air Products
ICWW
Bienvenue Gate
Inner Harbor Navigation Canal: France Street N&S
Inner Harbor Navigation Canal: 9th Ward
Pipeline Canal
Tidal Gate



updated Sept 9, 2005

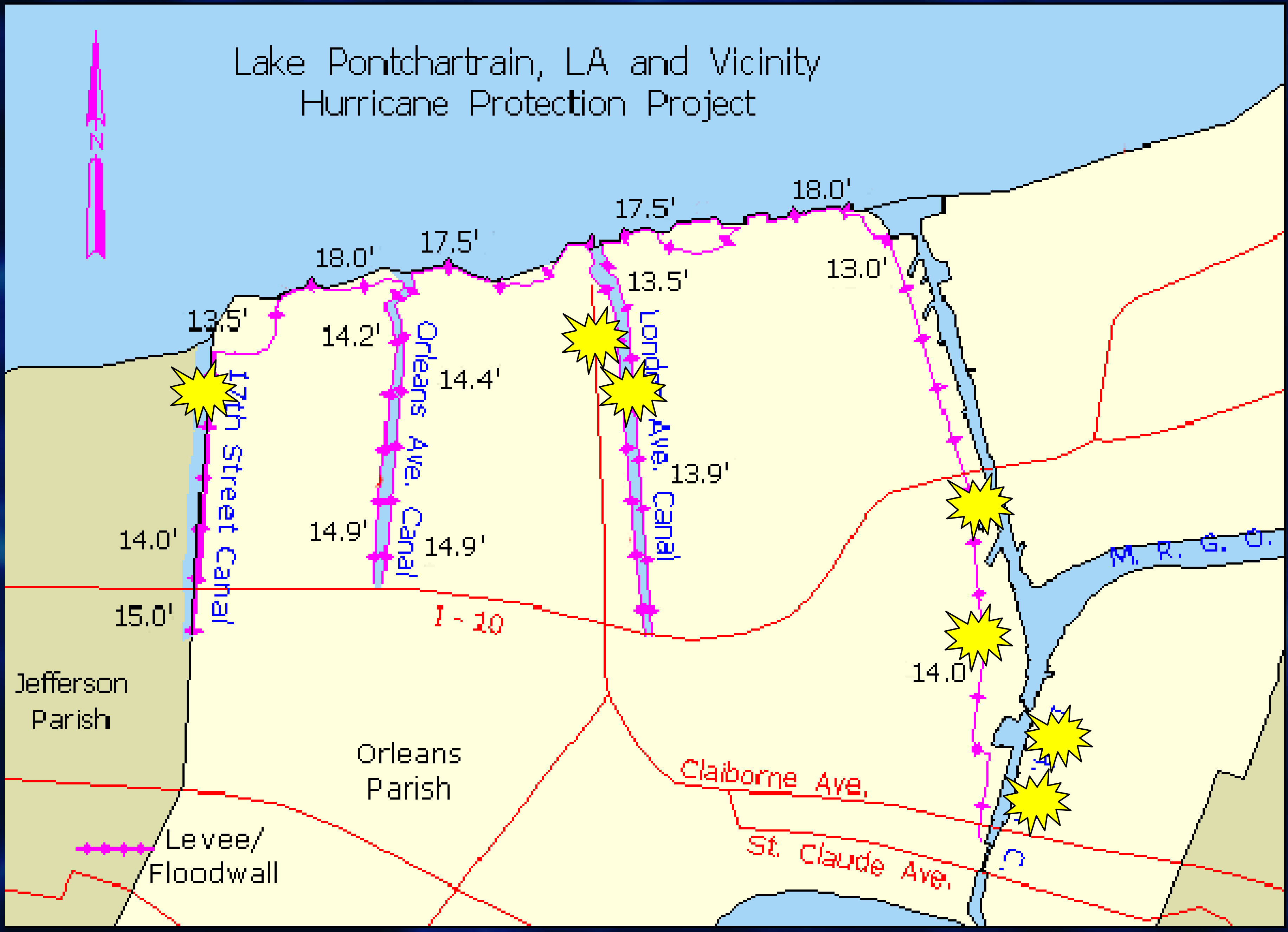
17^{th} Street Canal

17th Street Canal



17th Street Canal

17th Street Canal

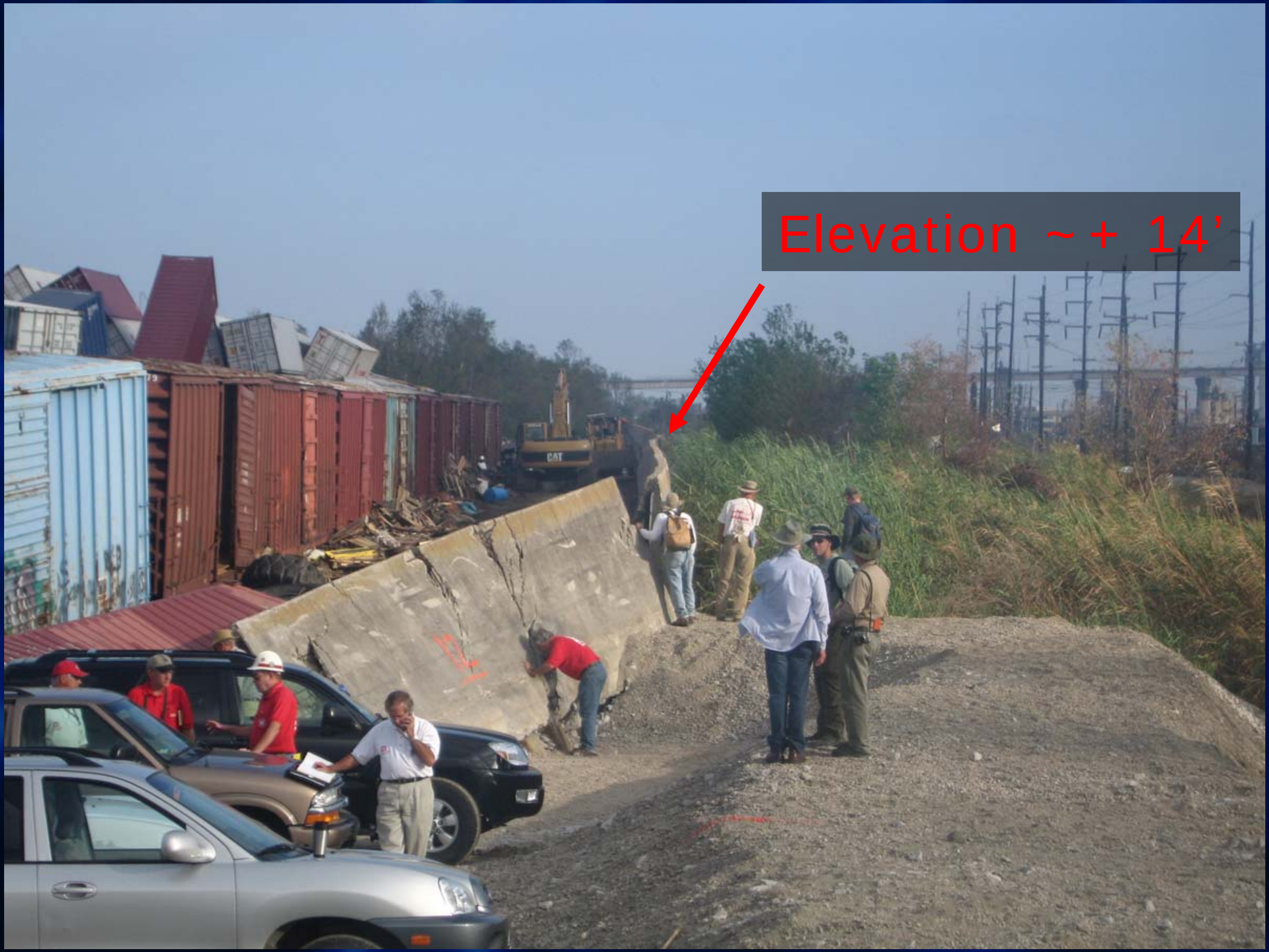


Lake Pontchartrain, LA and Vicinity
Hurricane Protection Project
N
18.0'
17.5'
17.5'
18.0'
13.5'
13.0'
13.5'
14.2'
14.4'
13.9'
14.0'
14.9'
14.9'
15.0'
14.0'
17th Street Canal
Orleans Ave. Canal
London Ave. Canal
M. R. G. O.
I - 10
Claiborne Ave.
St. Claude Ave.
Jefferson Parish
Orleans Parish
Levee/
Floodwall
updated Sept 9, 2005

Port of New Orleans

...and crane damage at the APM Container Terminal.

Inner Harbor Navigation Canal: France Street South



Inner Harbor Navigation Canal: France Street South

Inner Harbor Navigation Canal: France Street South

Inner Harbor Navigation Canal: France Street South

Inner Harbor Navigation Canal: France Street South

Inner Harbor Navigation Canal: France Street South

Inner Harbor Navigation Canal: France Street South


MAERSK
MAERSK
SEALAND
MAERSK
SEALAND
MAERSK
SEALAND


107
107
MAERSK LINE
45

New Orleans Industrial Canal

Hurricane Wave Forces On Piers and Bridges


Huntington Beach Pier, California
(1988 Storm)

Catalina Island Ferry Terminal, 1960's
Hs= 10 feet, Tp = 7 sec, Still Intact

White Beach Pier- Still Intact

Paulus Hook Ferry Terminal, Jersey City, NJ

US 90 Bay St Louis-Pass Christian

US 90 Ocean Springs-Biloxi (West View)

