Geotechnical Dimensions of October 2012 Hurricane Sandy along the US East Coast

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George F. Sowers Symposium

State of the Art Lecture

Tuesday May 05, 2015

3:30 pm – 4:15 pm

Acknowledgements

- Geotechnical Extreme Events Reconnaissance (GEER) and all team members

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- Prof. T.D. O'Rourke

Outline

- Background, definitions and building codes
- Key observations from Hurricane Sandy
  - Coastal Geomorphology
  - Coastal Infrastructure
  - Urban Infrastructure
- Recovery
- Beyond recovery and the engineers' role
- Performance based building codes
- Resiliency & Action plans
- Concluding remarks

GEER Effort

- On the ground within less than a week
- Observed geotechnical related damage first hand
- Lessons learned

- Report:
  - V1: Feb 16, 2013
  - V2: Feb 19, 2014
  - http://www.geerassociation.org/GEER_Post%20EQ%20Reports/Sandy_2012/index.html

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GEER Association Report No. GEER-032
Version 2: February 19, 2014

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Definitions

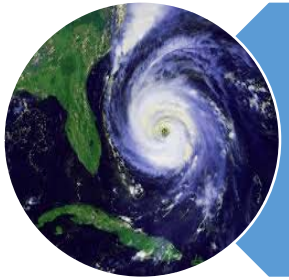
Sustainability

The creation and maintenance of conditions under which humans and nature can exist in productive harmony and fulfill the social, economic and other requirements of present and future generations.

Resiliency

The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions or extreme events.

Extreme events



Lower-probability (compared to normal) loading, transient in nature, imposes a shock to the system, high-impact , hard to predict? but …can be anticipated through risk assessment.

Extreme events & Engineering response

Chicago Fire 1871

- Changes to building & fire codes

Unintended consequences

State and Madison Streets after the Chicago Fire in 1871

http://www.vintag.es/2013/06/ruins-of-chicago-after-1871-fire.html

Extreme Events & Engineering Response

Santa Barbara Earthquake 1925

- First local government seismic building code
- Subsequent events lead to further developments.

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SANTA BARBARA HAS ITS FAULTS

BY COLIN CAMPBELL

THE FARMERS' ALMANAC says to watch for earthquakes when the moon runs high. Charlotte King of Salem, Oregon, predicts seismic activity according to the intensity and duration of her migraine headaches. Biologist Marsha Adams sees correlations between solar flares and earthquakes. Stock market prophet Joseph Granville made the front pages with his prediction that a Richter magnitude 8 quake would strike Los Angeles on April 10, 1981. John Gribbin and Stephen Plagemann claim in their book *The Jupiter Effect* that the unusual planetary alignment of March 10, 1982, will trigger disastrous quakes in southern California.

"But Granville was wrong, wasn't he?" says Professor Arthur Sylvester, 43, a geologist and earthquake researcher at UCSB. "Granville doesn't understand earthquakes any more than Edgar Cayce or any of the other psychics do. A friend of mine once discovered a one-to-one correlation between cycles of earthquakes and cycles in the stock market. If you believe the psychics, then maybe you should use earthquakes to predict the stock market."

Professor Sylvester's methods are not designed to thrill the readers of *National Enquirer*. He uses laser beams to measure the slow changes in distance between points on the mainland and points on the Channel Islands, and for the last four years he's been in charge of the radon gas sampling program at UCSB.

"Mark Shapiro of Cal Tech isn't predicting any quakes," says Professor Sylvester, "but he's discovered that radon gas in deep wells along the San Andreas fault bubbled up faster just before the 1979 Imperial Valley quake. Then last fall his radon detectors at Lake Hughes and Lytle Creek again showed increases." Also last fall, Professor Sylvester announced significant increases in radon at the detectors along the Mission Ridge, More Ranch, and Mesa faults in Santa Barbara.

The Santa Barbara Channel is one of the most seismically active zones in California: nearly 500 quakes have struck here since the turn of the century. The city itself rides a crustal block bordered by the Mission Ridge fault to the north and the Mesa fault to the south. The Mesa fault extends west from Stearns Wharf to Haley Street, parallels Highway 101 to Modoc Road, then goes under La

Left: State and Ortega streets, June 29, 1925. A magnitude 6.3 quake kindled earthquake consciousness in local engineers, architects, politicians, and geologists.

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- **Ref: GEER**

Saffir-Simpson Hurricane Scale Storm Type

Tropical depression	<39 mph	<63 km/h
Tropical storm	39–73 mph	63–117 km/h
Category 1	74–95 mph	119–153 km/h
Category 2	96–110 mph	154–177 km/h
Category 3	111–129 mph	178–208 km/h
Category 4	130–156 mph	209–251 km/h
Category 5	>156 mph	>251 km/h
Unknown		

Storm Type

- Tropical cyclone
- Subtropical cyclone
- Extratropical cyclone / Remnant low / Tropical disturbance

WELL FORECASTED 24HR+

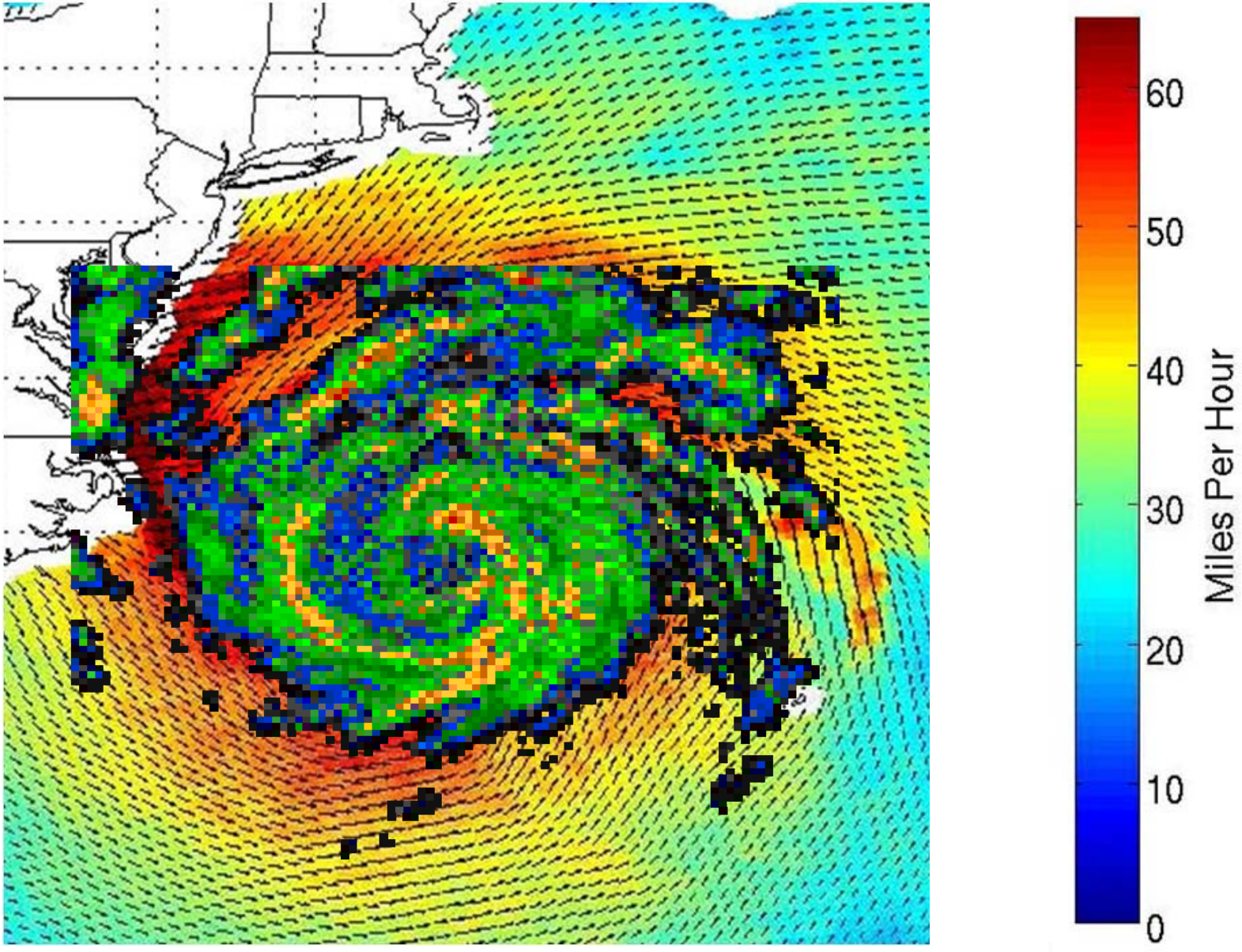
Landfall on Oct 29, 2012
Brigantine, NJ

121029_1625

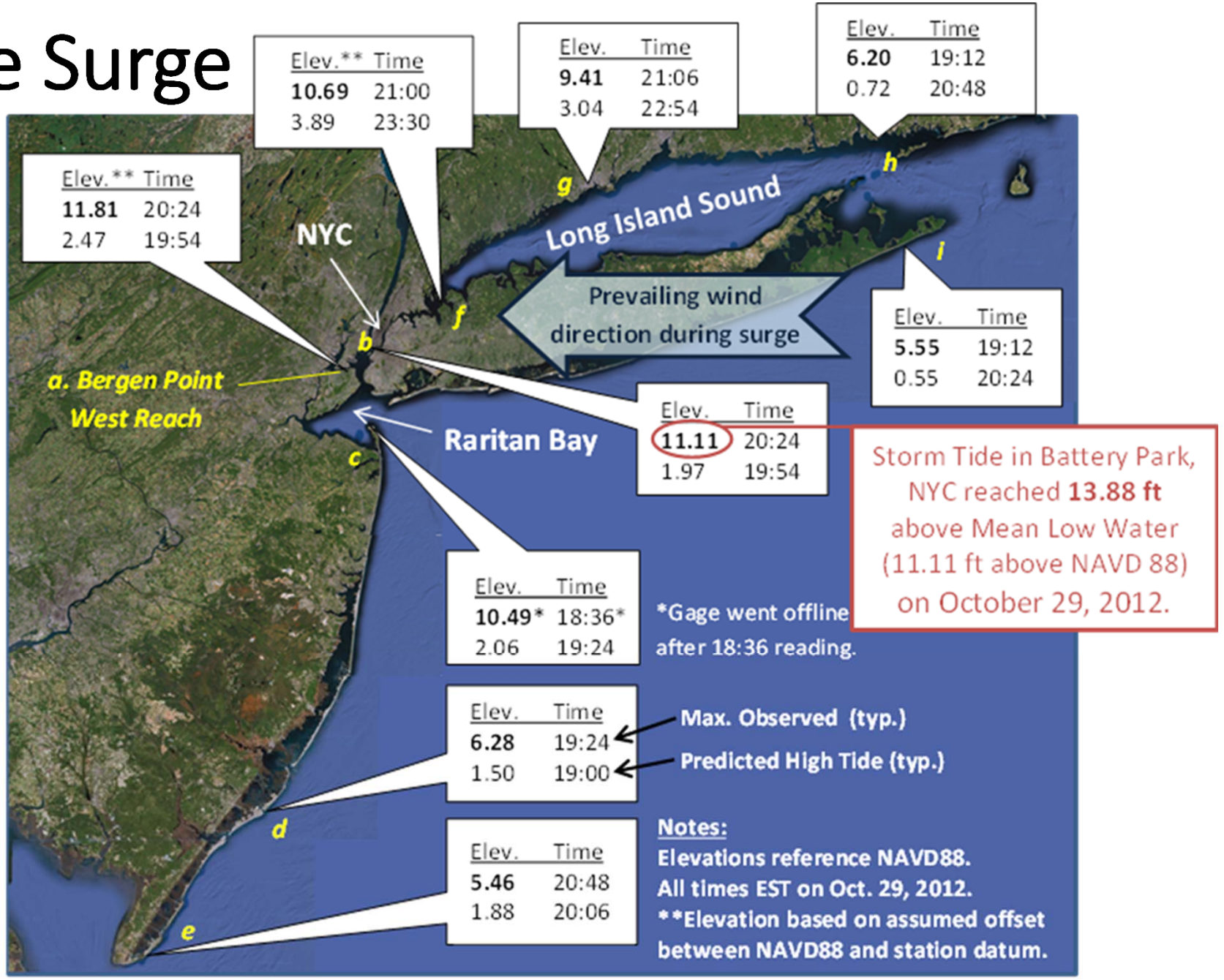
Hurricane Sandy

- > 250 Killed (~159 in US)
- $65 Billion Property and Business Losses (Sandy Task Force)
- 8.5 Million Homes & Businesses Without Power
- NYC Evacuation & Shutdown of MTA & Public Transport
- 800,000 Daily Public Transit Commuters Affected
- 1400 Sunken Vessels
- Wall Street Shut 2 Days
- Record Flooding (Surge)
- 24 U.S States affected (includes entire eastern seaboard)

