Geotechnical Effects and a 6-Year Outlook of the 2012 Hurricane Sandy in the Eastern United States

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ABSTRACT: *Hurricane Sandy was the deadliest and most destructive event of the 2012 Atlantic hurricane season. It originated as a storm off the coast of West Africa that turned into a tropical wave in the southwestern Caribbean Sea, and then into a hurricane that moved slowly north along the United States East Coast. Numerous regional coastal communities and urban centers in New Jersey (NJ) and the New York City (NYC) metropolitan area experienced widespread flooding, extreme winds, and heavy damage that disrupted daily life and business in Lower Manhattan, the world's financial capital. Consequences with great geotechnical engineering interest include: (i) modification of the regional coastal geomorphology due to storm surge, with the birth of new inlets, erosion, scour of soil at the shorelines; (ii) damage in coastal communities that revealed the vulnerability of residential building foundations not designed according to modern flood protection standards; and (iii) interruption of service of buried structures and below ground infrastructure due to flood damage to non-structural components. This paper presents observations of characteristic damage to geotechnical infrastructure and alteration of the geologic setting collected and documented by the Geotechnical Extreme Events Reconnaissance Association (GEER; geerassociation.org) team that was activated while the hurricane reached NY-NJ. It was led by the first two co-authors with a core of ten GEER volunteers from academia and the industry, who were joined by a large team of local engineers with the support of public agencies, all working diligently to capture observations in a timely manner. A summary of the reconnaissance work, background research, main design impacts, and examples of improvement projects are provided. The importance of urban infrastructure resiliency and sustainability is discussed as a main lesson from this case history, and some actions needed to achieve those are proposed.*

KEYWORDS: Hurricane Sandy, GEER, geotechnical reconnaissance, New York - New Jersey, infrastructure, erosion, foundations, sustainability, resilience

SITE LOCATION: Geo-Database

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INTRODUCTION

Hurricane Sandy was unique in many respects with a record storm tide, moving very slowly and causing flooding of densely populated urban centers at an unprecedented scale. It formed in the Caribbean Sea as a combination of several weather fronts moving northeasterly along the coast, then turned abruptly to the west into a superstorm as it made landfall near Brigantine, NJ, on the evening of October 29, 2012. As the storm approached, the counterclockwise wind currents caused the predominant high velocity wind direction over Long Island (LI) and NYC to come from the east, which drove devastating storm surges into the coastal areas of NJ and NYC (Blake et al., 2013). From Jamaica to Canada, Hurricane Sandy caused devastating flooding and high winds, destroyed housing and infrastructure, left millions of residents without power and shut down Wall Street for two days, causing over 70 billion dollars in damages (NOAA, 2018). Per the Red Cross, this event claimed the lives of at least 50 people in the Caribbean, followed by 117 people in the United States (U.S.).

Observations of geotechnical engineering interest included: (i) modification of the coastal geomorphology due to the regional storm surge with creation of new inlets, soil scour at the shorelines, and patterns of soil erosion that were influenced by marshes, dunes, and barrier islands; (ii) damage of residential building foundations due to storm surge in coastal communities and overall performance according to design standards at the time of construction as compared to potential improvement using modern flood protection standards; and (iii) service interruption of critical transportation and power infrastructure due to flood damage to non-structural components, buried structures, and below ground infrastructure. This paper summarizes damage to geotechnical infrastructure, which is documented in greater detail in the GEER Report No. 23 (Hashash et al., 2013), and selected developments up to the end of year 2018. Key observations of the GEER team that contribute to a comprehensive case history of a major hurricane are presented, resulting in geotechnical engineering design and philosophy shifts in future planning of metropolitan areas towards resilient yet sustainable designs against extreme natural events.

EVENT TIMELINE AND KEY CHARACTERISTICS

Sandy was a late-season cyclone or hurricane that started as a tropical disturbance off the coast of West Africa and later became a hurricane in the southwestern Caribbean Sea. It moved northeasterly along the U.S. East Coast and turned abruptly, becoming a superstorm as it made landfall near Brigantine, NJ, on October 29, 2012. As the storm approached, the counterclockwise rotation directed high velocity winds to be from the east, driving devastating storm surges into coastal areas of NJ, western LI, and the boroughs of Queens, Brooklyn, and Staten Island (SI). The maximum recorded storm surge (NOAA, 2013), defined as the observed water level (storm tide) minus the predicted astronomical tide levels, reached 3.855 meters or 12.65 feet (ft). Manhattan experienced an inundation of 1.7 m (5.5 ft) above ground from a surge of 3.5 m (11.4 ft). Blake et. al (2013) provide a detailed description of the storm and its path, which is shown in Fig. 1.

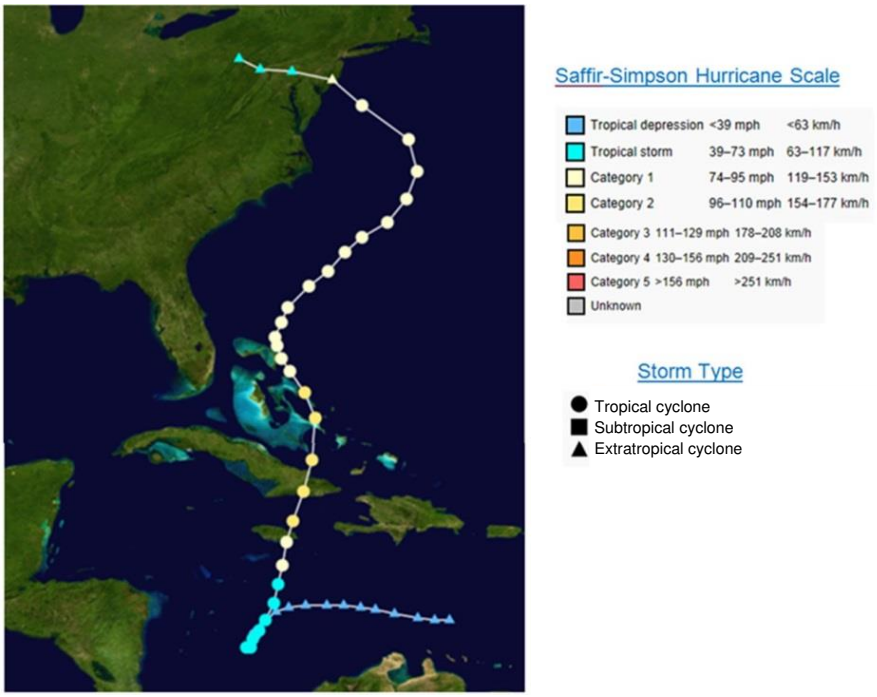


Figure 1. Map of Hurricane Sandy at six-hour intervals. Peak sustained wind speeds are colored per the Saffir-Simpson scale. The shape of points reflects the nature of the storm (based on Cyclonebiskit map with NOAA data and NASA background).

HISTORICAL HURRICANES AND STORMS IN THE REGION

Every year, historically in late summer and fall, tropical storms originate in the Atlantic Ocean, east of the Caribbean. Some travel as hurricanes into the Gulf of Mexico and others travel up the East Coast, developing into hurricanes with decreased wind speed as they make landfall. Those that do not make landfall can still be felt strongly along the coast by their winds and rainfall, which cause coastal flooding and inland rivers to swell and overflow. Coastal areas may be exposed to surges that exceed normal tide level, resulting in flooding. The shape of the coastline and the wind direction affect the height of the surge.