I-10 Bridge, Lousianna

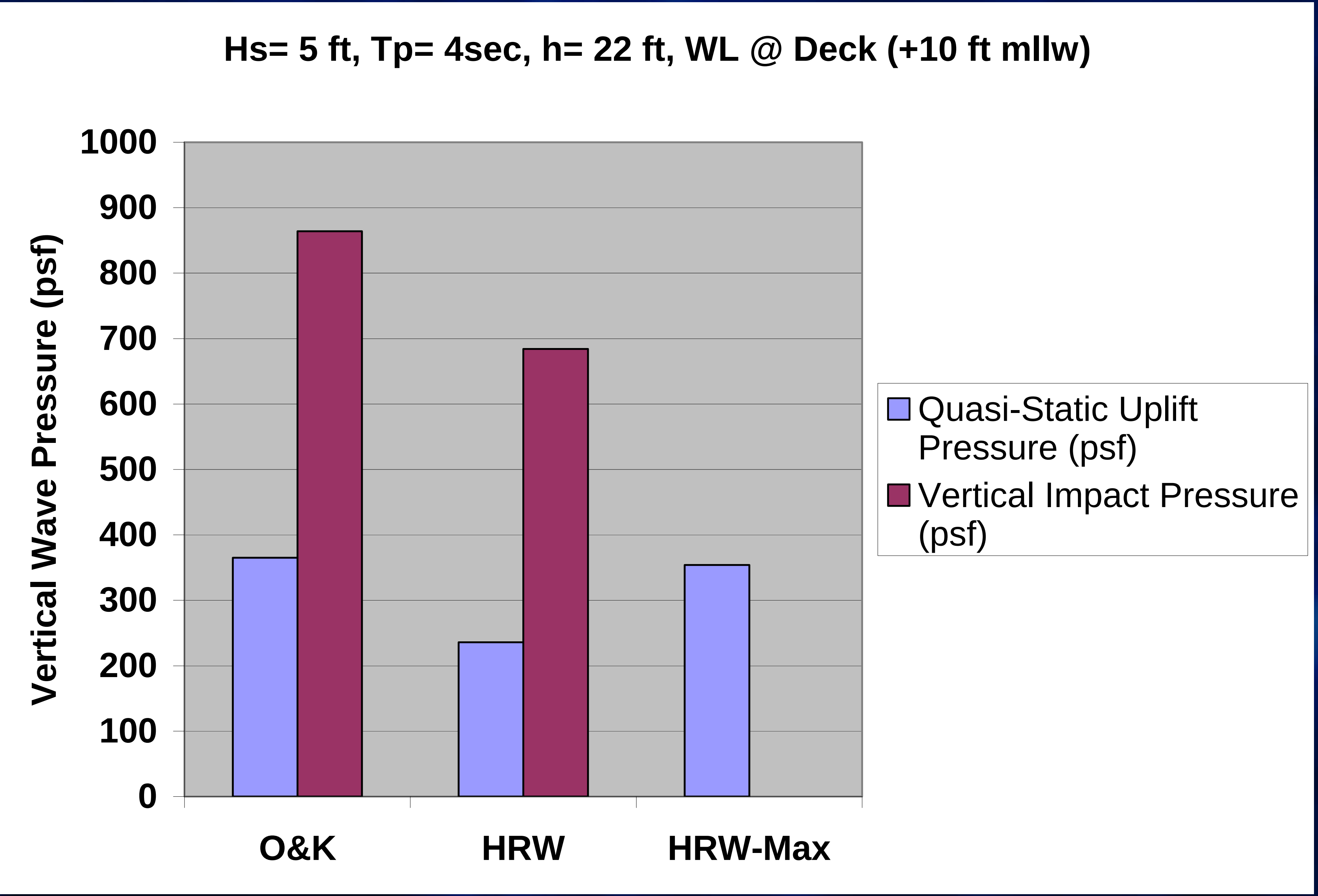
I-10 Bridge, Lousianna

Design Conditions

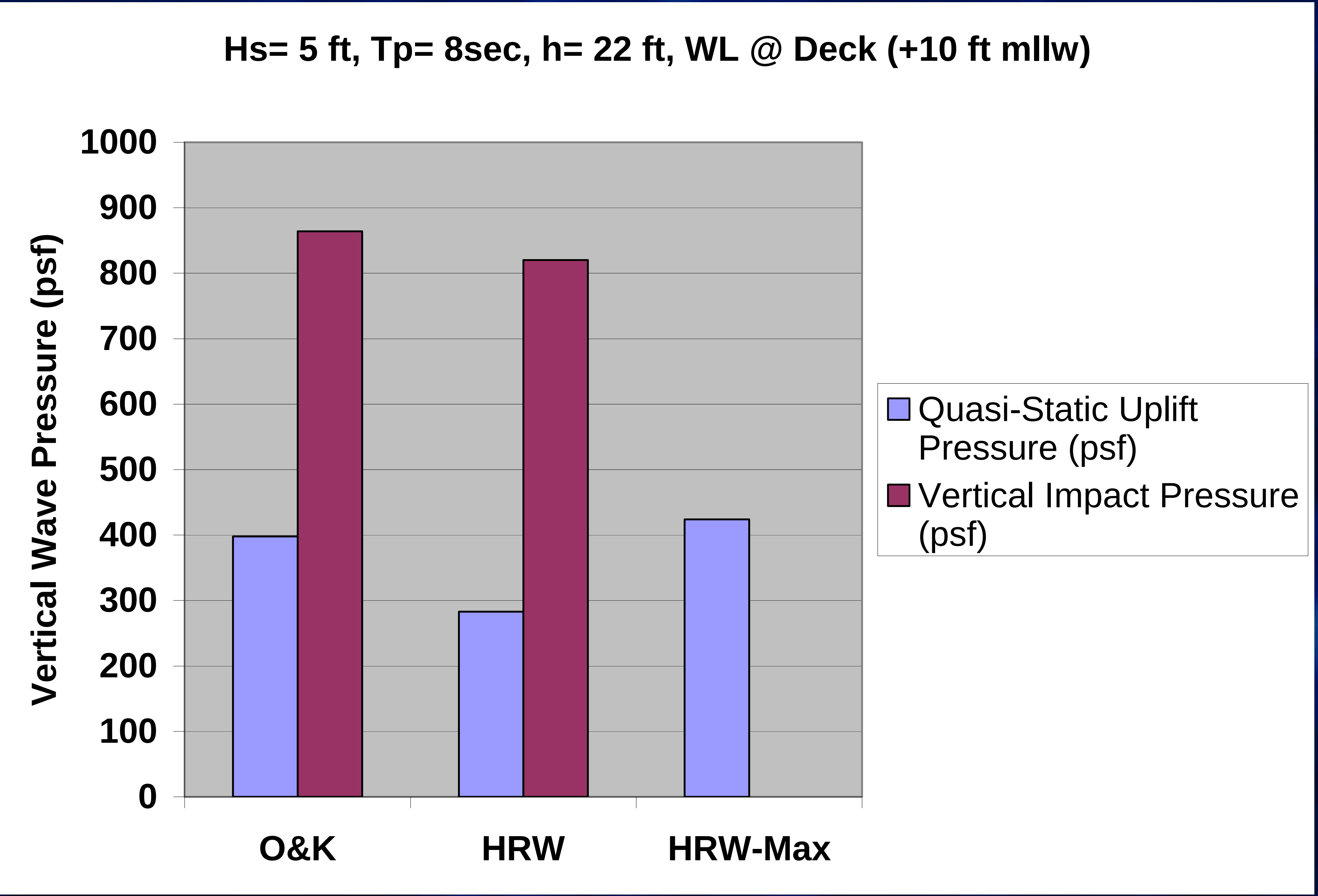
- All Variables For A Range of Return Periods
  - Tide Levels
  - Storm Surge Levels
  - Wave Conditions
    - Wave Height, Period, Duration By Direction
    - Hmax is Typically Used For Design
  - Tidal/Hurricane Induced Currents
  - Bathymetry (including short and long-term scour effects
- Basis For Selecting Design Frequency
  - Safety (Prevent Loss of Life)