Counter Clockwise Winds

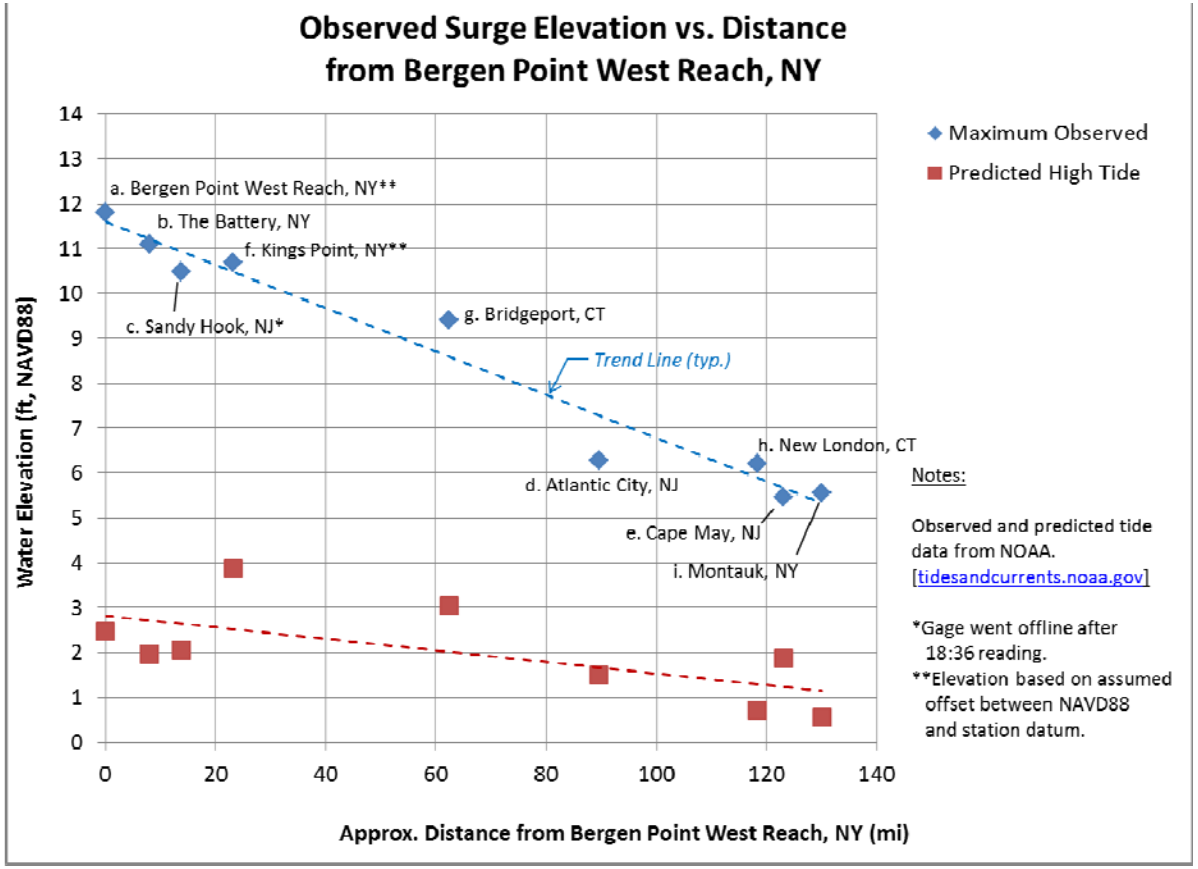


The Surge



Hashash et al (2014) – Geo Atlanta

Funneling Effect



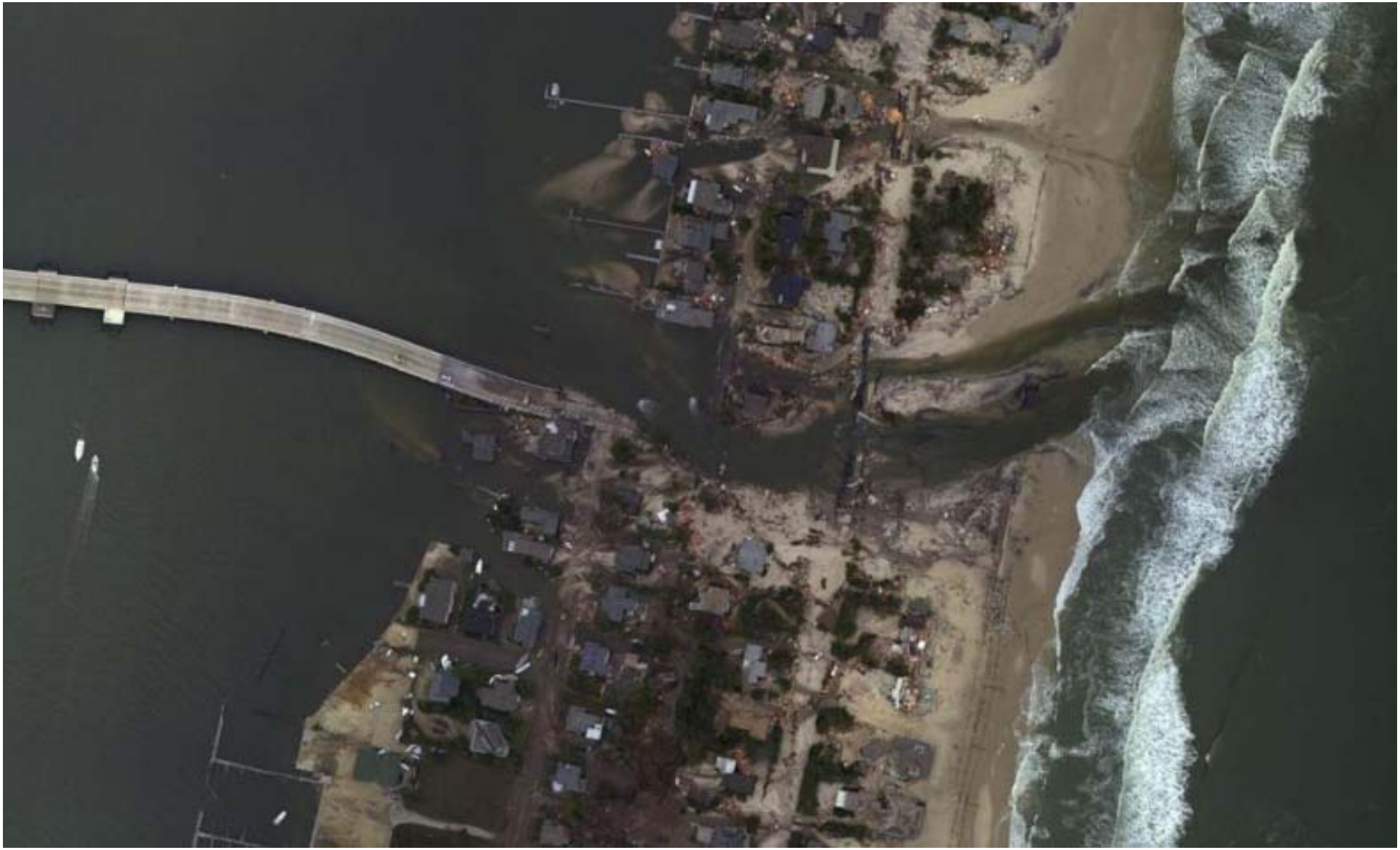
Surge elevation as a function of distance from Bergen Point West Reach, NY, illustrating how surge was “funneled” towards Raritan Bay and inner Long Island Sound.

Coastal Geomorphology & Natural Coast Line

Locations of four new inlets formed during Hurricane Sandy

Mantoloking – Bayhead, NJ

Mantoloking, NJ



Fire Island, Long Island

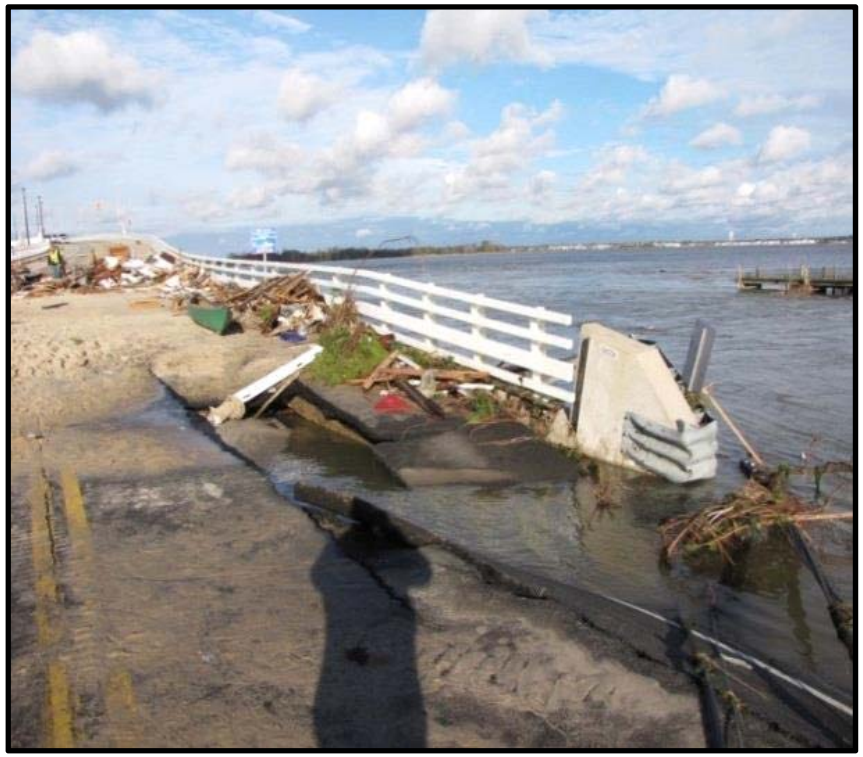
Damage to Coastal Infrastructure

- **Coastal bridges** experienced erosion at approaches and abutments.
- **Structural damage** was worst in communities with direct exposure to the open ocean.
- **Concrete masonry unit block wall foundations** generally performed poorly.
- **Concrete wall foundations**: generally no structural damage, but vulnerable to scour.
- In **wood frame houses, foundation** washout due to inadequate anchorage.
- **Old dwellings**.
- **Wooden bulkheads** in Atlantic City, NJ, breached.
- **Underground gas pipelines** were disrupted due to buoyancy forces displacing the pipe networks.
- **Sewage treatment plants** were flooded and damaged, causing uncontrolled discharge.
- **Dunes and vegetated strips** had a positive effect in reducing foundation damage.

Coney Island

Observations

Coastal Bridges: Mantoloking Bridge



T-wall settlement of 4 ft due to damage to the north side of the east abutment of Mantoloking Bridge

Coastal Bridges, RT. 72

Severe erosion observed at Rt. 72 east abutment, looking south-east (NJDOT 2012a)