Based on 100-year historic data, Category 1-3 storms that impact NYC coastal area (see Fig. 2), typically occur every six years. However, in the last 25 years, this frequency has been reduced to about three years. Older records from the 19th century identify occurrence every 14 years, which could be due to variations in data keeping. Major events have created wind gusts of 84-180 kilometers per hour (km/h), or 52-113 mph, and surges of 0.9-5.5 m (3-18 ft). The effect of many of these events was not as severe, as they occurred in low tide or were too far away from the city. Reported events by the NYC and Nassau Offices of Emergency Management are:



Figure 2. Images from historic hurricanes in 1938 (left) and Hurricane Gloria in 1985 (right) (NYC Office of Emergency Management).

- 1821, NYC experienced a hurricane that passed directly over parts of NYC on September 3, with a 3.9m (13 ft) surge in one hour, causing the East and Hudson rivers to merge in lower Manhattan. Only a few deaths were reported, likely due to home scarcity.
- 1893, Hog Island experienced a Category 1 hurricane in Queens, off the Rockaways, that destroyed the resort island Hog.
- 1938, NY - New England experienced a Category 3 hurricane that killed almost 200 people, crossing over Long Island (LI) into New England, with millions of dollars in damages and electrical power shutdown in Manhattan and the Bronx.
- 1954: Hurricane Carol made landfall in eastern LI and southeastern Connecticut, sustaining winds of over 160 km/h (100 mph). Though the storm's track was 65 km (40 mi) east of the boroughs, major flooding occurred throughout NYC.
- 1955: Hurricanes Connie and Diane triggered major rains of more than 0.3 m (12 in) and flooding in August, although the eye of the storms did not cross over the five boroughs. Diane caused more than 200 deaths in PA, NY, and NJ.
- 1960: Hurricane Donna created a 3.4 m (11 ft) storm tide in the NY Harbor, causing extensive pier damage.
- 1972: Tropical Storm Agnes combined with another storm system in June and resulted in flooding from North Carolina to New York State, causing 122 deaths and more than $6B in damage when adjusted for inflation.
- 1985: Hurricane Gloria was a Category 3 hurricane that first hit North Carolina and caused devastation along the East Coast. It became Category 1 by the time it reached LI, but it still caused serious damage. The U.S. Army Corps of Engineers (USACE) estimated that Gloria could be catastrophic had it been a little closer to the city and had it arrived

at high tide.

- 1995: Hurricane Felix lingered near the East Coast for nearly a week in 1995, affecting the entire Northeast.
- 1996: Tropical Storms Bertha and Edouard struck. In July, Bertha caused heavy rainfalls in NYC. Then Edouard moved toward NYC around Labor Day, causing NYC to close schools, but then later changed course and headed toward the Atlantic.
- 1999: Tropical Storm Floyd brought sustained 97 km/h (60 mph) winds and 25-40 cm (10-15 in) of rain in NY/NJ in one day in September. Hundreds of people evacuated, NYC schools closed, and emergency storm shelters opened.
- 2011: Hurricane Irene became a tropical storm before making landfall in NYC in August with winds of 105 km/h (65 mph) and rainfall of 18 cm (7 in). Coastal rockaway areas with 370,000 residents and 34 health care facilities were evacuated. Estimated damages amounted to $100M; federal disaster assistance for 8,000 residents amounted to $13.6M.

GEER TEAM

Following an initial meeting held on November 2, 2012, two major GEER reconnaissance groups were formed to cover the NYC boroughs and NJ, as some NYC subway and bus lines were only been partially restored and significant portions of the subway, road, and commuter rail network remained non-functional. The initial goal was to visit accessible areas and collect perishable data, which were later supplemented with background information. In the days following the storm and in subsequent weeks (in collaboration with the NYC Department of Buildings and other city and state agencies), the GEER-NYC team collected data in Manhattan (Lower West and East Sides and the Battery Park waterfront), Staten Island (beachfront), Brooklyn (Red Hook, Bridge Park), and Queens (Rockaways, Long Beach, Broad Channel). The GEER-NJ team visited the coastal area from Brigantine to Belmar, Atlantic and Ocean cities, Longport, Ship Bottom and Long Beach Island, Seaside Heights, and Ortley. The observation location sites are shown on the map of Fig. 3.



Figure 3. GEER NYC and NJ teams' observation locations following the storm, and sites of information gained through collaboration with city and state agencies over the subsequent weeks (GEER, 2014).

IMPACTS

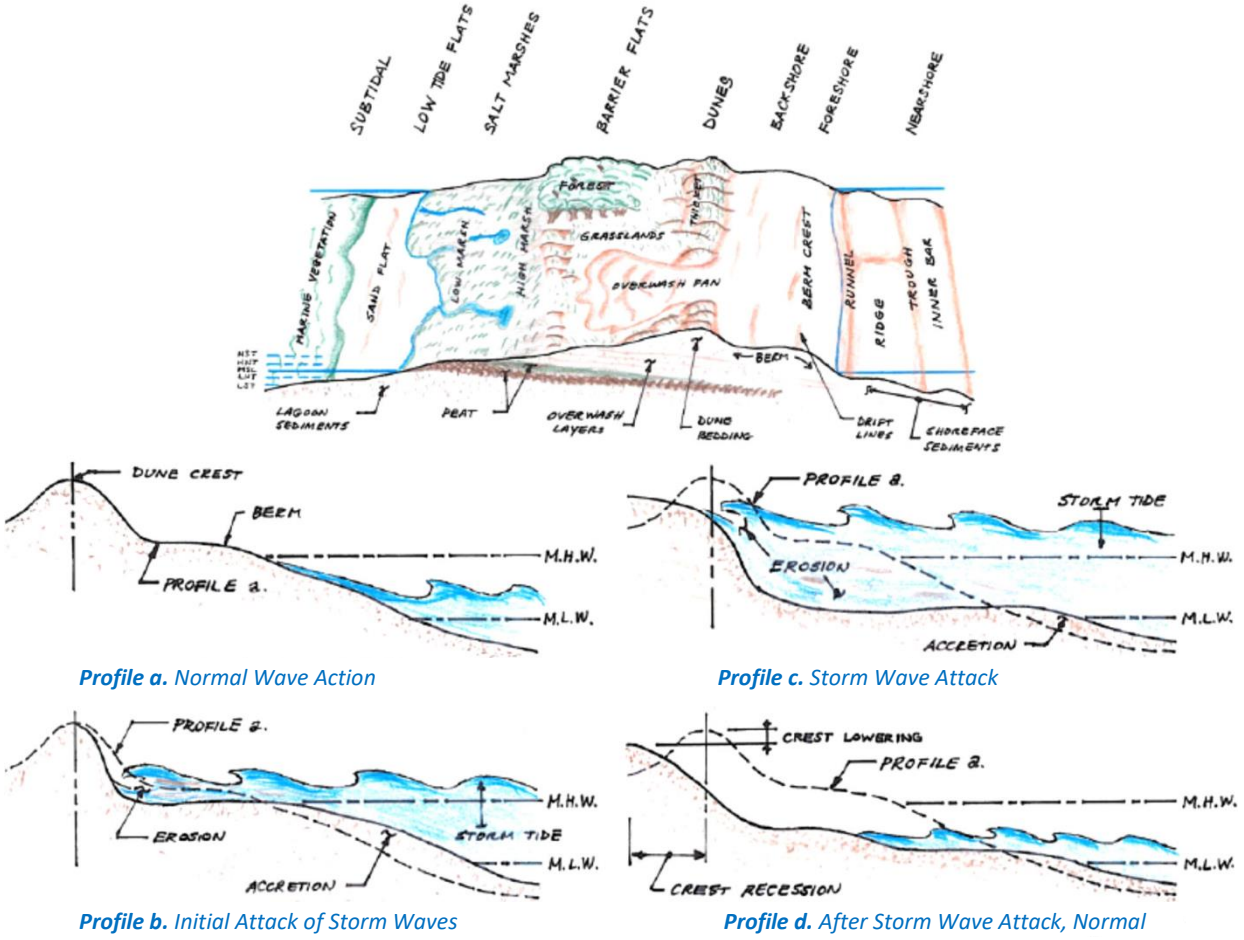
Coastal Geomorphology and Natural Coastline