  - Economics (How Often Can You Afford To Repair/Replace)

Vertical (Uplift) Loads

- Slowly Varying (Quasi-static) And Peak Impulse Wave Loads on Decks and Beams
  - Model Tests
  - El Ghamry (1965)
  - Wang (1970)
  - French (1971)
  - Overbeek and Klabbers (2001)
  - HRW, McConnell et al (2005)



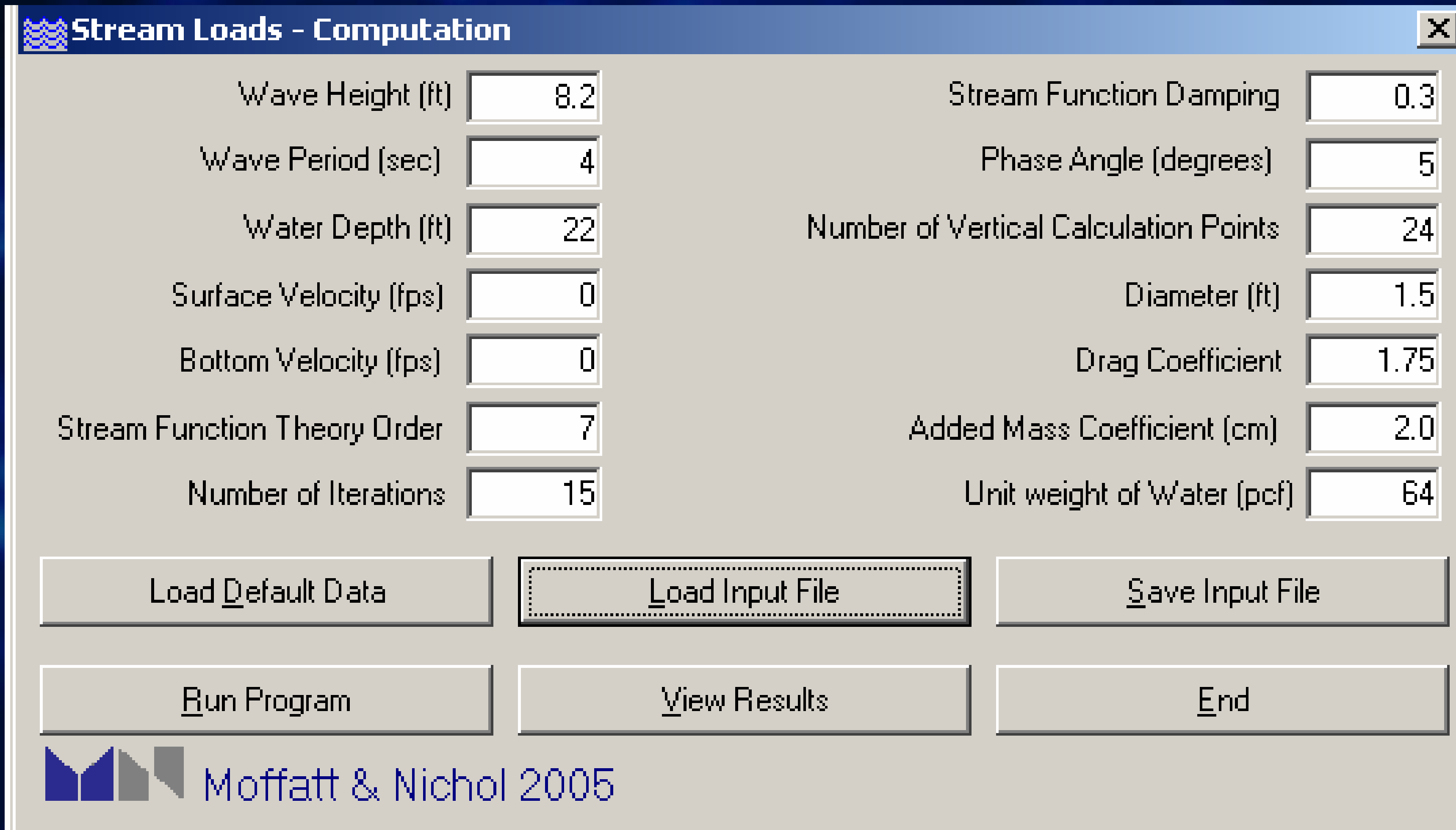
Hs= 5 ft, Tp= 4sec, h= 22 ft, WL @ Deck (+10 ft mllw)
Vertical Wave Pressure (psf)
1000
900
800
700
600
500
400
300
200
100
0
O&K
HRW
HRW-Max
Quasi-Static Uplift Pressure (psf)
Vertical Impact Pressure (psf)