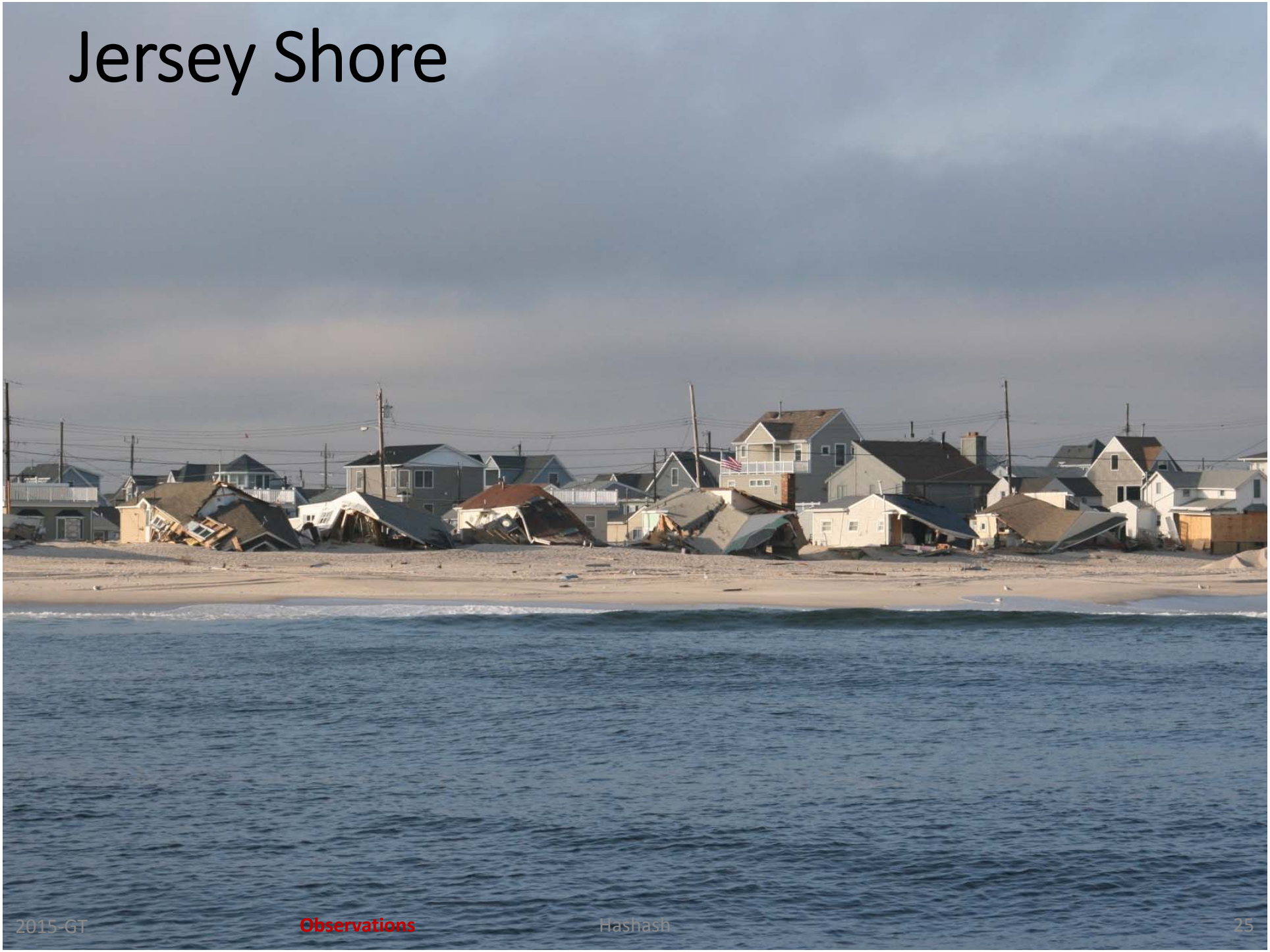
Direct Exposure to Ocean: Jersey Shore

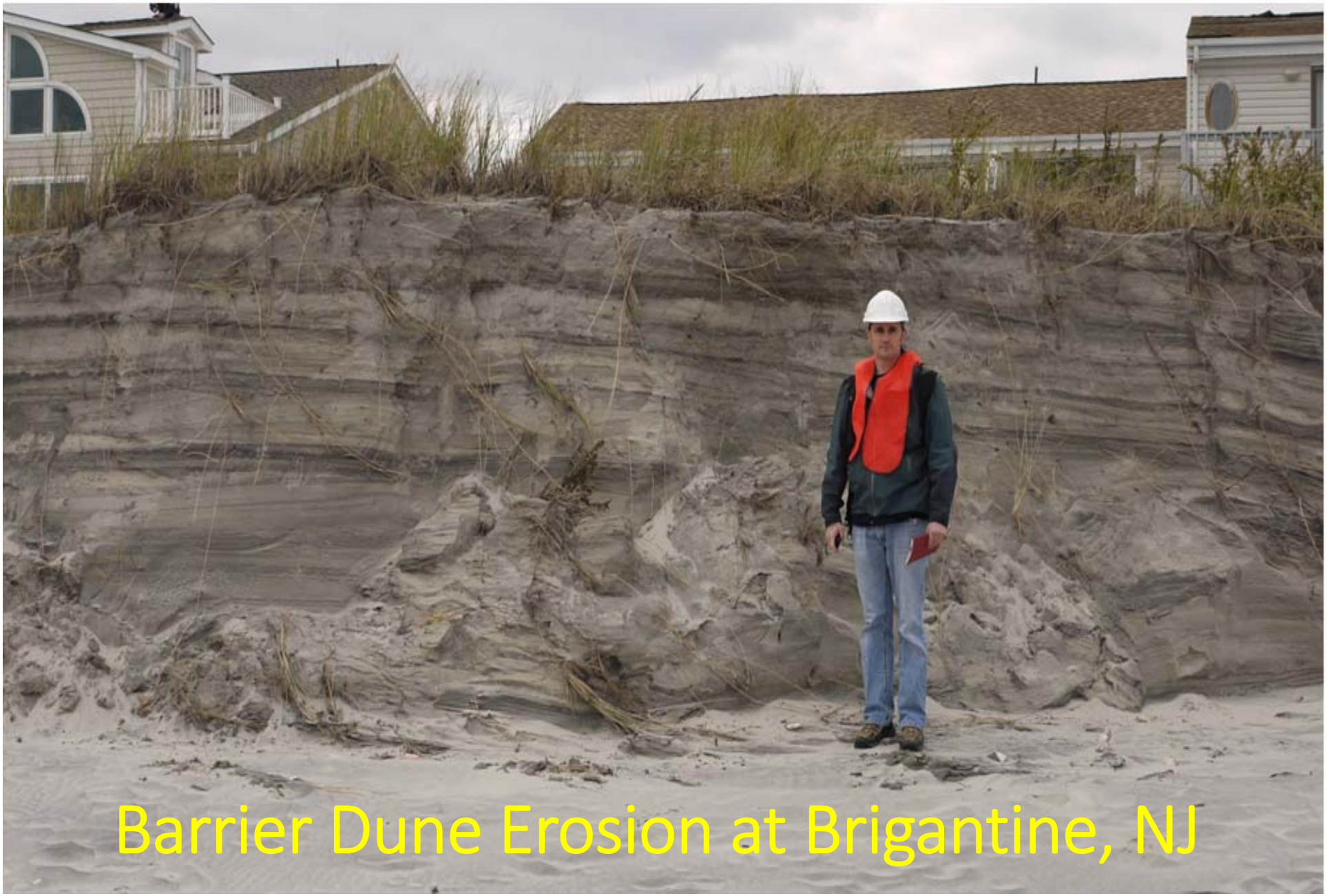
Direct Exposure to Ocean: Lavallette, NJ

Direct Exposure to Ocean: New Dorp Beach, Staten Island

Row of houses completely removed and debris moved inland

Jersey Shore




Barrier Dune Erosion at Brigantine, NJ

Concrete masonry unit block wall foundations, Breezy Point

Concrete masonry unit block wall foundations, Breezy Point

Fire Island

Timber Pile Foundations, Ship Bottom, N.J.

Damaged Board Walk, Rockaway Beach

Casino Pier, Seaside Hts., Nj

Staten Island

Wooden Bulkheads

Backfill soil washed away, exposing severely corroded tie rods in Atlantic City, NJ

Damage to Urban Infrastructure

-Primarily related to flood inundation.

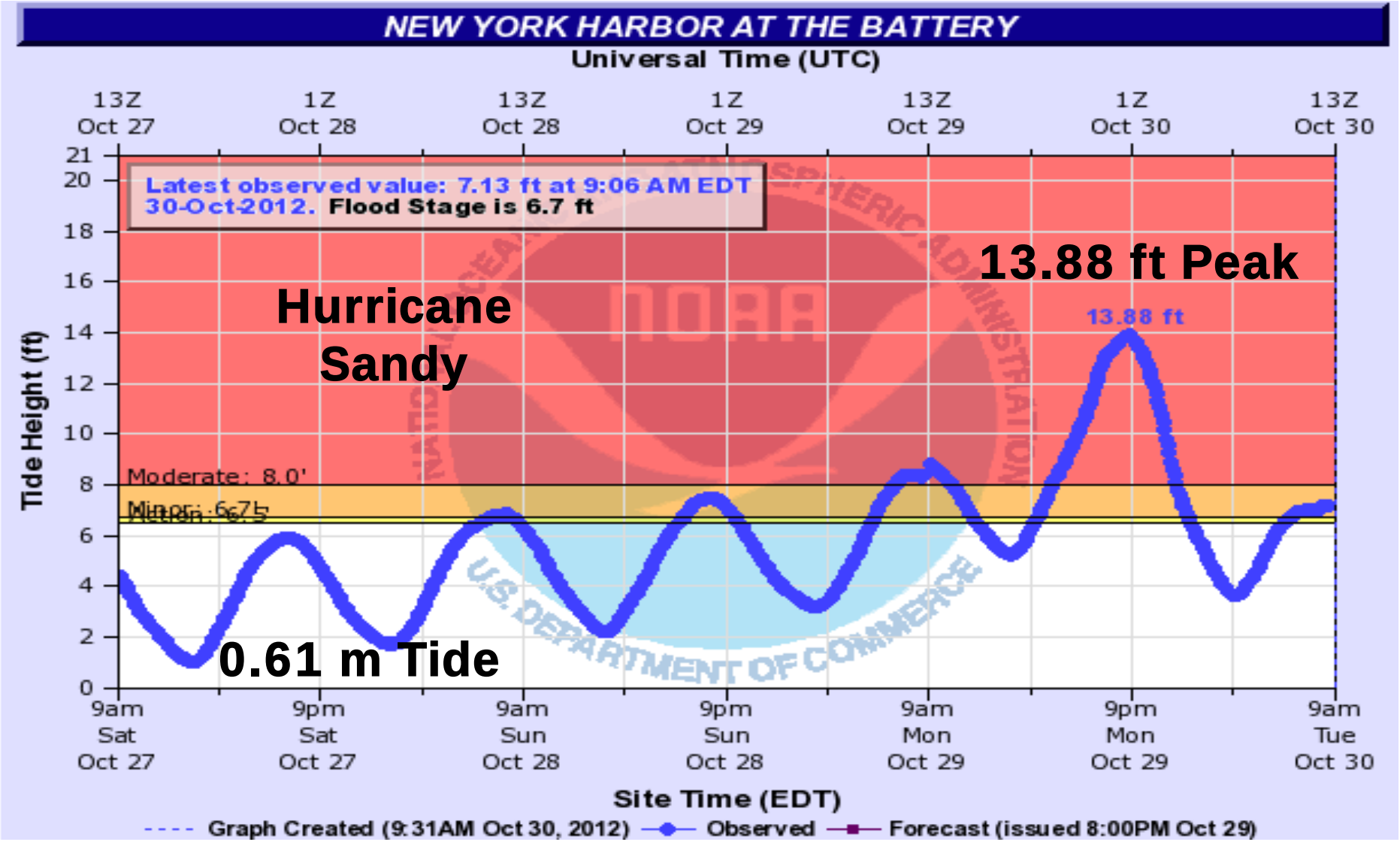
-Below-grade subway stations, tunnels, parking garages, and foundation excavations experienced widespread flooding that was widely reported in the media.

-Little structural damage, service was significantly affected, as the utilities and ventilation systems were severely damaged.

-Flooding underground utilities. Many large office buildings were shut down.

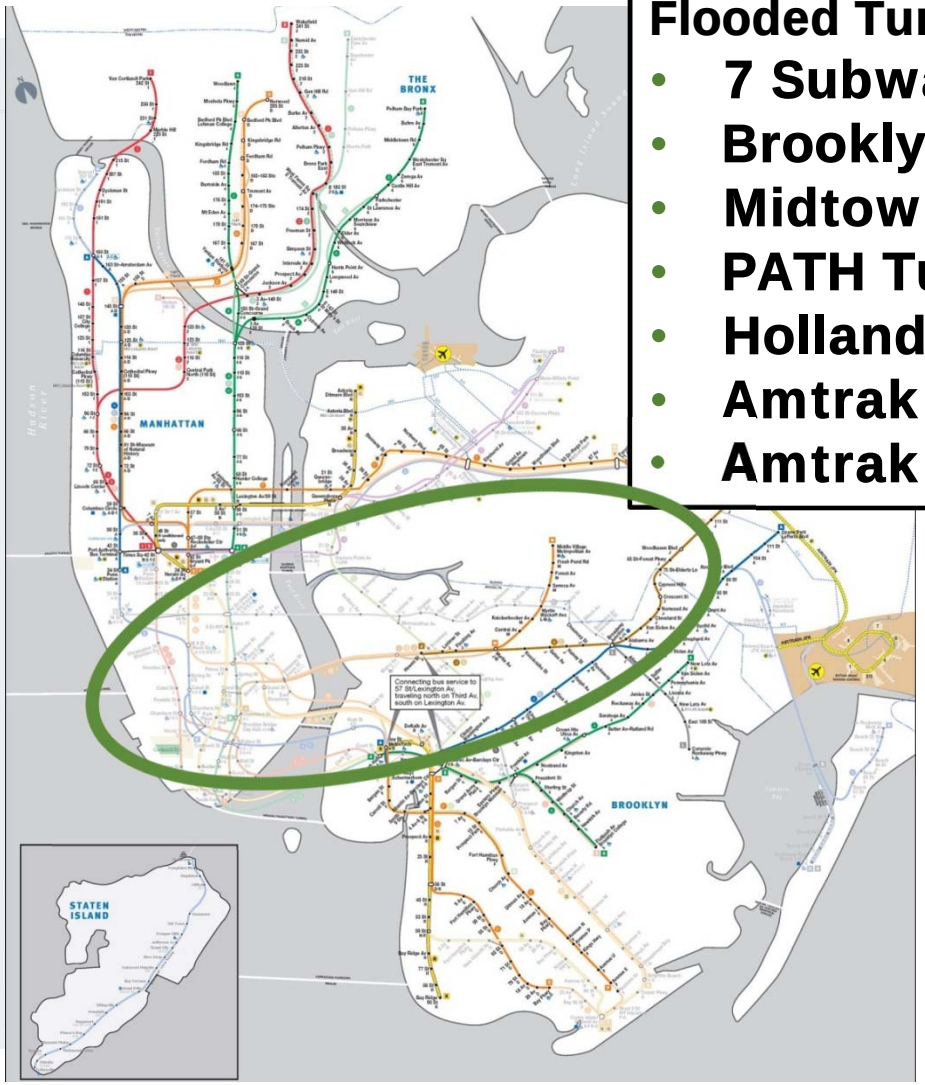
-Queens, NYC, two major washouts along the earth embankment crossing Jamaica Bay took a large segment of the Rockaway (A) subway line out of service.