The affected shoreline is primarily made up of eroding headlands and a series of barrier islands that run roughly parallel to the mainland. The barrier islands are natural buffers that protect the mainland and the back-bay from storms and waves coming from the ocean, and are composed of loose sediment held in place only by gravity and roots. While there are

competing theories on the details, the consensus is that barrier islands began to form after the last glaciation, migrating up the coastal plain as sea level rose to its current levels (Haslet, 2009). As sea level kept rising, the shorelines moved inland and wave action helped the barriers migrate landward (Fig. 4). Strong ocean waves pick up beach sand and move it offshore, steepening the beach during a storm. Then dune lines are eroded and, if they're overtopped, waves can push sand and dunes landward over the marshes. The wash overs build the bay-side of the island, maintaining a barrier between the ocean and the mainland (Fig. 5).

Climate change is expected to increase the current sea level rise rate by a factor of two to three in the next hundred years (Stutz & Pilkey, 2009). Paradoxically, gradual sea level rise can create shallow bays that generate new barrier islands along certain types of coastline. However, rapid sea level rise combined with a decline of sediment supply can inundate islands, causing them to disappear. This is the main reason for the rapid erosion of islands along the Mississippi Delta, Eastern Canada, and the Arctic (NASA, 2011). While islands react differently based on the regional geology, waves, and tides, the rate of rise is essential in the outcome of disappearance or creation of barrier islands. Man-made efforts such as dredging open navigation channels or structures along the beach interfere with natural processes and the island's long-term ability to preserve itself.

Along the NJ shore, coastal hydrodynamics depend on local bathymetry, barrier islands, and shoreline structures. The coast is divided roughly into three zones of different wave climatology (Psuty & Ofiara, 2002), with most of the waves arriving directly onshore from the southeast in Ocean County. The south counties Atlantic and Cape May are exposed to waves from the east-northeast, while the north county Monmouth has no barriers, yet it is protected from waves by New England and Long Island. This indicates that local features have great effects on the hydrodynamics and sediment transport (USDA, 1989), with the combination of fetch and tides being key in producing record-flooding levels.



Profile a. *Normal Wave Action*

Profile c. *Storm Wave Attack*

Profile b. *Initial Attack of Storm Waves*

Profile d. *After Storm Wave Attack, Normal*

Figure 4. Barrier environments (top) and beach profile changes (bottom) in response to a coastal storm (Refs: A. Dyer from Leatherman, S.P., 1979; Godfrey, 1976; and U.S. Army Corps of Engineers, 1974).

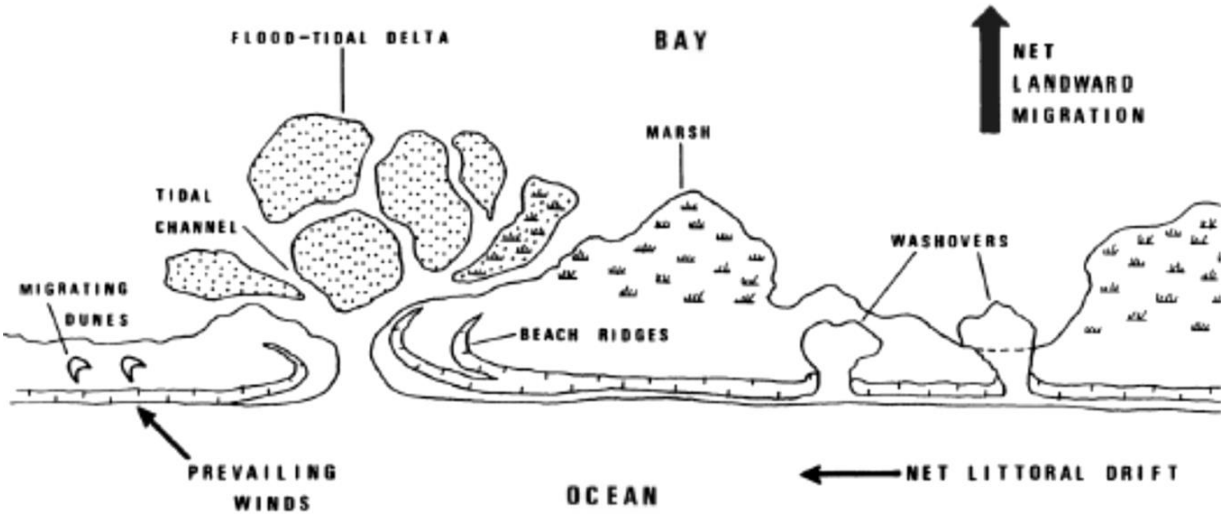


Figure 5. Geologic processes that build up a barrier island, allowing landward migration with sea level rise (Johnson, 1982).

Figure 6 depicts the wind direction, fetch, coastline shape, and normal tidal cycle. The counterclockwise wind currents caused an eastern high velocity wind direction over LI and NYC. This pattern was verified by the GEER team's observation that many of the thousands of fallen trees in LI fell to the west. The following factors contributed to an increase of the surge:

- The westward direction of the winds created a long fetch distance from the east towards Raritan Bay and LI Sound.
- The "constricted" shape of both the Raritan Bay and LI Sound narrowing to the west caused the surge height to increase as it moved into those areas due to a "funneling" effect.
- The slow storm movement resulted in the maximum surge being superimposed above the astronomical high tide.

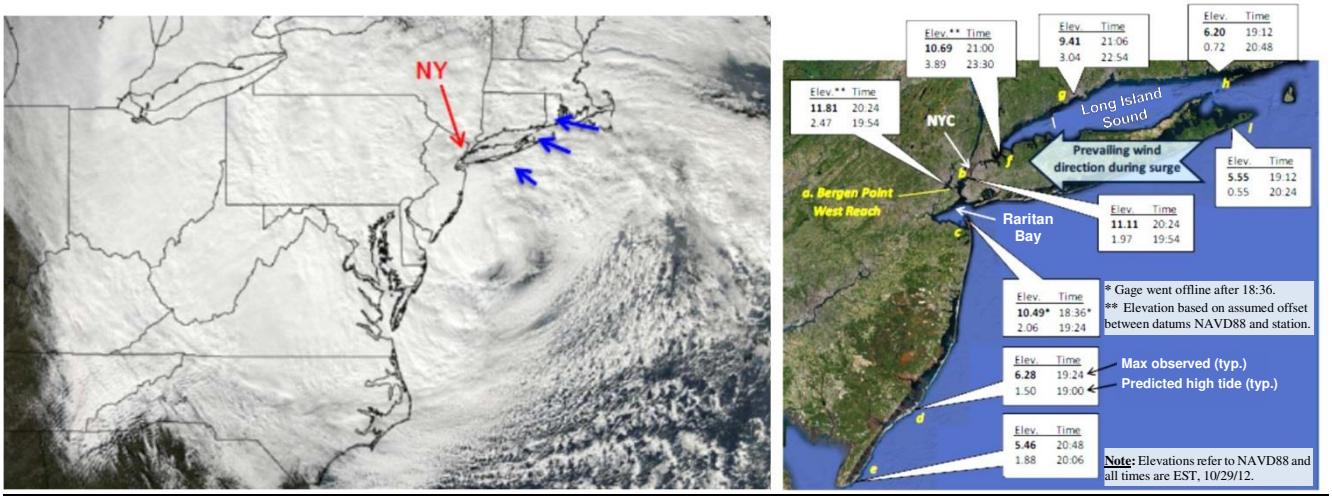


Figure 6. Hurricane Sandy's circulation on 10/29/12 at 2:20 pm EDT; blue arrows show wind direction close to landfall in southern NJ (left; nasa.gov/ hurricanes/ h2012_Sandy). Observed and predicted tide from NOAA stations (right).