Hs= 5 ft, Tp= 8sec, h= 22 ft, WL @ Deck (+10 ft mllw)
Vertical Wave Pressure (psf)
1000
900
800
700
600
500
400
300
200
100
0
O&K
HRW
HRW-Max
Quasi-Static Uplift Pressure (psf)
Vertical Impact Pressure (psf)

Lateral Loads

- Wave Loads On Slender Members (e.g., piles, beams)
  - Loads Dominated by Flow Separation (drag)
  - Stream Function or Fenton Wave Theories
  - Morrison Equation (u, du/dt with depth for lateral loads)

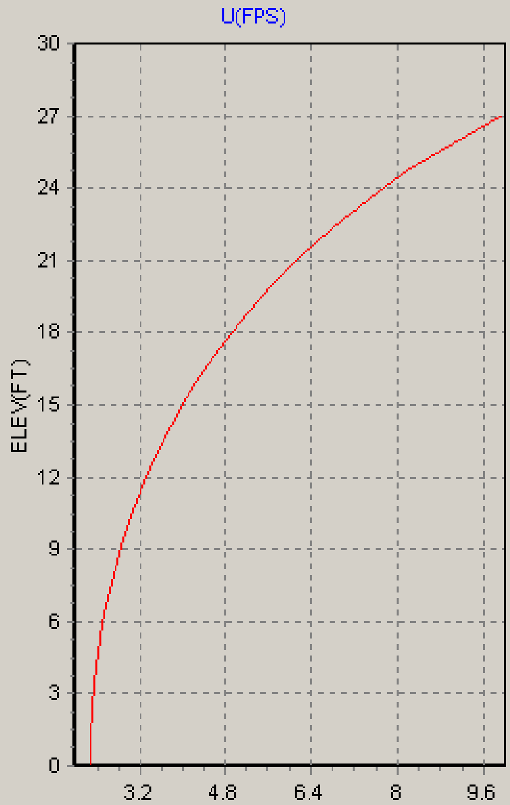
- Wave Loads On Plates and “Large” Structures
  - Loads Dominated by Wave Pressure
  - Minikin, Miche-Rundgren
  - Goda Wave Pressure Equations
  - McConnell et al (2005)
- Current Loads On Submerged Bridge Superstructure


Stream Loads - Computation
Wave Height (ft) 8.2
Wave Period (sec) 4
Water Depth (ft) 22
Surface Velocity (fps) 0
Bottom Velocity (fps) 0
Stream Function Theory Order 7
Number of Iterations 15
Stream Function Damping 0.3
Phase Angle (degrees) 5
Number of Vertical Calculation Points 24
Diameter (ft) 1.5
Drag Coefficient 1.75
Added Mass Coefficient (cm) 2.0
Unit weight of Water (pcf) 64
Load Default Data
Load Input File
Save Input File
Run Program
View Results
End
Moffatt & Nichol 2005

Phase

0.00
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
45.00
50.00
55.00
60.00
65.00
70.00
75.00
80.00
85.00
90.00
95.00
100.00
105.00
110.00
115.00
120.00
125.00
130.00
135.00
140.00

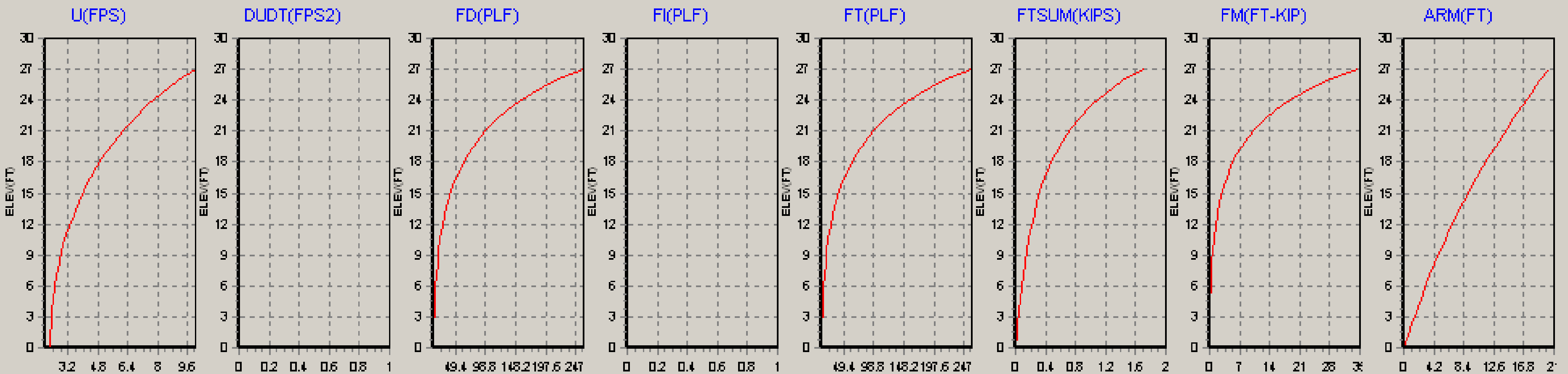
ELEV(FT)	U(FPS)	DUDT(FPS2)	FD(PLF)	FI(PLF)	FT(PLF)	FTSUM(KIPS)	FM(FT-KIP)	ARM(FT)
0.00	2.27	0.00	13.50	0.00	13.50	0.00	0.00	0.00
1.18	2.28	0.00	13.61	0.00	13.61	0.02	0.01	0.59
2.35	2.31	0.00	13.94	0.00	13.94	0.03	0.04	1.18
3.53	2.36	0.00	14.51	0.00	14.51	0.05	0.09	1.79
4.71	2.42	0.00	15.34	0.00	15.34	0.07	0.16	2.40
5.88	2.51	0.00	16.44	0.00	16.44	0.09	0.26	3.04
7.06	2.62	0.00	17.87	0.00	17.87	0.11	0.39	3.70
8.24	2.74	0.00	19.67	0.00	19.67	0.13	0.56	4.39
9.41	2.90	0.00	21.91	0.00	21.91	0.15	0.78	5.10
10.59	3.07	0.00	24.66	0.00	24.66	0.18	1.05	5.85
11.77	3.28	0.00	28.02	0.00	28.02	0.21	1.40	6.64
12.94	3.51	0.00	32.12	0.00	32.12	0.25	1.83	7.46
14.12	3.77	0.00	37.11	0.00	37.11	0.29	2.39	8.33
15.30	4.07	0.00	43.18	0.00	43.18	0.33	3.08	9.23
16.47	4.40	0.00	50.56	0.00	50.56	0.39	3.96	10.18
17.65	4.77	0.00	59.53	0.00	59.53	0.45	5.06	11.16
18.83	5.20	0.00	70.47	0.00	70.47	0.53	6.46	12.19
20.00	5.67	0.00	83.82	0.00	83.82	0.62	8.22	13.25
21.18	6.19	0.00	100.14	0.00	100.14	0.73	10.45	14.34
22.36	6.78	0.00	120.15	0.00	120.15	0.86	13.28	15.46
23.53	7.45	0.00	144.73	0.00	144.73	1.01	16.86	16.62
24.71	8.19	0.00	175.04	0.00	175.04	1.20	21.40	17.79
25.89	9.02	0.00	212.55	0.00	212.55	1.43	27.17	18.99
27.06	9.96	0.00	259.15	0.00	259.15	1.71	34.52	20.21