Storm Water At Battery



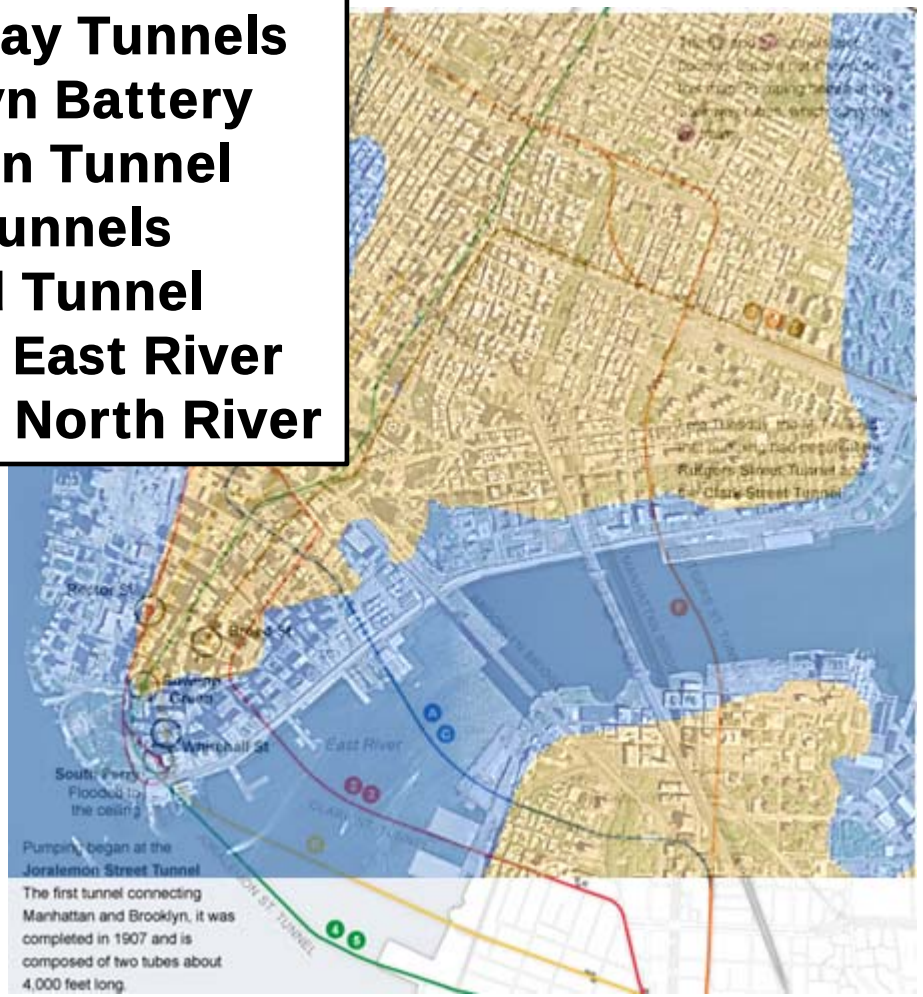
***Slide by T. O'Rourke**, Cornell University*
EERI NYNE October 24, 2013

Hurricane Sandy Inundation



Flooded Tunnels

- **7 Subway Tunnels**
- **Brooklyn Battery**
- **Midtown Tunnel**
- **PATH Tunnels**
- **Holland Tunnel**
- **Amtrak East River**
- **Amtrak North River**



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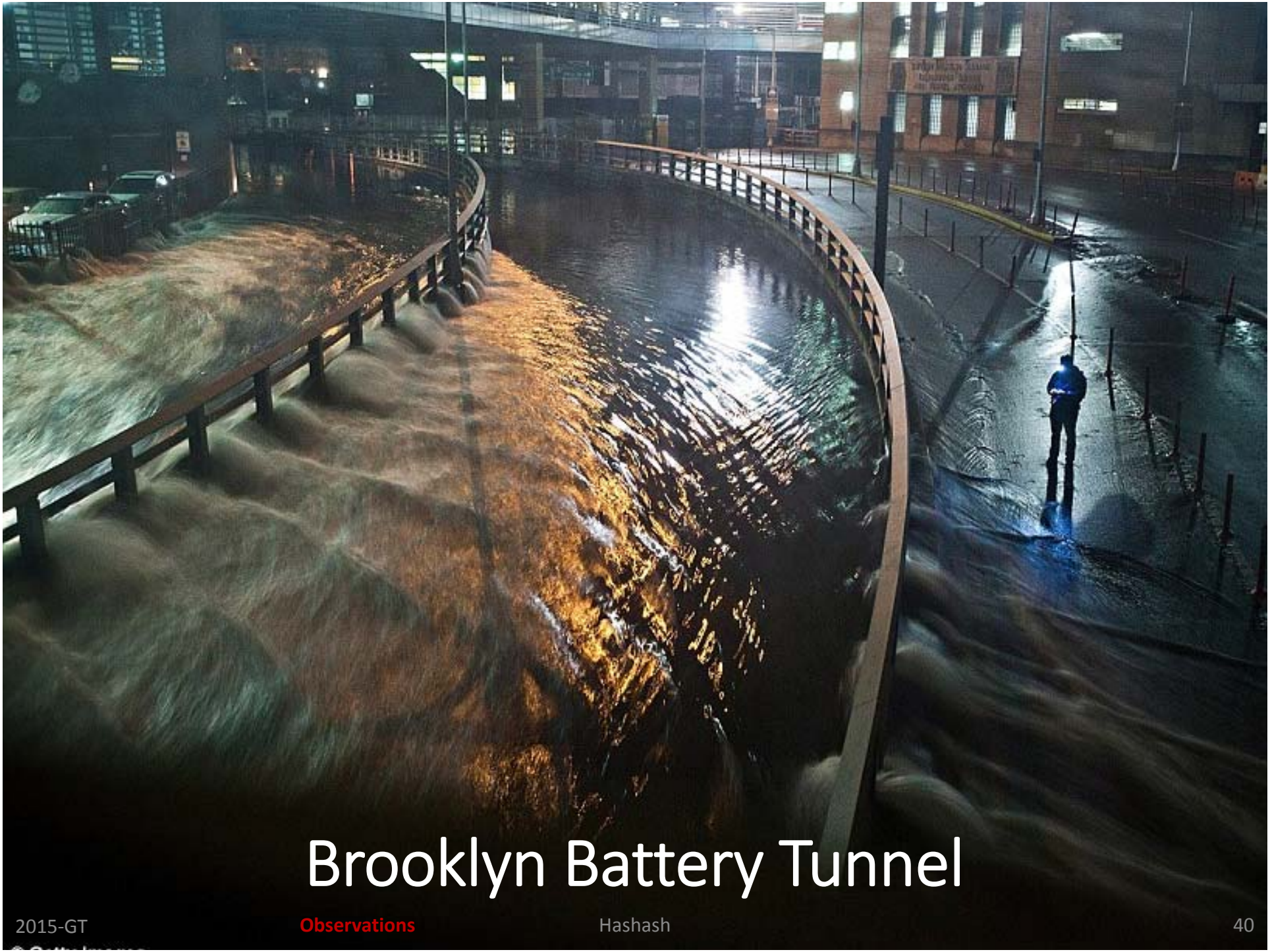
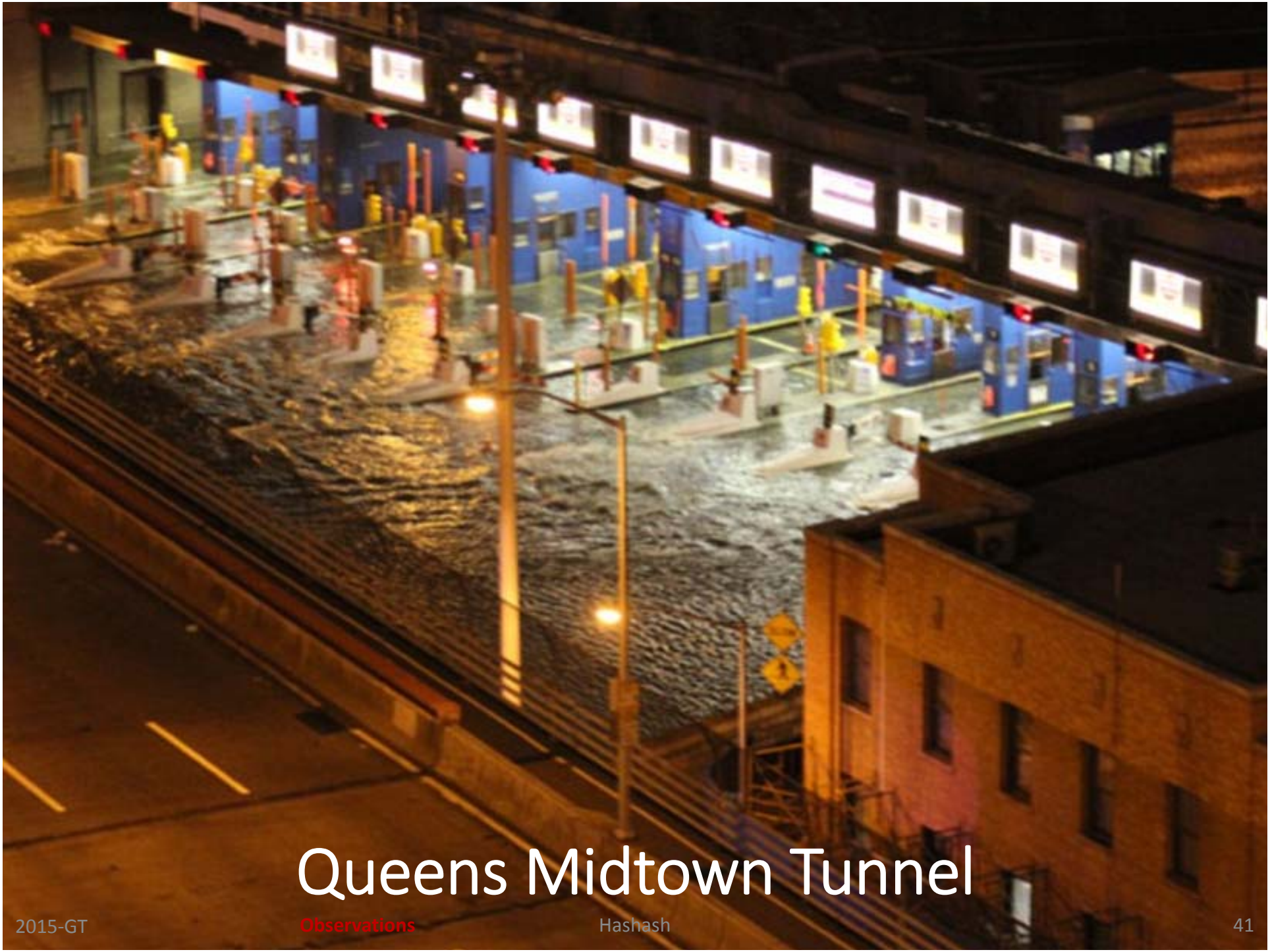
EERI NYNE October 24, 2013

NYC Flooded Tunnels

Type	Tunnel	Crosses	Length (ft)		Date Re-Opened
			Total	Flooded	
Subway	2-3 (Clark St Tunnel)	East River	6,700	600	11/04/12
Subway	4-5 (Joralemon St Tunnel)	East River	7,080	0	11/03/12
Subway	7 (Steinway Tunnel)	East River	5,910	1,000	11/03/12
Subway	A-C (Cranberry St Tunnel	East River	8,580	1,000	11/04/12
Subway	F (Rutgers St Tunnel)	East River	5,490	1,000	11/04/12
Subway	L (14th St Tunnel)	East River	7,350	2,700	11/08/12
Subway	E-M (53rd St Tunnel)	East River	5,545	800	11/04/12
Subway	R (Montague St Tunnel)	East River	10,115	4,025	12/21/12
Subway	G (Greenpoint Tunnel)	Newtown Creek	3,910	1,000	11/07/12
PATH	Blue (33rd - Hoboken)	Hudson River	5,500	significant flooding	01/09/13
PATH	Yellow (33rd - Journal Sq)	Hudson River	5,500	significant flooding	11/06/12
PATH	Green (Hoboken - WTC)	Hudson River	5,650	significant flooding	01/30/13
PATH	Red (WTC - Newark)	Hudson River	5,650	significant flooding	11/26/12
Vehicular	Brooklyn Battery Tunnel	East River	9,118	6,000	11/19/12
Vehicular	Midtown Tunnel	East River	6,545	flooded to ceiling	11/09/12
Vehicular	Holland Tunnel	Hudson River	8,558	fresh air ducts flooded	11/07/12
Vehicular	Battery Park Underpass	-		flooded to ceiling	11/13/12
Vehicular	West Street Underpass	-		flooded to ceiling	11/13/12
Amtrak/ NJT Rail	East River Tunnels 1 to 4	East River	3,949	2 of 4 tunnels flooded	11/09/12
Amtrak/ NJT Rail	North River Tunnels 1 and 2	Hudson River	14,575	1 of 2 tunnels flooded	11/09/12



Brooklyn Battery Tunnel



Queens Midtown Tunnel

NYC Subway Entrance

Flooding at the Cranberry Street Tunnel

(MTA New York City Transit/Leonard Wiggins)