The storm surge significantly modified the coastal NY/NJ geomorphology, with the birth of new inlets and severe erosion and scour of soil on the shorelines (Fig. 7). While devastating in their path, these effects were largely consistent with predictions.



Figure 7. Fire Island, LI: New inlet with narrowing point by embayment in yellow arrow (Ref: tmappsevents.esri.com/).

Salt Water and Street Trees

Salt water flooding typically causes chronic stress and even mortality of street trees. When Hurricane Sandy struck, salt water was associated with significant physiological stress of NYC street trees, which consist mainly of red maple and London plane species. While the immediate physical impact of the hurricane on the trees was anticipated, the number of trees left standing with significant long-term health problems due to the salt water was unexpected. An estimated 46,000 trees situated on the 1,426 km (890 mi) of flooded NYC streets were impacted by Sandy, excluding trees in parks, forests, and homes. Studies (Hallett et al., 2018) showed that more than 50% of the flooded London plane study trees died and those that remained alive continued to decline for several years. Red maples were more salt-tolerant, with only 10% of the flooded trees dying and no major long-term physiological stresses on the surviving trees. In contrast, unflooded red maples were affected, possibly due to lower rainfall or higher temperature exposure at their locations. Since street trees in urban coastal areas are likely to be impacted by floods, research since Sandy has been identifying genotypes of trees that are hyper-tolerant to high saline conditions.

Bridges

GEER observations of seven NJ bridges (NJ 35 - Cheesequake/Manasquan River Drawbridges; Railroad Drawbridge - Manasquan River; NJ 70 - Metedeconk River; NJ 37 - Mathis/Stanley Tunney; NJ 528 - Mantoloking; NJ 72 - Henderson Memorial) and data by the NJ Department of Transportation, Transit Authority, and Ocean County Engineering suggest that bridges remained mostly serviceable immediately or soon after the storm. Two primary themes of damage were identified: (i) flooding effects to drawbridges (e.g., Morgan Drawbridge, Fig. 8) and their electrical systems, and (ii) soil erosion at approaches and abutments (often supported on structures formed by fill within a perimeter soldier pile wall) in several bridges, averaging at 1.5 m (5 ft) of soil removal (e.g., Fig. 8: Rt. 72 Bridge, Fig. 9: Mathis Bridge). The exception was the Mantoloking Bridge that was unserviceable for a long period due to undermining of its abutments and approaches. Figs. 10 and 11 show large floating debris, including houses, that destroyed the T-wall, forcing the coping and sidewalk to cantilever out by about 3 m (10 ft).



Figure 8. Morgan Drawbridge (left; NJ Transit) and Rt. 72 abutment erosion, looking south-east (right; NJDoT).



Figure 9. Erosion at Mathis Bridge southwest abutment (eastbound Rt37) (39.949350°N, 74.113902°W; GEER 2014).



Figure 10. Foundation undermining at east abutment of Mantoloking Bridge (40.040058°N, 74.051886°W; GEER, 2014).



Figure 11. Mantoloking Bridge east abutment erosion (40.040058°N, 74.051886°W, Ocean Ct. Eng., 2012; GEER, 2014).

Urban Infrastructure

Damage in the dense urban NYC area of lower Manhattan was primarily related to flood inundation. High water marks and evidence of flood damage to approximately 1.2-2.1 m (4-7 ft) above street level were observed throughout low-lying neighborhoods (e.g., South Street Seaport) and water front areas (Fig. 12). Below-grade subway stations, tunnels, parking garages, and excavations experienced widespread flooding. While access to many of these locations was restricted to the GEER team due to ongoing recovery work, evidence of flood inundation was visible from the surface, e.g. at the Battery Park underpass and Bellevue Hospital. Based on reports in the days and months following the storm, the flooded tunnels included the Brooklyn Battery, Holland, and Queens-Midtown highway tunnels, the PATH rapid transit tunnels, NJ Transit / Amtrak / LI Railroad Hudson and East River rail, and seven subway tunnels. Several subway stations and open excavations were flooded, including South Ferry, which flooded to the ceiling, as well as an excavation at the World Trade Center site (Figs. 13-14).



Figure 12. South Street Seaport (40.706685°N, 74.003554°W), 11/4/12: High water line on window of a restaurant (left); typical flooded basement (middle); flood damage (right). (GEER Report, 2014).



Figure 13. Flooded Battery Park underpass (40.701600°N, 74.011742°W) on 11/4/12 (left, by GEER 11/3/12); E30th St. (40.739830°N, 73.973263°W) Bellevue Hospital (middle, by GEER 11/3/12); South Ferry station (right, by MTA 10/30/12).

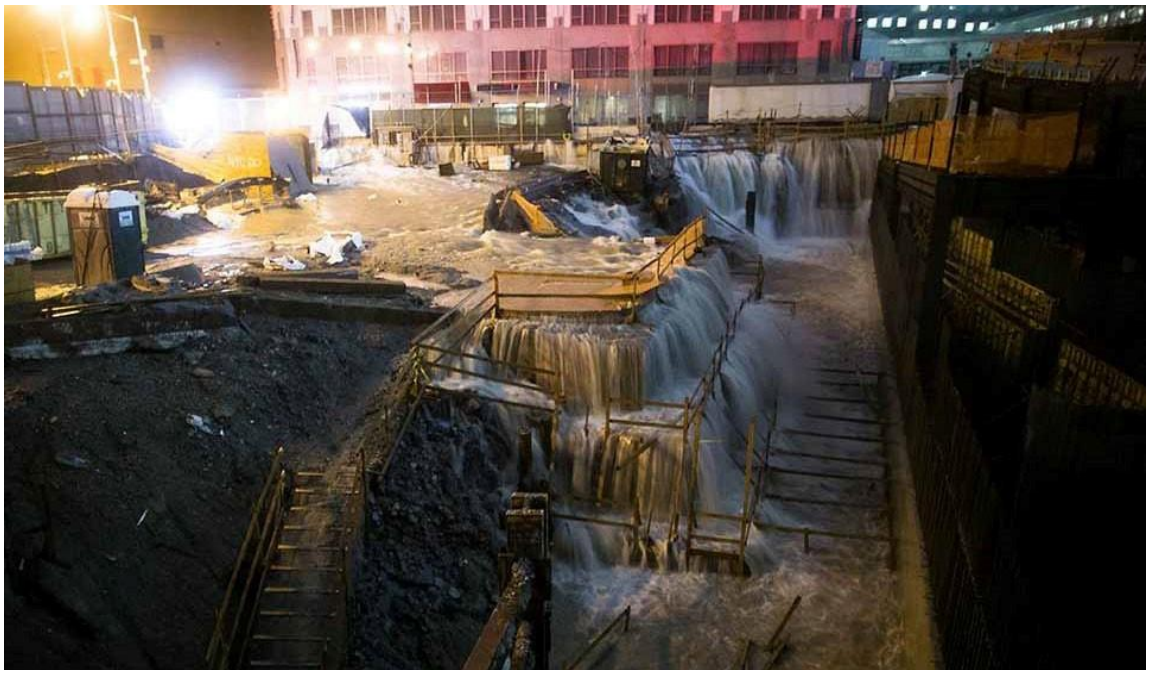


Figure 14. Open excavation flooding at the World Trade Center site (Photo: Associated Press).