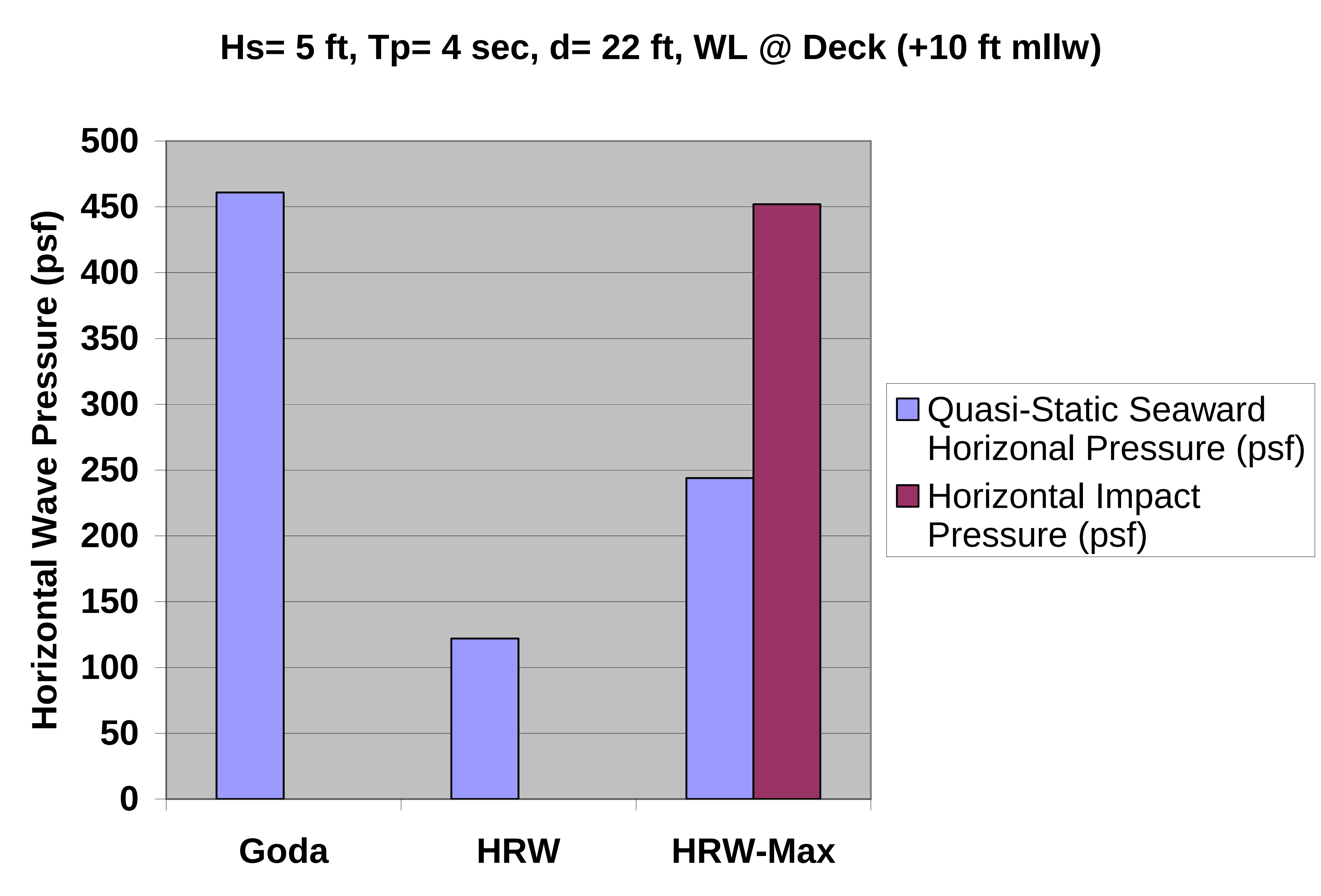


Close

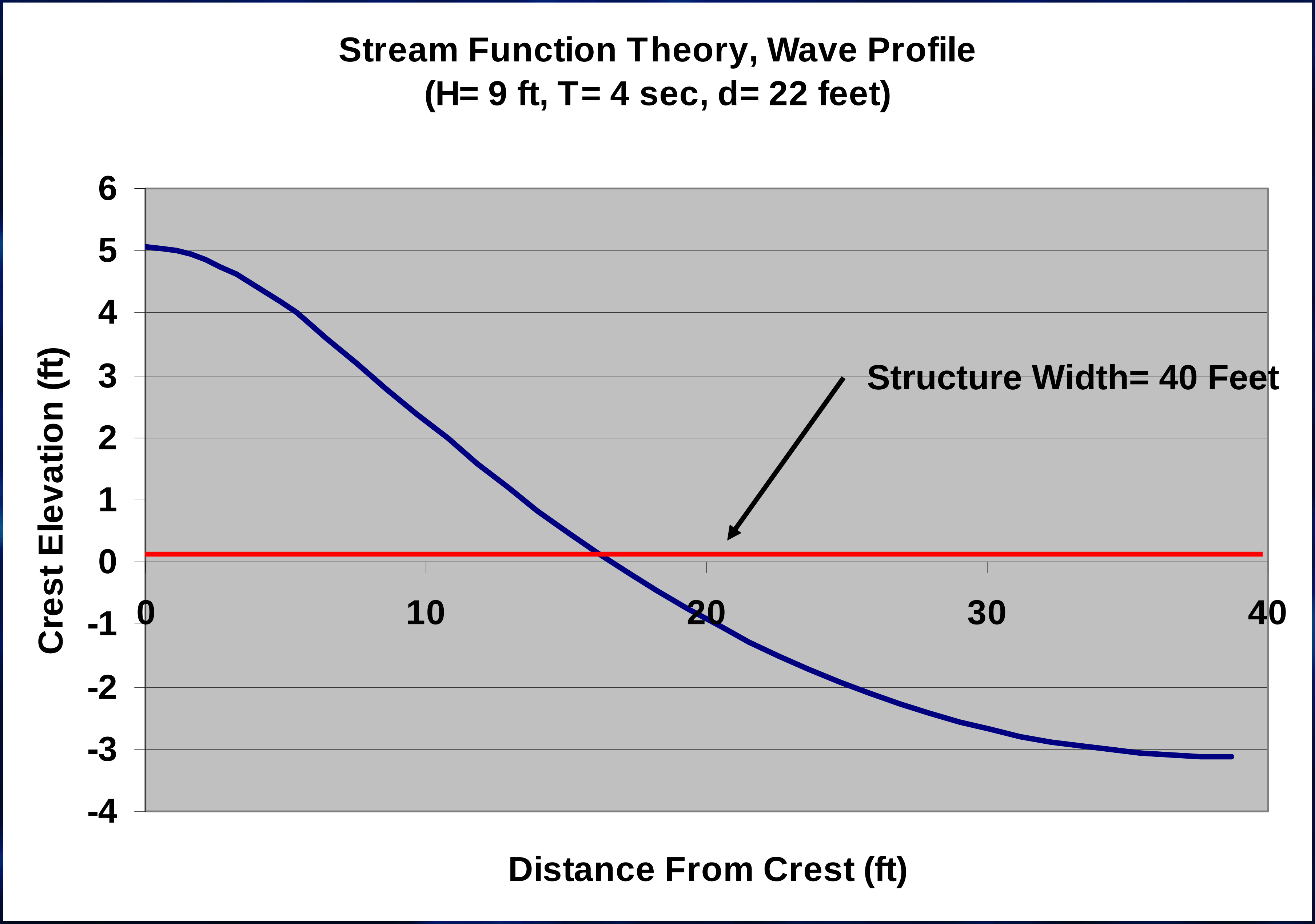
Export to Excel

Plot Graph - Preview

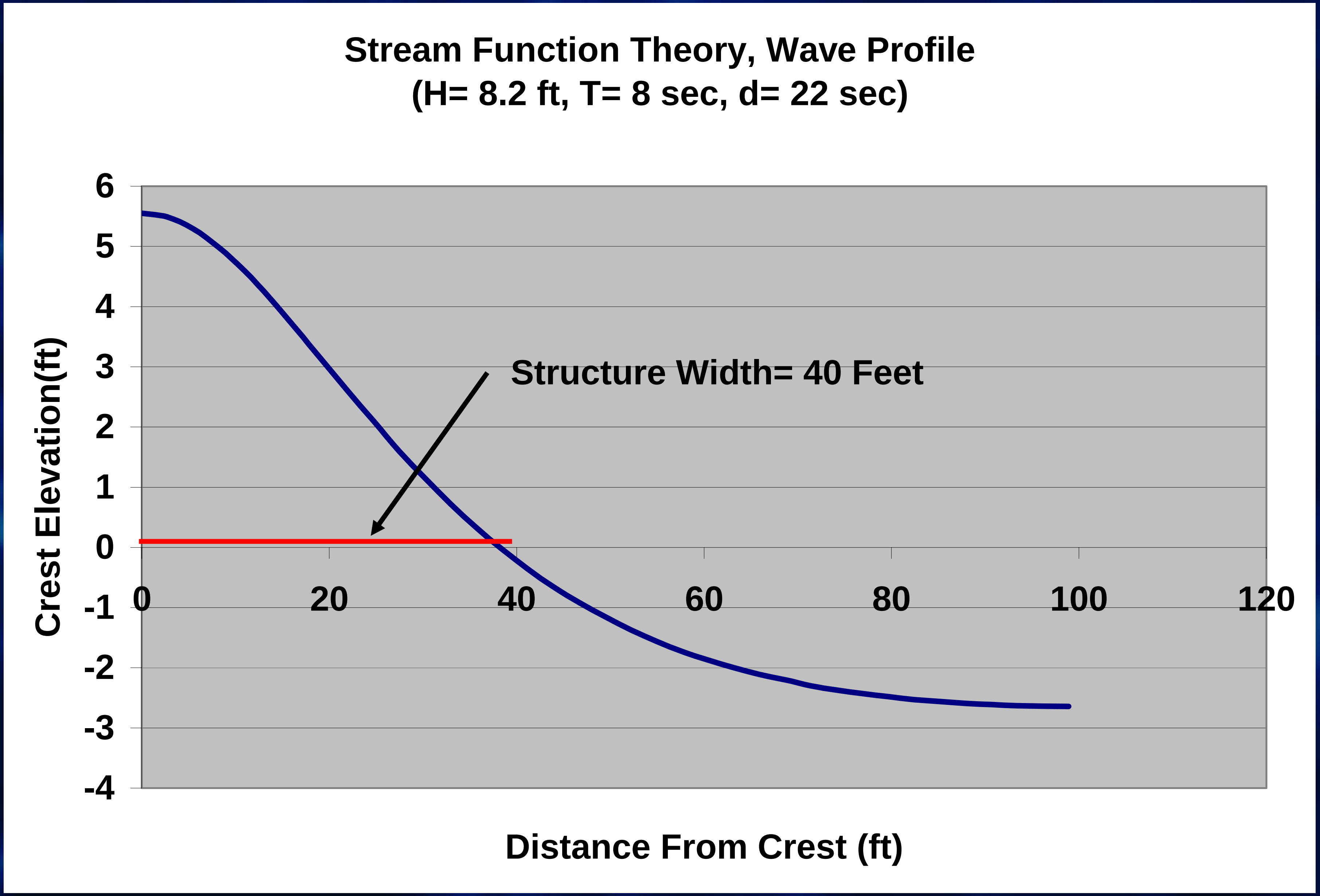


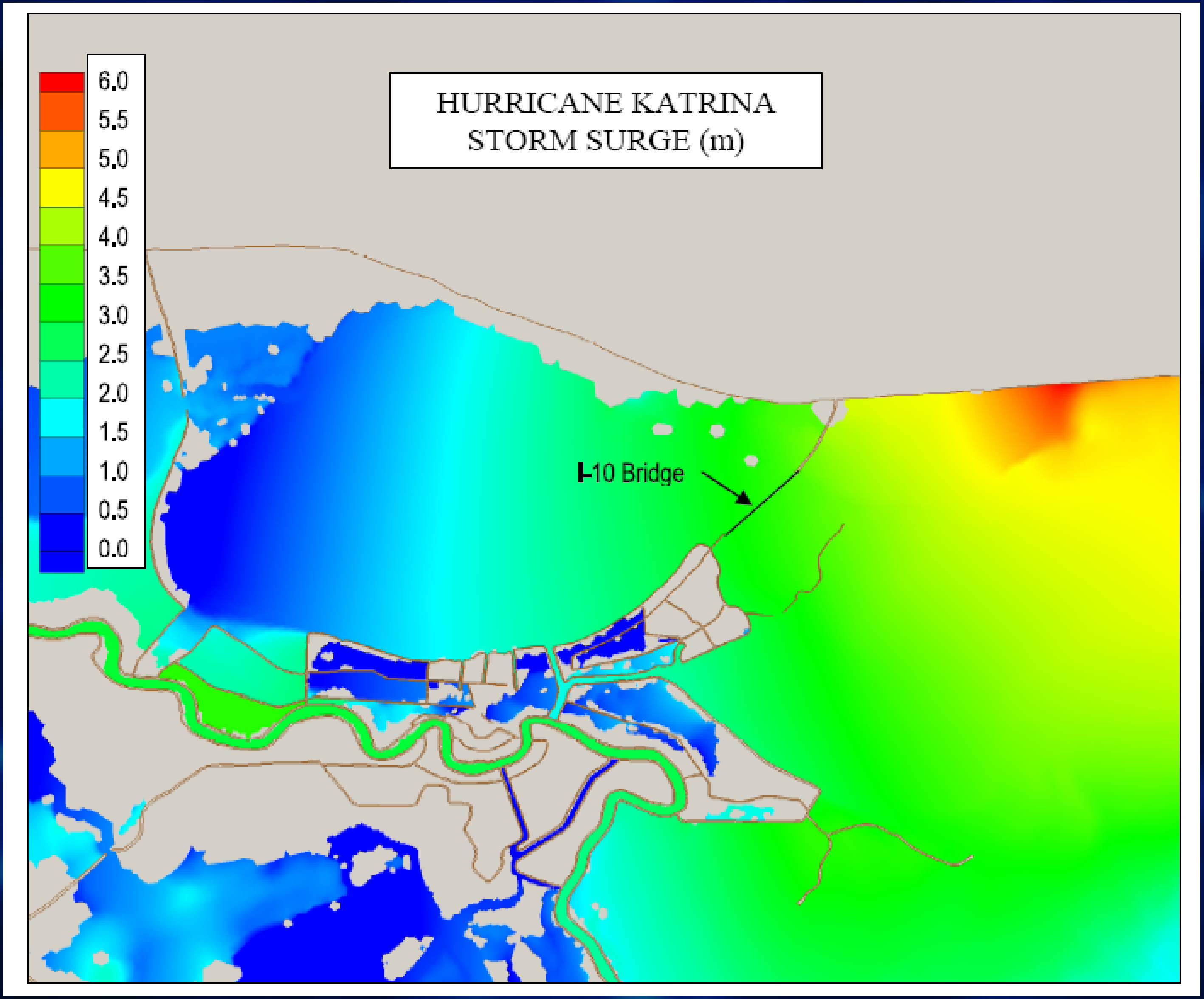


Hs= 5 ft, Tp= 4 sec, d= 22 ft, WL @ Deck (+10 ft mllw)
Horizontal Wave Pressure (psf)
500
450
400
350
300
250
200
150
100
50
0
Goda
HRW
HRW-Max
Quasi-Static Seaward Horizonal Pressure (psf)
Horizontal Impact Pressure (psf)