Rockaway subway [A] line, Queens

Washout and Damage to earth embankment exposed old LIRR infrastructure

Mitigation


WTC – Ground Zero
© AP

Water mark and flooding, South Street Seaport

Recovery

News Organizations – Web (2013)

Recovery

News Organizations – Web (2013)

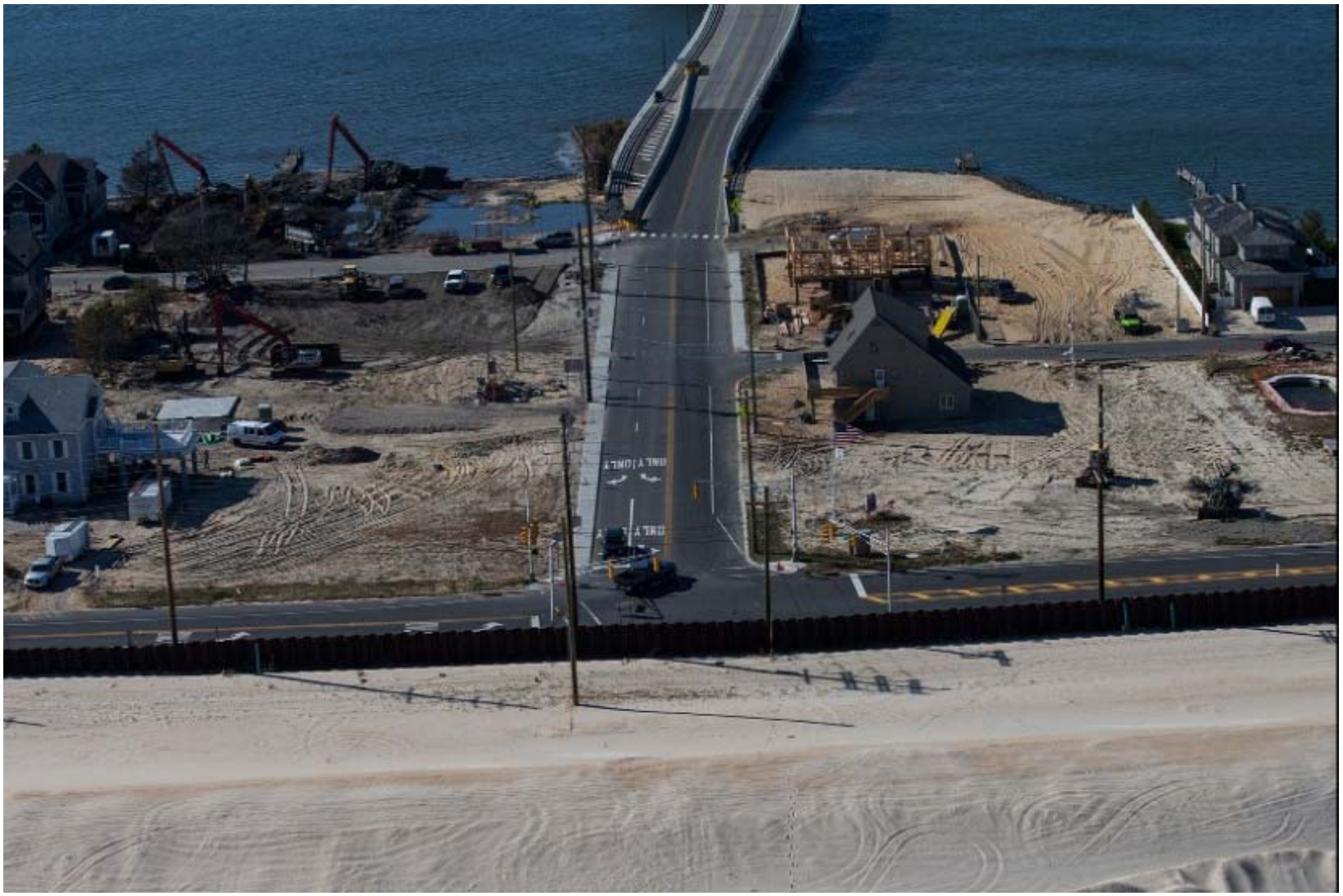
Recovery

News Organizations – Web (2013)

Recovery – rebuilding in place

News Organizations – Web (2013)

Recovery – rebuilding in place



News Organizations – Web (2013)

Recovery - abandoned

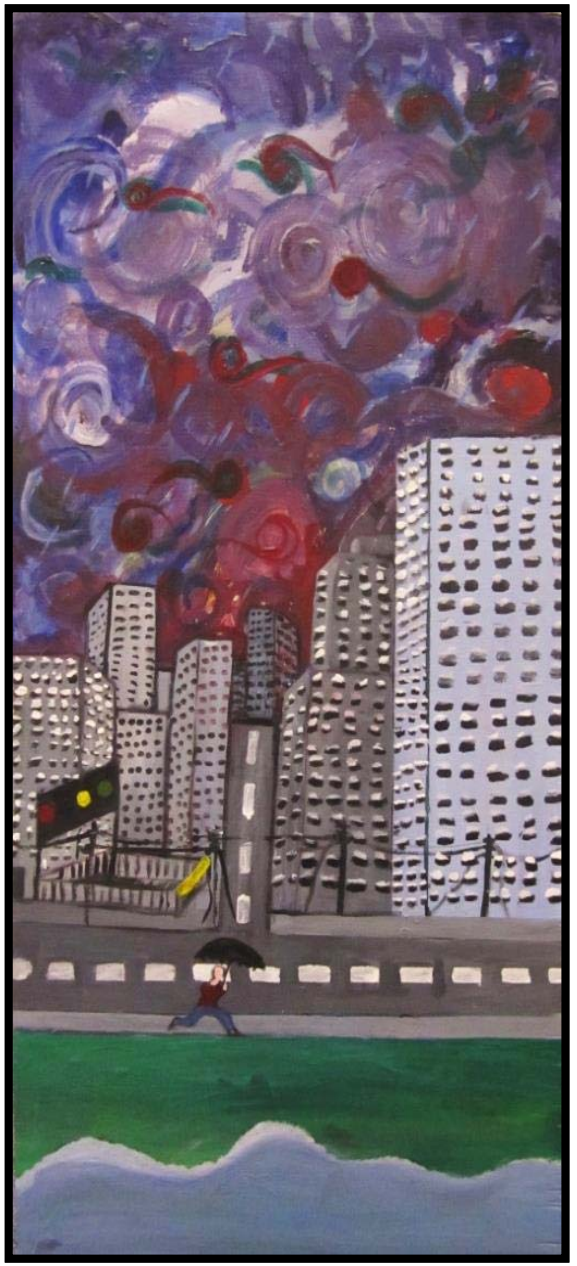
News Organizations – Web (2013)

Inspired by the perspective of children

New Normal

Resiliency

Sustainability



Beyond Recovery

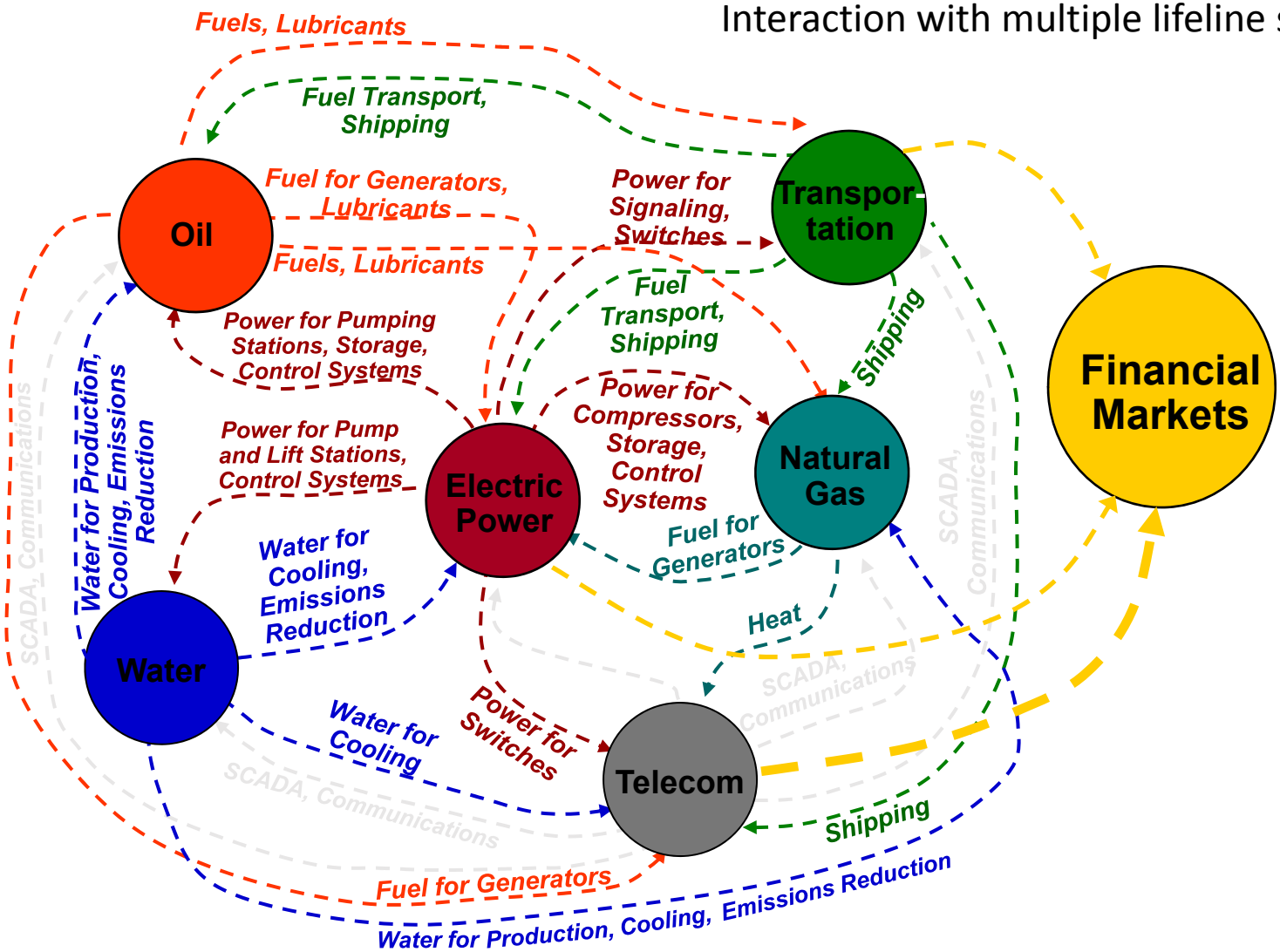
- Do the project right versus do the right project, e.g. rebuild the same structure?

- Environmental change (more than climate change), coastal subsidence, and sea level rise, e.g. liquefaction vulnerability in new Zealand.

- Intense rain event, e.g Toronto Subway Summer 2013.

Interdependent Systems – System of Systems

System performance is the driving factor
Interaction with multiple lifeline systems



O'Rourke from Peerenboom, Fisher, and Whitfield, 2001

Questions and the Engineers' Role

Immediate

- **Safety of communities and continuation of everyday life**.
- Short-term geotechnical solutions to retrofit or rebuild.
- Immediate solutions such as flood barriers, surge resistant foundations, and lifting houses above the flood plain
- Innovative solutions such as removable flood wall systems and living shorelines and reefs.

Long-Term Challenge

- Translate the intents of resiliency and sustainability into quantifiable terms and incorporate them in a performance-based engineering framework that considers life cycle costs.
- For existing infrastructure, the factors of quantity/quality of information and life cycle status should weigh in on the decision to retrofit or rebuild.

Most current codes and regulations do not address these big-picture issues from a geotechnical engineer's perspective.

Questions and the Engineers' Role

Collaboration

- Planners, engineers architects and environmental scientists need to answer questions about **multi-hazard concerns** →

Multi-Hazard Concerns

- Should we build large-scale barriers to prevent storm surges from flooding an urban area?
- Will these barriers shift the flooding problem to other areas?
- Should we allow coastal areas to flood and enhance infrastructure resiliency by hardening in place so that functionality can be restored within a short period of time, or attempt to retreat from vulnerable areas through managed buyout programs?

Most current codes and regulations do not address these big-picture issues from a geotechnical engineer's perspective.

Beyond Recovery

- Performance based EQ engineering – a framework we can apply
- Building code – resiliency – few have it – see how it worked in CA
- Design of system not elements or components
- Low probability high consequence events
- Flood elevation map ⇔ USGS hazard maps – need to site specific assessment
- Codes often provide minimum requirements
- Pay now or pay a lot more later.

Building Codes & Performance Warranties

- If a structure is affected by an extreme event and performs poorly:
  - There is an expectation of how the structure should have performed but no implied warranty
- The only warranty is that the engineer complied with the standard of care
  - For most structures, demonstration that a design was performed in accordance with the building code will provide adequate proof of conformance to the standard of care

Code Basis for Performance-based Design

- Section 104-

"The provisions of this code **are not intended** to prevent . . . or **to prohibit any design** or method of construction. . . provided that any such alternative has been approved.

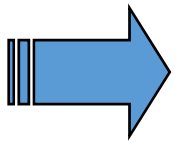
An alternative. . . design shall be approved where the building official finds that **the proposed design is satisfactory and complies with the intent of the provisions of this code**."