While most tunnels experienced minimal structural damage, utilities and ventilation systems were severely damaged and required lengthy repairs. Indicatively, the [R] Montague St. subway and the World Trade Center PATH tunnels were out of service for 2-3 months. The R line was taken out of service again in 2013 for lingering flood damage repairs. The Canarsie Tube of the [L] subway line was inundated with 265,000 m^3 (7M gallons) of saltwater that caused corrosion of cabling, circuit breakers, and disabling of power/track equipment. The duct bank alongside the track, which provides walkway for emergency egress, sustained heavy damage and exhibited a partial collapse. With an initial 15-month shutdown plan, a complete overhaul is still necessary today, in 2020 (Fig. 15), as the L line is critical with a large portion of its daily 400,000 riders travelling to 14th Street stations, some of which are not easily reached by other lines. The Queens [A] Rockaway subway line was out of service for nearly seven months due to two major washouts at the earth embankment crossing Jamaica Bay, which exposed the old Long Island Rail Road (LIRR) infrastructure (Fig. 16).



Figure 15. Canarsie tube of [L] line: damage from Sandy (left) and work needed to repair it (right) (MTA, 2017).

NYC flooded tunnels and re-opening dates are presented in Table 1 (from Kaufman et al., 2012; Khinda, 2013; North American Tunneling Journal, 2012; and other news media reports). Underground grid utilities were also affected, including power, telephone, and telecommunications (internet and cable TV). The map of lower Manhattan on Table 1 shows flooded tunnels along with the historic shoreline (Viele, 1865) and the limit of the Sandy flood inundation line (O'Rourke, 2012).



Figure 16. Earth embankment washouts in Queens, along Rockaway subway [A] line after Sandy with old LIRR infrastructure exposed (left) and post mitigation work (right). Photos by Khinda, ed. (2013).

Table 1. Lower Manhattan flooded tunnels data/map with inundation (O'Rourke, 2012) and historic shoreline (Viele, 1865).

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



Many office buildings were shut down for weeks due to lack of utility services and/or escalator and elevator damage caused by ground floor and basement flooding. Salt water, combined with electrical services that were not shut down, caused severe corrosion of power equipment, which required replacement. At the time of Sandy, the NYC Building Code required for emergency generators to be situated at the lower basements. Numerous fuel tanks and pumps were damaged by basement flooding, including the 5-basement Verizon Building (Fig. 17) at 140 West St. next to the World Trade Center Memorial, a main office that provides telecommunication services for the NY Stock Exchange (NYSE). Even though the emergency generators were on the 10th floor, they did not operate because of the lack of fuel. The other Verizon central office providing this service is on Broad St., which was also flooded, so Verizon fuel trucks were dispatched to the 140 West St. where pumps were set up at street level and fuel was pumped to the 10th floor for the generators to power telecommunications critical for opening the NYSE.

The storm surge exceeded predictions and caused unprecedented damage to the infrastructure of Consolidated Edison (Con Ed), which supplies electricity to nearly all of NYC's 3M customers (representing 8.3M people and 250,000 businesses) and provides 41% of the city's natural gas service. Precautionary measures were taken, including sand bags and "aqua dams" (polyethylene berms filled with water) at substations and vaults, pre-emptive de-energizing of equipment, isolation of 26 steam main segments, and the pre-emptive shutdown of the East River generating station and the Brooklyn Navy Yard co-generation steam plants. Still, the East River, E13th St., and Seaport substations were flooded, resulting in the loss of almost a third of NYC's

generating capacity south of 34th St. for four days, thus causing severe delays to the recovery effort and the restart of subways (Fig. 17).



Figure 17. Flooded lobby of the Verizon building (left, Photo by Governor A. Cuomo); Power outage south of 34th St., 10/29/12 in Lower Manhattan which lasted for four days (right, Photo by I. Baan, NY Magazine).

The impacts could have been worse. Luckily the timeframe of late October 2012 coincided with relatively low electricity demand and Con Ed had enough reserve capacity to meet post-storm demands, even after significant damage to a large portion of power-generating capacity and power-importing infrastructure. Had Sandy hit during a peak summer demand period, the reserve capacity would not have been sufficient and, therefore, long-lasting outages may have occurred. Also, had the peak storm surge coincided with high tide at LI Sound (which occurs two hours later than high tide at NY Harbor; see Fig. 1), it is likely that the generating facilities in Astoria, Queens, would also have been flooded, resulting in a loss of an additional third of NYC's generating capacity (NYC SIRR, 2013).

Coastal Communities and Building Foundations

Storm surge, flooding, and erosion impacted residential housing and municipal infrastructure foundations in coastal areas investigated by the GEER team (Fig. 3). Destruction of wood-frame houses in Staten Island (SI) was common, as observed based on the "before" and "after" aerial photos of a row of houses (Fig. 18), which were completely removed by the storm. This area is underlain by glacial outwash sands, often overlain by man-made fill. Most of the structural/foundation failures occurred in dwellings built prior to 1938, typically developed as summer residences in areas with direct exposure to open ocean, constructed less robustly than modern, permanent-residence, homes (Eschenasy, 2013). Moving inland, dunes, and vegetated strips had a positive effect in reducing the damage.



Figure 18. Aerial photographs from New Dorp Beach, SI, before and after Sandy. Row of houses completely removed and debris moved inland. (Images from tmappsevents.esri.com/website/swipe_sandy/).

A common damage pattern among wood frame houses was the pulling off their foundation due to inadequate anchorage (e.g., Sea Bright, NJ, Fig. 19). Theses house were subject to flotation, which not only causes distress, but removes dead load from foundations, making them more susceptible to breakage. Particularly, Concrete Masonry Unit (CMU) wall foundations and piers performed poorly, and were found buckled, broken, or completely removed, causing tilt, dislocation, or collapse of the superstructure (Fig. 19). In Sea Gate, Brooklyn, a concrete beachfront retaining wall foundation was undermined by erosion and subsequently broke, while the soil behind the wall was washed out (Fig. 20). In Breezy Point and Roxbury, Queens, two-story wood-frame homes, on CMU block wall and pier foundations, sustained major structural damage, including being pulled off their partially or completely destroyed foundations (Fig. 20). On the other hand, foundations of high-rise residential buildings (typically piles) generally performed well.



Figure 19. Sea Bright, NJ, beach cabana (40.350086°N, 73.972954°W) pulled off its base (Photo by AP/Wenig; 11/19/12).