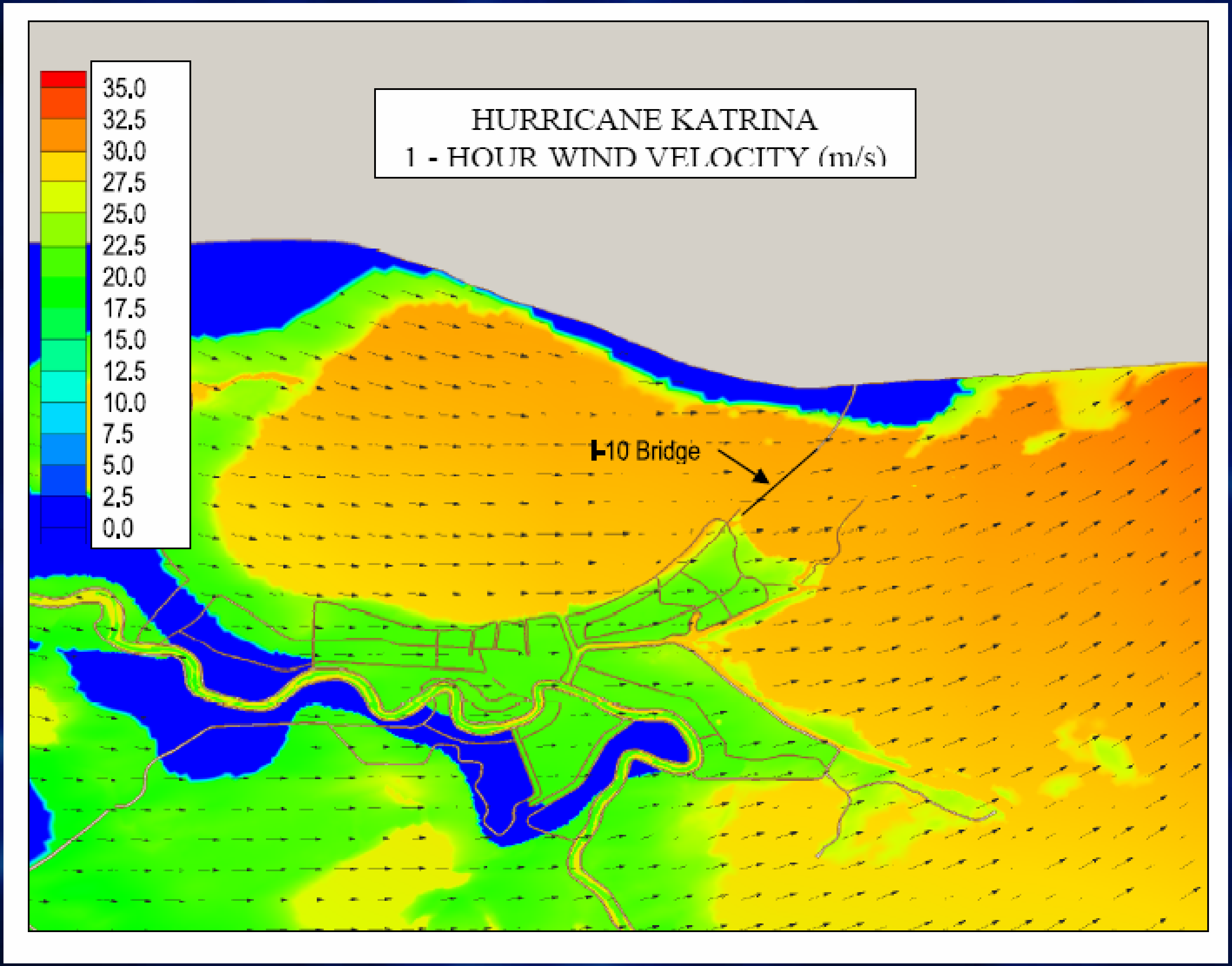


Stream Function Theory, Wave Profile
(H= 9 ft, T= 4 sec, d= 22 feet)
Crest Elevation (ft)
6
5
4
3
2
1
0
-1
-2
-3
-4
0
10
20
30
40
Structure Width= 40 Feet
Distance From Crest (ft)

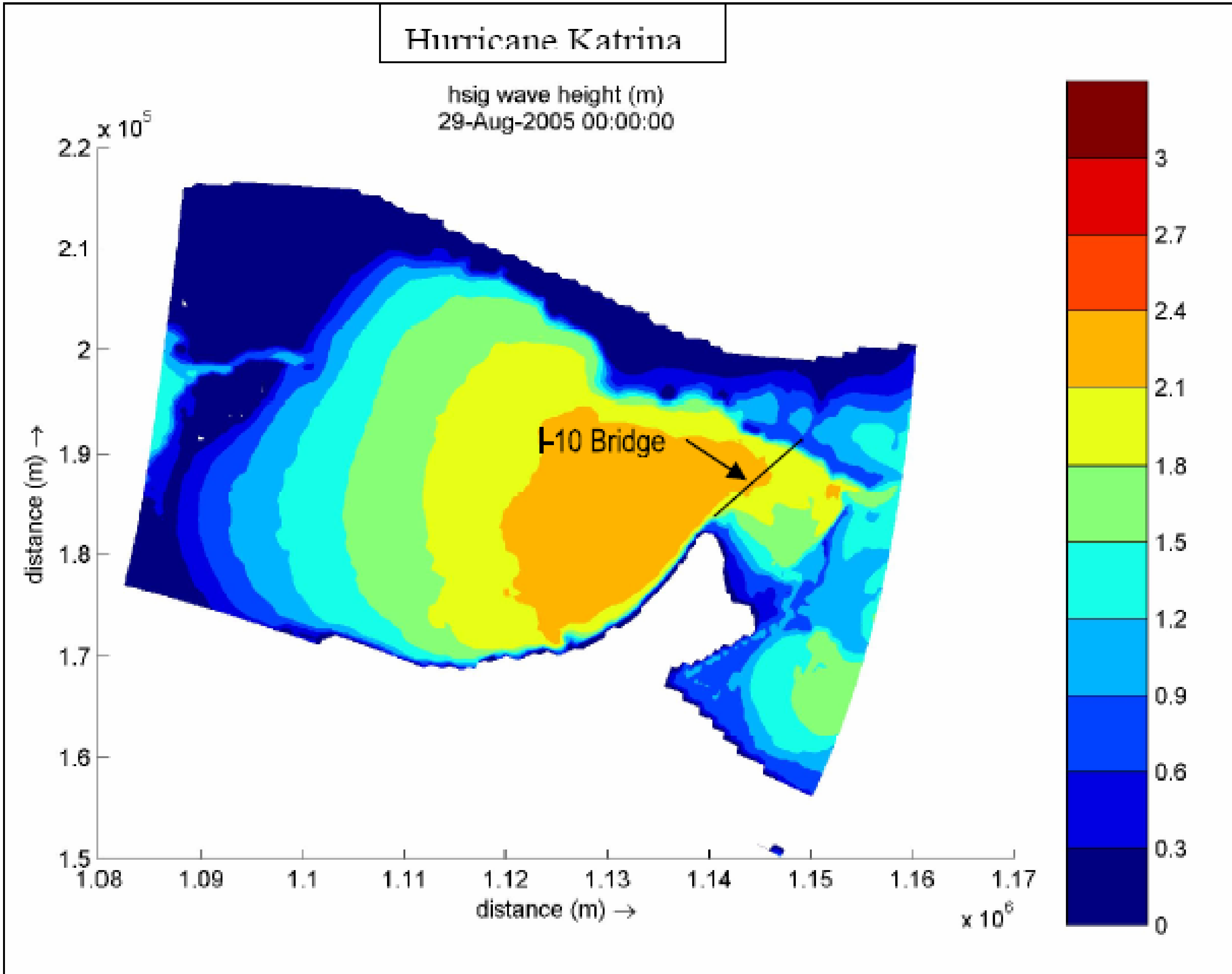

Stream Function Theory, Wave Profile
(H= 8.2 ft, T= 8 sec, d= 22 sec)
Structure Width= 40 Feet
Crest Elevation(ft)
6
5
4
3
2
1
0
-1
-2
-3
-4
0
20
40
60
80
100
120
Distance From Crest (ft)



HURRICANE KATRINA
STORM SURGE (m)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
I-10 Bridge



HURRICANE KATRINA
1 - HOUR WIND VELOCITY (m/s)
35.0
32.5
30.0
27.5
25.0
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
I-10 Bridge


Hurricane Katrina
hsig wave height (m)
29-Aug-2005 00:00:00
x 10^5
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
distance (m) →
I-10 Bridge
1.08
1.09
1.1
1.11
1.12
1.13
1.14
1.15
1.16
1.17
distance (m) →
x 10^6
3
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0

CONCLUSIONS- HURRICANES

- **Ports Extensively Damaged**
  - **From Wave and Water Levels**
  - **From Scour and Overtopping**
- **Moorings/Ships Vulnerable to Water Level Rise and Currents**
- **Extensive Building & Yard Damage**
- **High Risk of Ship Permanently Moored Vessel Impact Damages**
- **Properly Built Ports Can Survive**
- **Utility Systems Vulnerable**

Recommended Actions For Moving Forward

- "Learn From History"
- Invest In Hurricane/Tsunami Risk Studies
  - Similar To Bridge Evaluations
  - Both Engineering and Economic Efforts
  - Estimate Damages Due Events
  - Prepare Damage/Service Interruption Cost
  - Weigh Corrective Actions Against Potential Damage/Interruption Cost
  - Invest In Cost-Effective Corrective Actions
  - Prepare Detailed Emergency Response Plans

Recommended Actions For Moving Forward

- A Silver Lining…
  - Forensic Studies Important…
  - Opportunity to promote the dialogue
    - Cost-Benefits For Ports & Waterways
    - Same For Flood Protection