Towards Performance Based Design

To transform engineering assessment and design ...

Traditional Approach

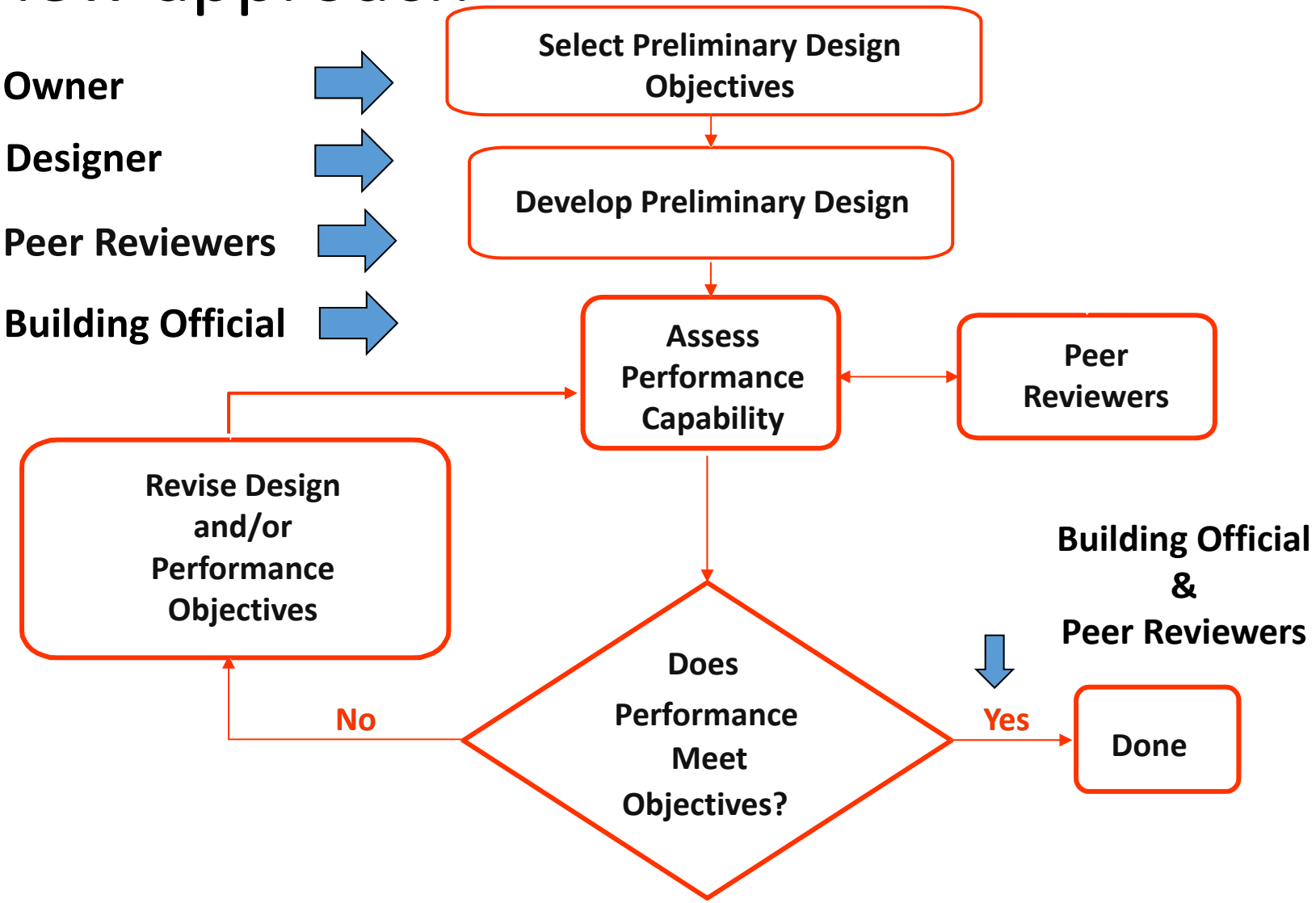
- Non-scientifically defined hazard
- Indirect design approaches
- Undefined and uncertain outcomes



Perform.-Based Approach

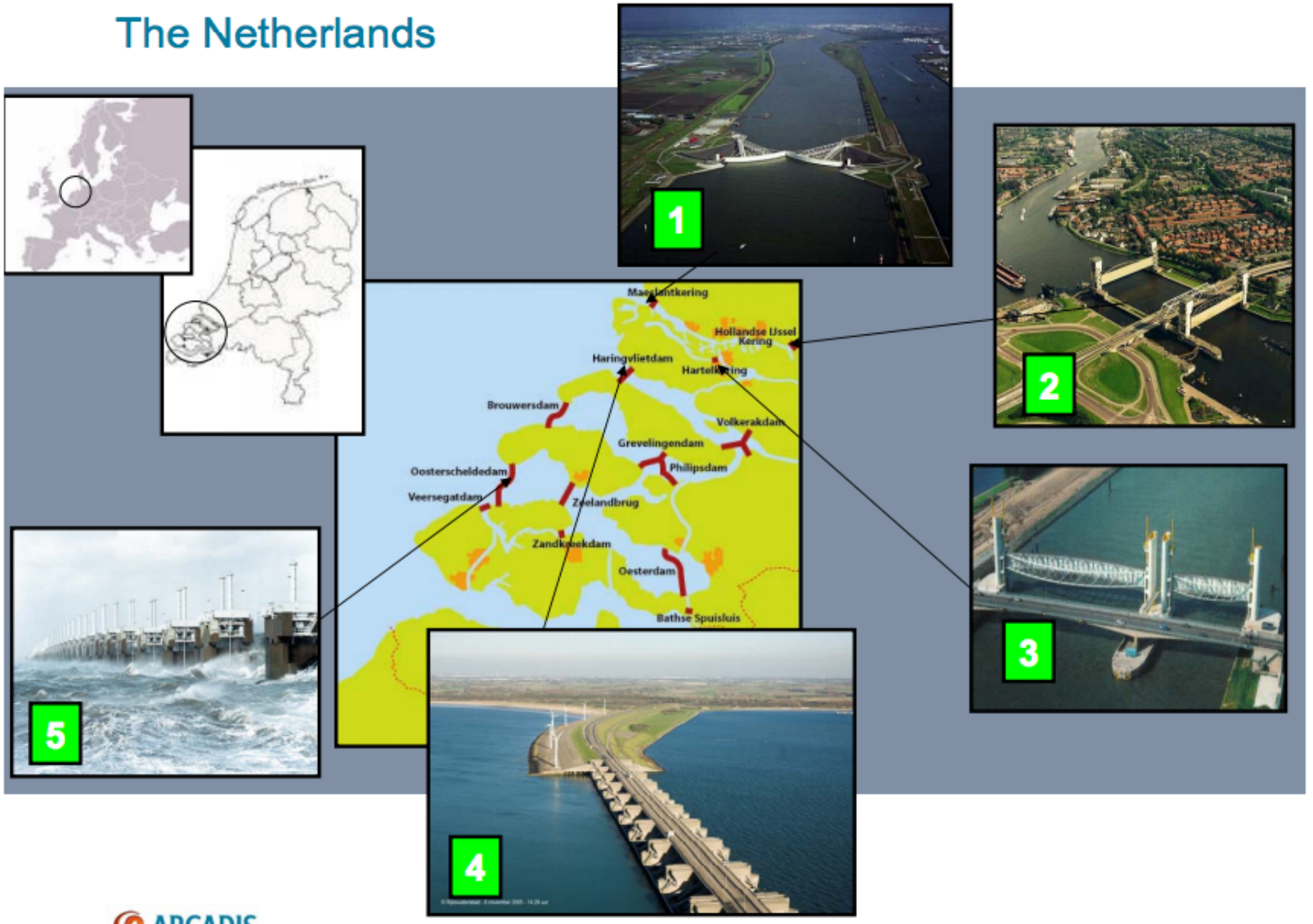
- Scientifically-defined hazard
- Direct design approaches
- Defined outcomes with probabilities of achieving them