Figure 20. Undermining of beachfront retaining wall and loss of retained soil, Sea Gate, Brooklyn (left, 11/9/12); Destroyed CMU wall foundation, Breezy Point, Queens (right, 11/12/12). Photos by NYCDoB (GEER, 2014).

A spectacular failure was observed by the GEER team at a two-story home at Pehola Park, Long Beach Island, which was sheared off its piles due to storm surge forces as well as wave action. Only the upper story of the home was visible, found near its original location. The site's approximate ground elevation was 2.35 m (7.7 ft) and the high-water mark was about 0.7 m (2.3 ft) above ground. The surrounding homes were intact, with the only difference being that this home was at a lower elevation than the others (Fig. 21). This pattern of lower story disappearance and/or flattening was observed in other areas as well.

Damage to shorefront and residences was evident in areas of Brooklyn, Queens. Nassau's Long Beach also suffered significant damage, with flood evidence ranging from 0.8 to 1.5 m (2.5 to 5 ft) above street level, causing nearly all basements and first floors to flood. Construction in the area is typically a diverse stock of wood frame "bungalow" houses, two- or three-story wood and brick veneer townhouses, three- to six-story apartments, and high-rise towers. Often the ocean fronts include

concrete pile-supported wooden boardwalks, and some homes are separated from the beach by concrete or sheet pile retaining walls. In Rockaways, Queens, the boardwalk had been lifted off its piers and damaged or destroyed over its entire length, with debris carried up to 60 m (~200 ft) inland (Fig. 22).



Figure 21. Timber piles remain in place after a home was sheared off in Pehola Park (39.610016N, 74.206657W, GEER, 2014).



Figure 22. Damage to Boardwalk at Rockaway Beach, Queens (40.583445°N, 73.81553°W). Photo by cnbc.

Severe soil erosion was observed along Father Capodanno Blvd in Midland Beach, Staten Island (SI), where sinkholes undermined the street, curb line, sidewalks, utility poles, and house foundations (Figs. 23, 24). Throughout the area, wood decks, trees, cars, and other debris had been deposited inland. Concrete wall foundations generally sustained little or no structural damage, though they sometimes experienced erosion and scour along their perimeter.

Timber and pile bulkheads, which were supported by tierods attached to deadman anchors (pile spacing 1.5 m or 5 ft on center),

along a section of the shore in Atlantic City, NJ, were breached.. The breaches were attributed to the destruction and washing away of the timber facing . The surge and water washing through the breaches exposed the tierods and anchors (Fig. 25).



Figure 23. Scour undermining at Seaver Ave & Father Capodanno Blvd, SI (40.575944° N, 74.083015° W, 11/4/12). Damage to stair foundation and drain (left) and sidewalk, utilities, and light pole foundation (right). Photos by GEER (2014).



Figure 24. Scour undermining of street and utilities at Seaview Blvd, SI (40.579283°N, 74.077849°W, 11/4/12, GEER, 2014).



Figure 25. Bulkhead in Atlantic City, NJ: backfill soil washed away, exposing severely corroded tie rods (GEER, 2014).

Treatment Plants and Other Critical Facilities

For varying durations, several Waste Water Treatment Plants (WWTP) stopped operating due to flooding (GEER, 2014; Kenward et al., 2013), something that resulted in large amounts of untreated or partially treated waste flowing into the environment (Fig. 26). Storm surge often flooded and inundated plants and pumping stations with sea water. Some plants had

to shut down or divert sewage into waterways due to power outages and flooding (e.g., Fig. 26 shows untreated waste spilled in the LI South Shore Estuary from the Bay Park Sewage Plant in East Rockaway). GEER visited the WWTP that processes waste water from Yonkers. Founded on filled land along the east bank of the Hudson River, it experienced one of the largest overflows with 4.5M m^3 (1.2B gallons). The river frontage has a rip-rap revetment at the south and a steel seawall (Fig. 27) about 1.5 m (5 ft) higher than the north rip-rap. Normally, the plant handles daily 360 m^3 (95M gallons) of waste water; during in Hurricane Irene in 2011, it processed 1,150 m^3 (300M gallons). After Sandy, loss of gravity flow caused more than 2.8 m (9 ft) of tail water and therefore flooding of below-grade areas (Fig. 27), something that damaged equipment including boilers, the alarm system, pipes, and motors.



Figure 26. Untreated waste spilled in NY Harbor (left, photo Getty/Tama) and buried cars (middle, photo Bloomberg/Korby). Overflow from Bay Park Sewage Treatment Plant, East Rockaway (right, photo by D. Kuntz; Kenward et al., 2013).

Preparedness allowed for on-site decisions that accelerated recovery to 3-4 days for primary treatment and 21 days for normal operations to resume. Planning before the storm prevented longer disruptions (e.g., sandbagging prevented flooding of the feeder, the control center, and the emergency generator), whileon-site staff were properly trained to manually operate system components that failed.



Figure 27. Yonkers Joint WWTP: junction of rip-rap revetment and seawall, looking south (left); vent grates in aeration blower building where water entered, with flood water elevation shown by plant superintendent (right); GEER (2014).

RECOVERY AND REBUILD

In NY, actions taken since the unprecedented damage caused by Hurricane Sandy were presented in a 2018 NY Times report by J.K. Bavishi, Director of NYC Mayor's Office of Recovery and Resiliency. The $20B NY plan includes upgrading buildings and critical infrastructure as well as strengthening 190 km (120 mi) of coastline. The existing building stock has been modified to adapt to evolving climate risks through a multilayered approach, including: upgrading systems in one-to-four unit homes; changing zoning/land use policy; cooperating with FEMA on new maps; and educating owners about climate risks.

In 2015, NYC released the strategic plan for inclusive growth and climate action: "One New York: The Plan for a Strong and Just City", the first U.S. city resilience strategy with four visions that contain several goals and initiatives. The 2018 project status for buildings, coastal defense, infrastructure, and neighborhoods is shown in Fig. 28, along with Sandy's inundation and the 2050s projected 100-year floodplain and sea level rise (NYC, 2018). Proposed barriers have varied from berms and walls (extending along the edge of lower Manhattan) to barricades protecting the entire NY Harbor (using movable gates sized

appropriately so as to not impede shipping, like the Dutch barricades). Barricades would be needed across the lower NY Harbor near the Verrazano Bridge, west of SI at the East River near Throgs Neck Bridge, to prevent river flow from backing up and causing flooding upstream. Some barricades at tunnel entrances were installed, with solutions for subway entrances and ventilation openings (Hill et al., 2013).