Performance-based design
A new approach



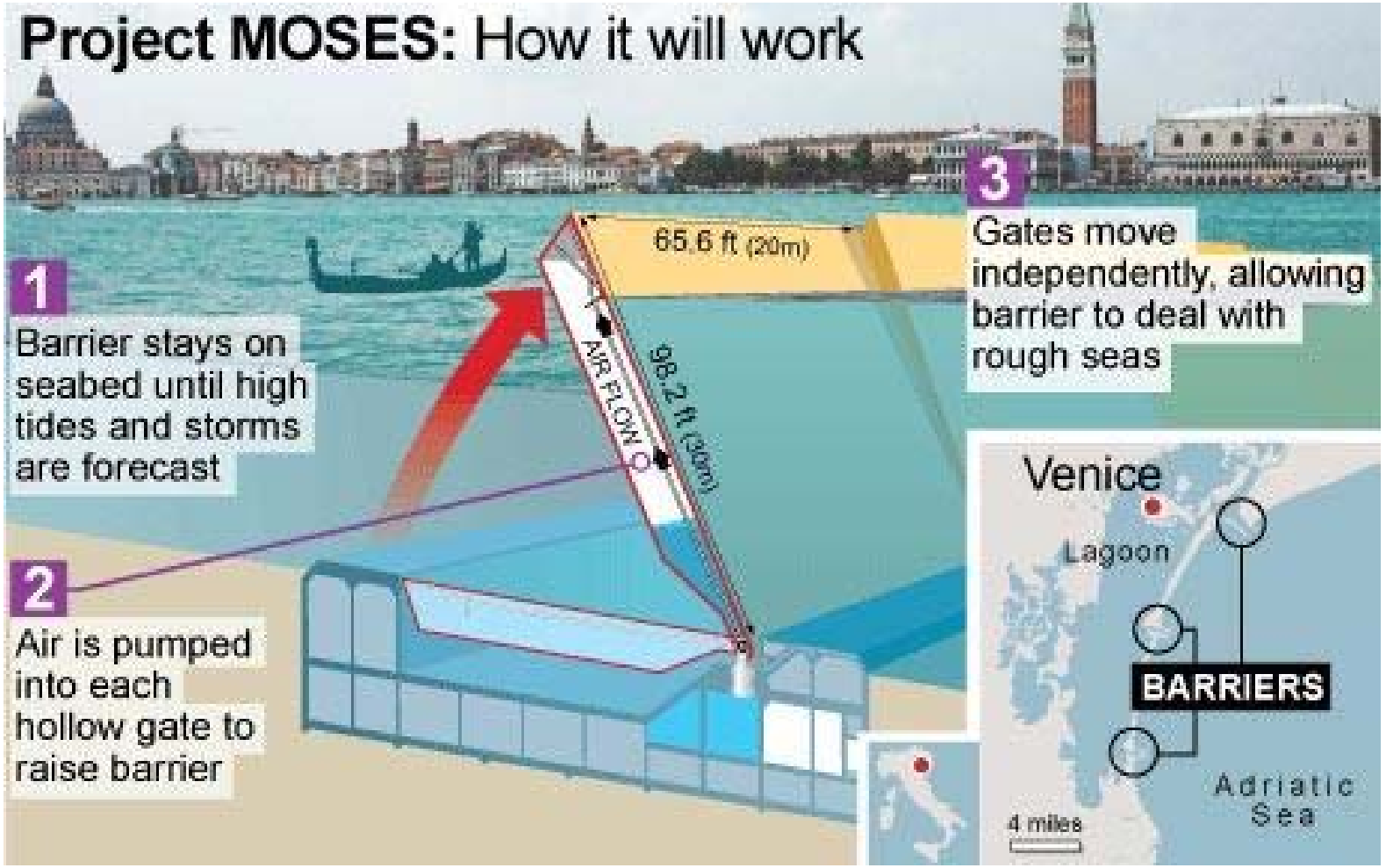
Adapted from R. O. Hamburger

Resiliency – The Netherlands



http://www.businessinsider.com/new-york-storm-surge-barrier-2012-11?op=1

Resiliency - Venice Lagoon



http://www.i-italy.org/node/11150

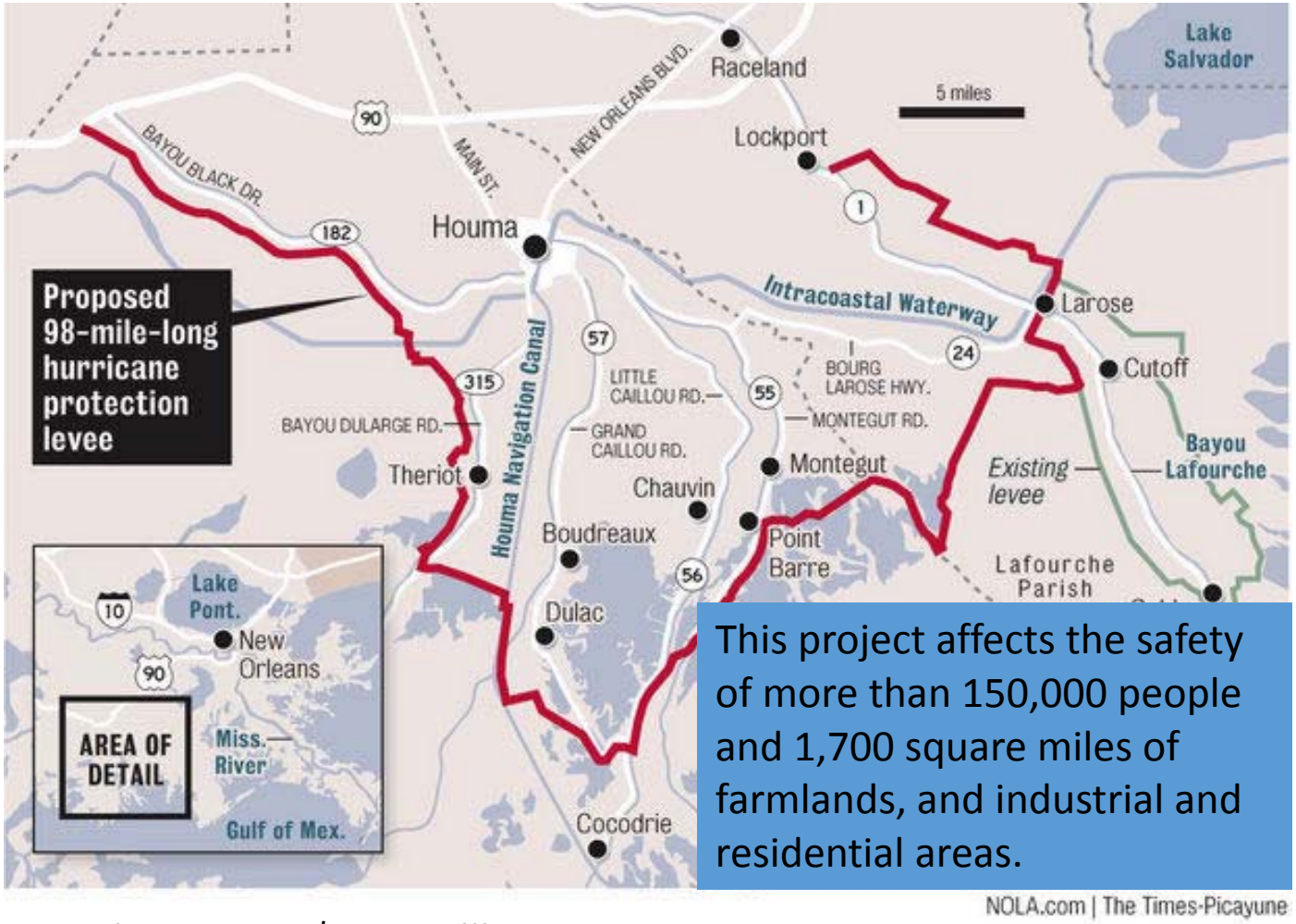
Cost~$7 B

Resiliencv After Hurricane Katrina

Cost
$14.6B

http://media.nola.com/hurricane_impact/photo/hurricane-graphicjpg-c6ae79c140e67e3e.jpg

Resiliency After Hurricane Katrina Morganza to Gulf Levee



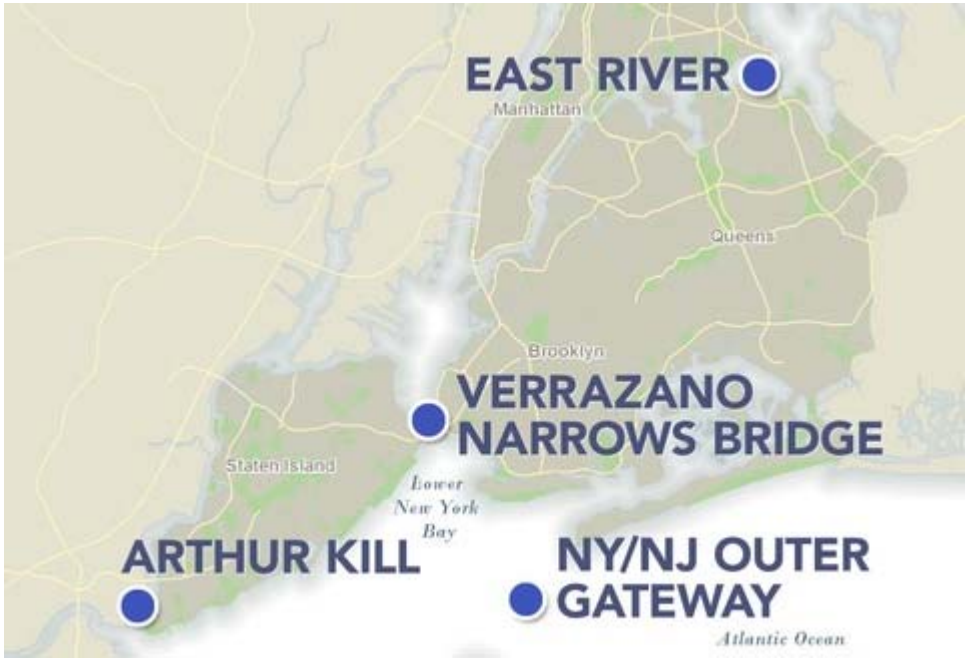
This project affects the safety of more than 150,000 people and 1,700 square miles of farmlands, and industrial and residential areas.

Initial Estimate: $680 Milllion
2013 Estimate: $10.3 Billion

http://www.nola.com/environment/index.ssf/2013/05/corps_of_engineers_concludes_1.html#comments

Also after Whittle (2013)

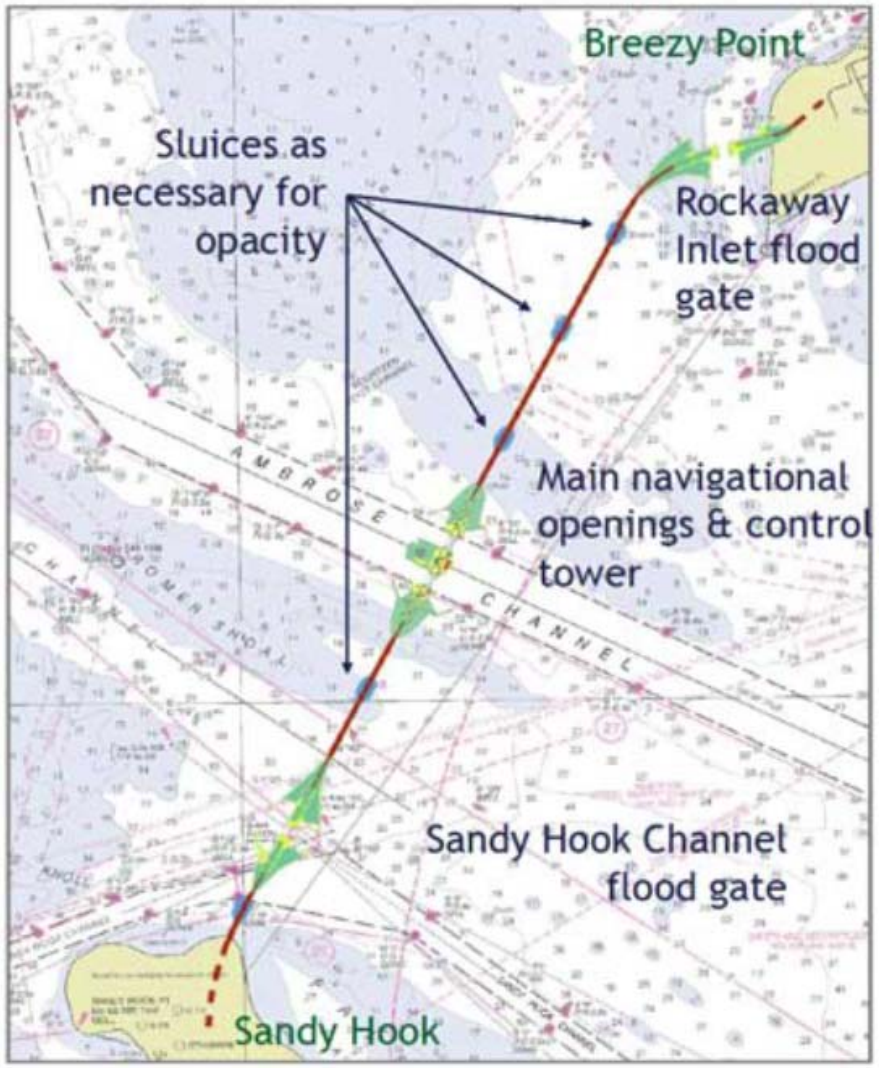
Resiliency – New York City Region



http://www.seagrant.sunysb.edu/articles/t/pbs-news-hour-engineers-consider-barriers-to-protect-new-york-from-another-sandy-coastal-processes-hazards-news

Cost estimate: >$7B

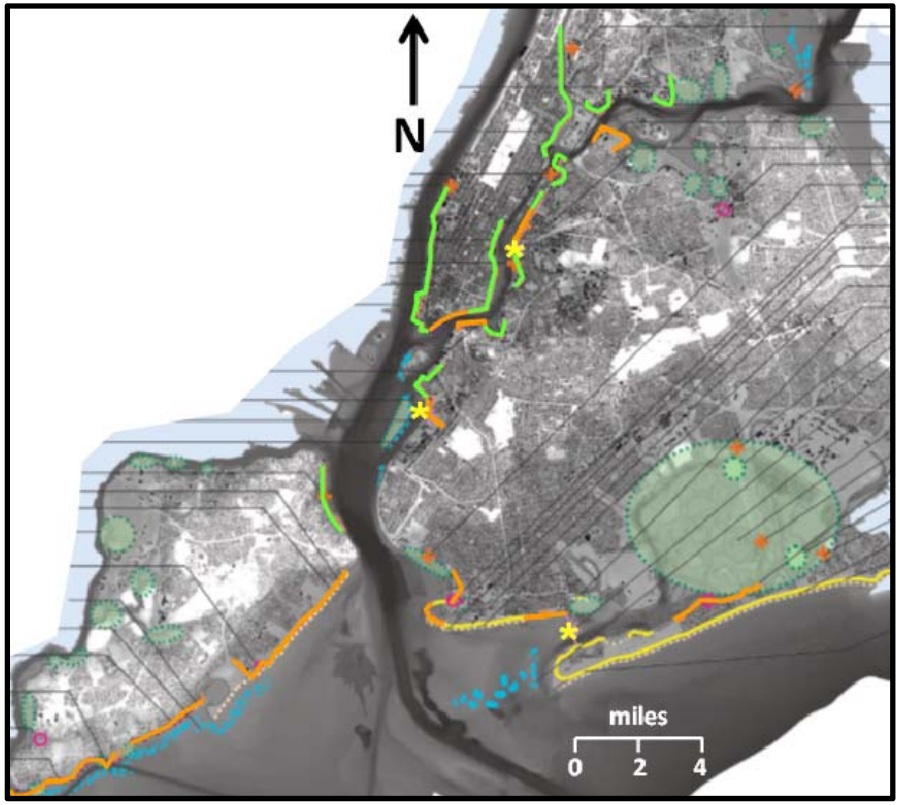
How about the rest of the US Gulf+Atlantic coastline: 3000 miles



Proposd surge barrier
(Forsyth, 2009)

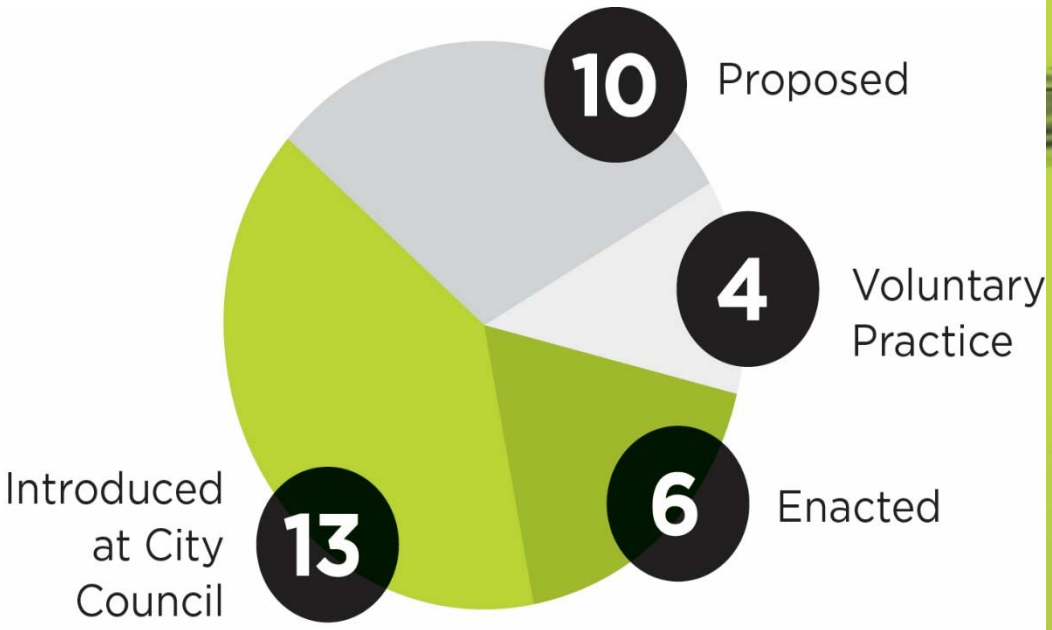
Also after Whittle (2013)

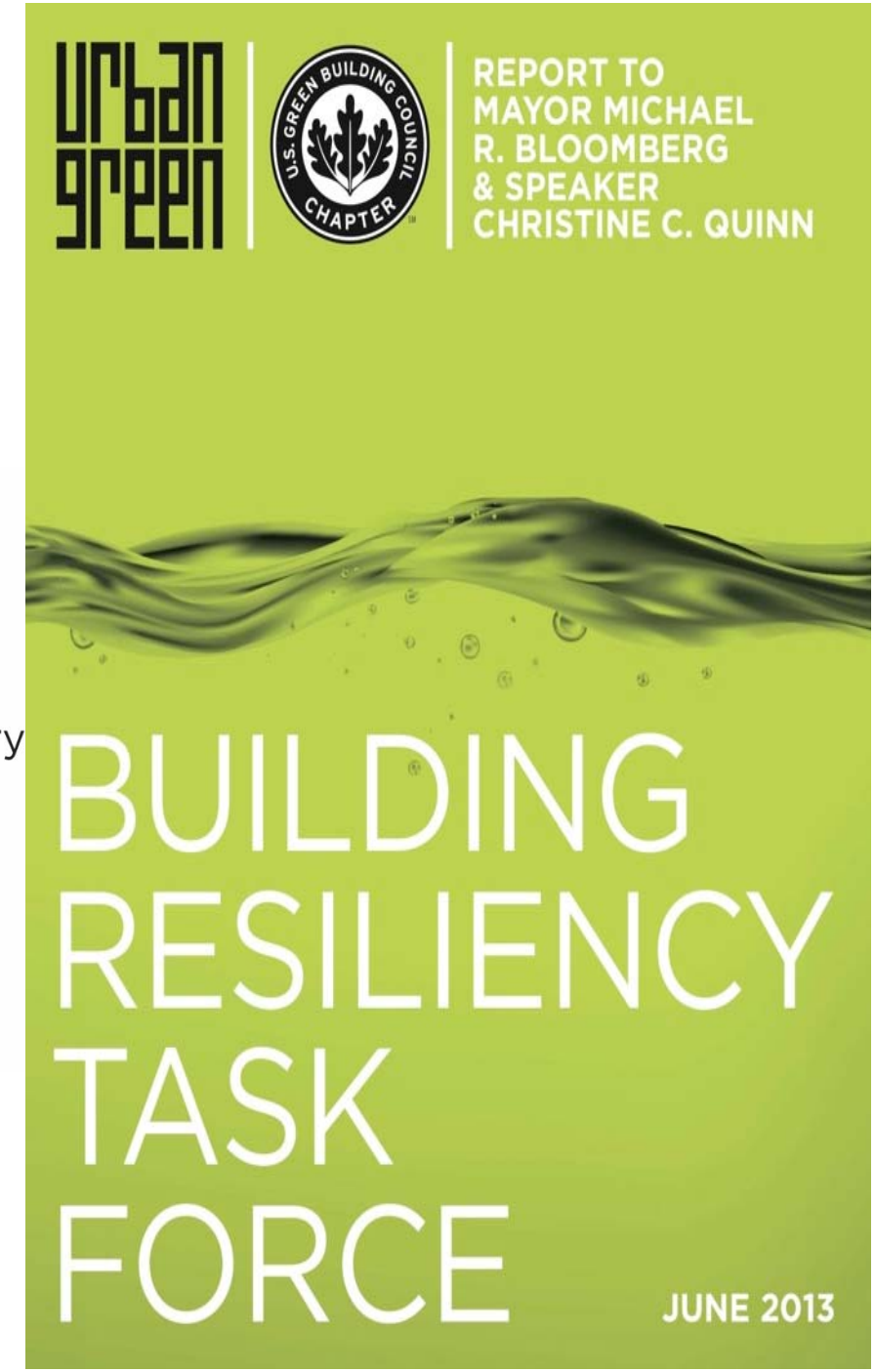
NYC Coastal Protection Plan



NYC Mayor's Comprehensive Coastal Protection Plan, indicating: (i) orange lines - bulkheads, revetments, or levees; (ii) yellow lines - dunes; (iii) green lines - Integrated Flood Protection System; (iv) yellow asterisks - local surge barriers; (v) blue dots - offshore breakwaters; (vi) green shaded areas - wetlands (ref: NYC Special Initiative for Rebuilding & Resiliency, 2013).

IMPLEMENTATION STATUS





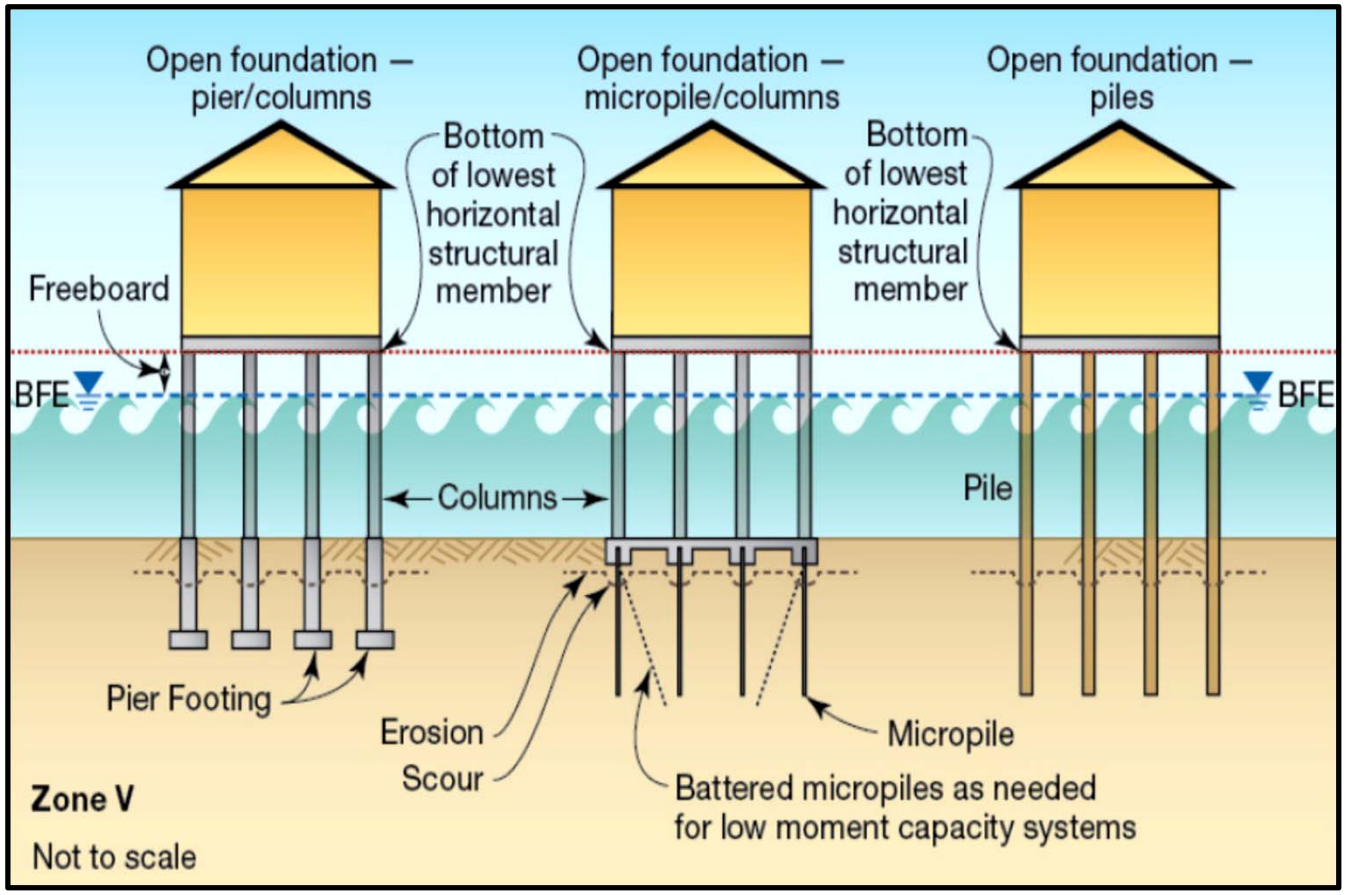
***Slide by C. Scheib** , Urban Green Council*
EERI NYNE October 24, 2013

Considerations for Removable Flood Barriers

- Time to erect and potential for false positives
- Integrity assurance given Hurricane Katrina Experience
- Will that shift flooding elsewhere

Limiting Tunnel Flooding – Tunnel Airbags

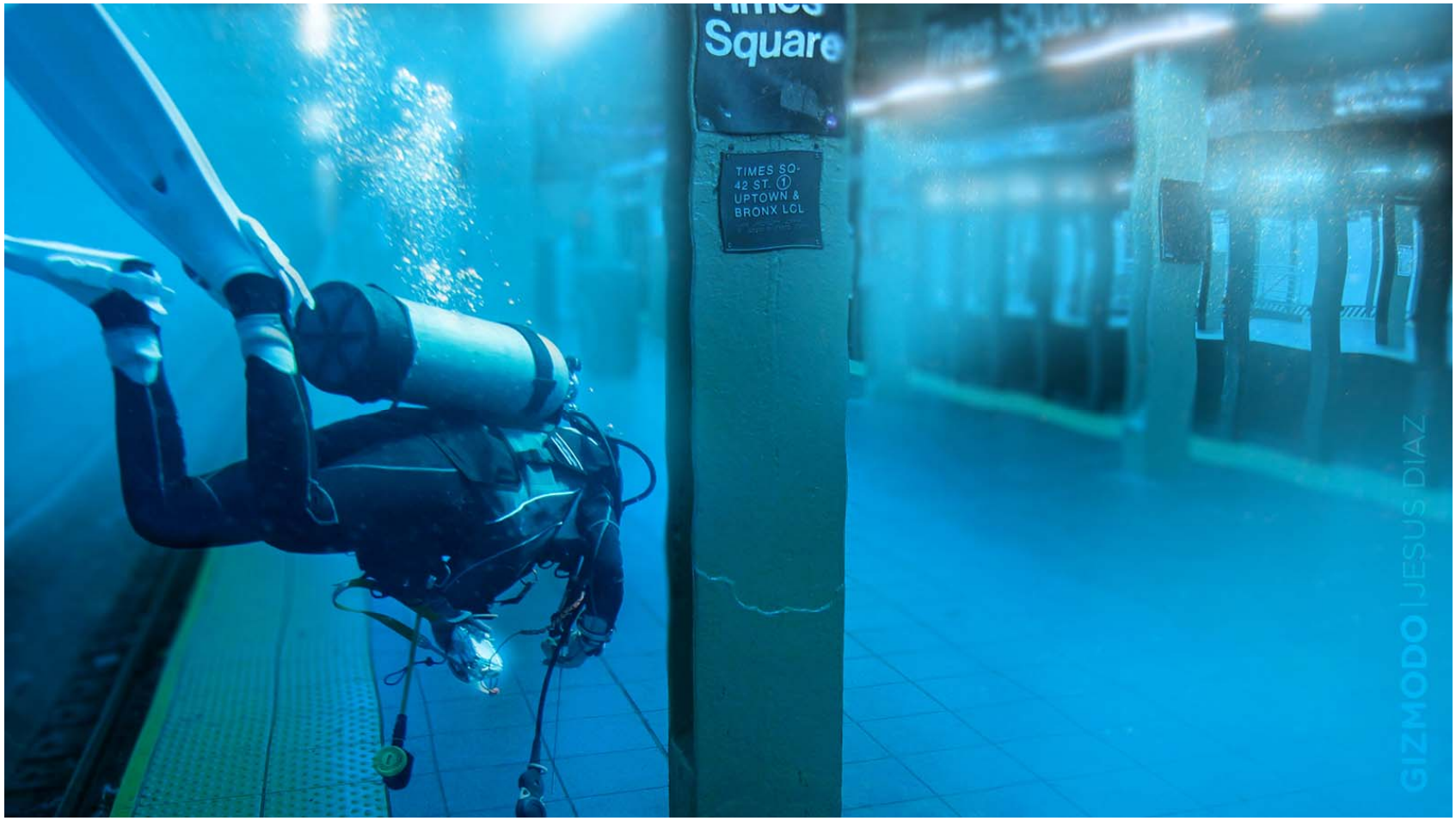
http://phys.org/news/2012-03-gallons-tunnel-inflatable-stopper.html



Examples of NFIP-compliant foundations in Zone V where bottom of lowest horizontal structural member is located above the BFE. (FEMA, 2013).

How about earthquakes (multi Hazard)

A sustainable alternative?
Learn to scuba dive …



http://gizmodo.com/5955689/sandy-could-really-flood-the-new-york-subway-system

Concluding Remarks

- Hurricane Sandy exposed the vulnerability, fragility and resiliency of Urban Centers to extreme weather events
- As a society we need to adapt to a new normal
- It is not sufficient to look back we need to look ahead
- Performance-based design is a good step toward Performance-based infrastructure system(s) design
- (Geotechnical) Engineering is not just about can we do it, but should we do it.
- The engineering challenges are significant
- An interconnected social and political challenge
- New Opportunities in practice and research

Thank You

Questions