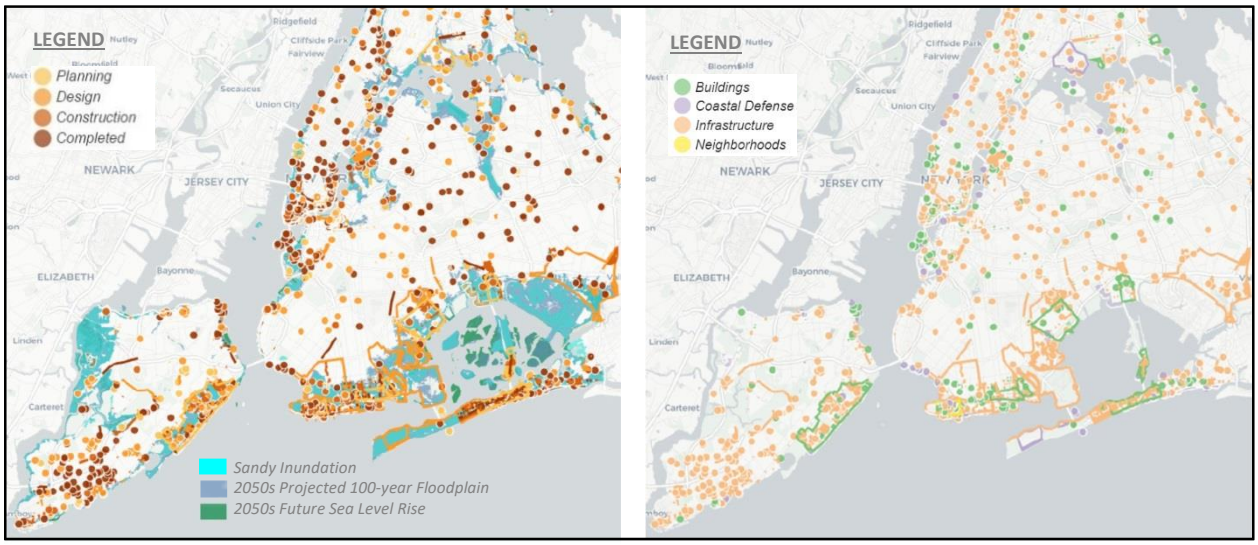


Figure 28. NYC Mayor's office map (maps.nyc.gov/resiliency/) of Recovery and Resilience OneNYC projects (NYC, 2018).

The NJ State issued a report five years after Sandy with: (i) a record of damage and response; (ii) an agency-by-agency response/recovery playbook applicable to other states exposed to hurricanes; and (iii) rebuild measures co-funded by FEMA, the Departments of Interior and Housing and Urban Development (HUD), and Federal Highway Administration (FHWA), such as: Sea Bright wall, Mantoloking and Brick sheet piling, Belmar Lake Como discharge, Brigantine pump stations, Little Ferry tide gate, and Wildwood/Stone Harbor storm water/flood control. The Union Beach project in Raritan Bay (Fig. 29) would rebuild beaches and dunes and restore 100,000 m^2 (25 acres) of degraded wetlands to better absorb flood waters, with levees, flood walls, tide gates, and pump stations.

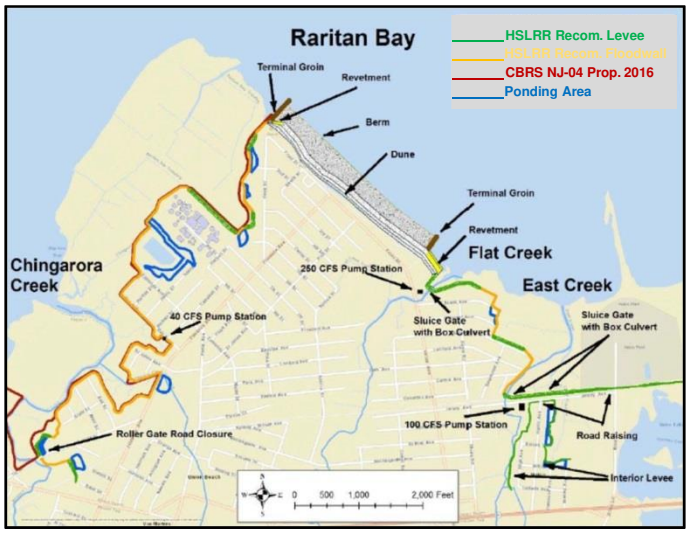


Figure 29. Union Beach plan overview from U.S. Army Corps of Engineering Limited Reevaluation Report (USACE, 2017).

Large-scale transportation infrastructure projects have progressed and many are completed, despite the complexity in scope and the regulatory and legal requirements. The NJDOT and NJ Transit have a $2B allocation, including federal relief funds.

An example of a completed project is the $340M Rt35 Reconstruction, which was a severely-damaged coastal emergency evacuation route that has since been rebuilt with state-of-the-art road construction and a thorough storm water drainage system (Fig. 30).



Figure 30. Rt 35 during Sandy (top); before/after photos at 3rd Ave, Ortley Beach (bottom, C. Raia, Toms River Township).

Billions were invested to strengthen the electric and gas distribution networks toward a more resilient energy utilities grid. Advanced technologies were implemented to spot outages faster and deploy repair crews more efficiently. These projects increase the reliability of utility services, but also boost the NJ economy by creating new jobs. Investments in continuing the functionality of small businesses supported the tourism, which reached 98M in 2016 (breaking the 87M record of 2013). Intense efforts were made to reopen all parks within three months of Hurricane Sandy's passing, despite the enormous damage done across the entire state park system (Fig. 31).

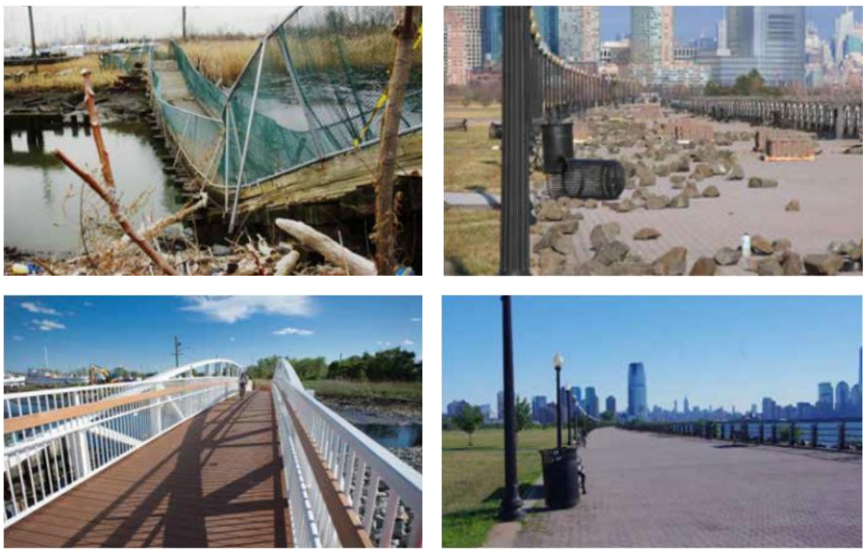


Figure 31. Liberty State Park (40.703100°N, 74.053700°W) before (top) and after rebuild (bottom). Photos by NJ State (2018).

Build It Back, NYC

The Build It Back (BIB) program assisted 8,600 homeowners, landlords, and tenants of one- to four-unit homes affected in NYC boroughs by rebuilding homes damaged or destroyed by Sandy in the fall of 2018. The goal was to invest and create resilient neighborhoods through sustainable design, e.g. by requiring new homes to be elevated above projected sea level rise and flood heights. The program was funded by HUD's Community Development Block Grant (CDBG) to rebuild and elevate homes to current stringent flood regulations (Fig. 32) for 12,500 families. Additional support was provided to homeowners with moderate repair needs or without flood insurance, while a few low-income, households received rental assistance (HUD, 2018). Geotechnical considerations included foundations for the elevated homes designed to resist undermining by future flood events. The new foundation systems included jacked or drilled piles as well as the choice to leave open space below the structures to allow for flow.



Figure 32. Build It Back elevated homes in New Dorp Beach, Staten Island (NYC Housing Recovery, 2018).

Rebuild by Design, NY/NJ

Launching "Rebuild by Design" was a joint effort by HUD and the Presidential Hurricane Sandy Rebuilding Task Force to seek community- and policy-based solutions to protect vulnerable U.S. cities from intense weather events following Sandy. In NYC, a competition brought together researchers, designers, engineers, government officials, businesses, policy-makers, and local groups to craft ten innovative, replicable solutions to protect and redevelop at-risk coastal communities in environmentally friendly and economically viable ways. One of the proposals was the Living Breakwaters on SI's South Shore (Fig. 33), funded by CDBG and executed by the NY Office of Storm Recovery (GOSR, 2018), with integrated purposes of:

- Risk Reduction: Address both event-based and long-term shoreline erosion to preserve or increase beach width; attenuate storm waves to improve safety and prevent damage to buildings and infrastructure.

- Ecological Enhancement: Increase the diversity of aquatic fish/shellfish habitats and oyster reefs in lower NY Harbor / Raritan Bay, a particularly rocky habitat that can function like the oyster reefs historically found in this area.

- Social Resiliency: Promote community education on coastal resiliency and ecosystem stewardship; foster and encourage citizen science; increase physical and visual access to near-shore waters for community activities.

Developed by SCAPE/Landscape Architecture with an interdisciplinary engineering team, Living Breakwaters strategically places about 1 km (3,200 ft) of breakwaters, 200-370 m (700-1,200 ft) away from the shore and 0.6-3 m (2-10 ft) below mean low water level. It combines wave attenuation and erosion reduction with habitat enhancement to enrich ecological quality (GOHR, 2018). Rebuilding of fish habitats and oyster populations is expected to bring commercial prospects, sediments

added to the shoreline will protect vulnerable beaches, while breakwaters work to accrete beach elsewhere (Fig. 34). Similarly, in NJ, Rebuild by Design includes several projects, such as: (i) CDBG ($380M) projects to be completed by 2022; (ii) Hudson River ($230M) communities and critical infrastructure flood-resistance structures (e.g., N. Hudson Sewerage Authority); and (iii) protection of Meadowlands ($150M) Little Ferry, Moonachie, Carlstadt, Teterboro, and S. Hackensack.



Figure 33. Living Breakwaters concept (SCAPE Landscape Architecture).

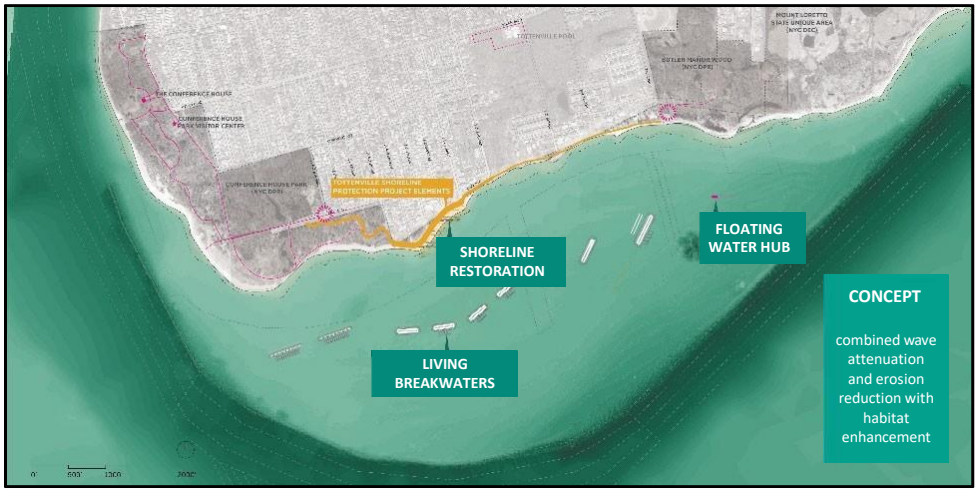


Figure 34. Living Breakwaters system: combined wave attenuation and erosion reduction with habitat enhancement.

Mitigation Program and Blue Acres Buyouts, NJ

In NJ, priority was given to needs for temporary housing assistance, health/social service benefits, and rental/rebuilding resources. The $1.2B Reconstruction, Rehabilitation, Elevation, and Mitigation (RREM) program rebuilds damaged homes (Fig. 35) using post-Sandy design standards. By 2017, about 6,200 of 7,600 RREM grantees had returned to their homes while the remaining received assistance for mortgage costs or rent payment. Other homes that were flood-prone were sold by willing sellers at pre-Sandy values, allowing families to relocate through DEP's Blue Acres voluntary buyout program that is expanding to other flood-prone areas. These properties are converted to open spaces to serve as a natural buffer for future storms.



Figure 35. A home at Otely Beach, NJ, before (left) and after(right) rebuilding. Photos by NJ (2017).

DISCUSSION AND CONCLUSIONS

A combination of increased urbanization worldwide and climate change exposes urban centers to extreme weather events more than ever before. Hurricane Sandy exposed the vulnerability of our communities and mega-cities to major flooding and resulting damage that occurs during severe weather events. The intensity and scope of the damage observed in the aftermath of Hurricane Sandy is unprecedented in scale. The hurricane affected jurisdictions and communities that had to immediately and intensely work to meet the dual challenges of sustainability and resiliency. Both NY and NJ states have adopted the FEMA (2013) Advisory Base Flood Elevation Maps that require flood-resistant design measures for homes located within flood zones. NYC developed a special initiative for rebuilding and resiliency, including economic growth strategies, to protect the city from future storms.

The efforts and the report of the Geotechnical Extreme Events Reconnaissance (GEER) Association were used extensively to create the rebuild planning for the affected areas. The geotechnical reconnaissance data became available to enhance the knowledge and advance the research on extreme events and hurricanes (GEER-23, Hashash et al., 2013). The GEER mission focused on observing engineering aspects related to: (i) permanent coastal geomorphology changes, soil scour, and erosion influenced by marshes, dunes, and barrier islands; (ii) damage and performance of foundations of coastal buildings as per the design requirements at their time of construction; (iii) performance of buried structures and underground infrastructure; and (iv) service interruption of critical infrastructure due to damage to non-structural components. Additional lessons learned included the importance of: flood protection, preventive measures, coordination between agencies, and the appropriate location of power/control equipment.

A major conclusion regarding geotechnical infrastructure was that solutions for resiliency, such as the ability to "spring back", and sustainability that minimizes long-term effects do not always align. For example, dunes and vegetated strips improved the resiliency of coastal communities after Hurricane Sandy, while being relatively inexpensive to maintain. In contrast, flood barriers may increase resiliency by protecting underground and surface facilities from inundation, but they will need to be raised at increasing cost to sustain their effectiveness to a rising sea level. For below-grade infrastructure in dense urban areas, it is clear that individual resiliency-enhancing measures may be adopted on a local scale, but collaboration across multiple agencies, jurisdictions, owners, operators, and the public is just as critical. The delay of the NYC subway system recovery (due to damage of the electric grid) highlighted the need to improve sustainability, both locally and regionally, through coordination of interconnected systems.

Hurricane Sandy raised questions that need to be discussed among multi-disciplinary professionals, including planners, engineers, architects, and environmental scientists. For example, should we consider a potential shift of the problem toward other areas if we build large-scale barriers to prevent storm surges from flooding an urban area? Should we allow coastal areas to flood and enhance infrastructure resiliency so functionality can be restored rapidly, or should we instead attempt to retreat from vulnerable areas through managed buyouts? Should a transition from existing legacy systems to a sustainable paradigm be gradual or sudden?

Several answers, and particularly the quantification and incorporation in designs of resiliency and sustainability intents, are driven by geotechnical considerations and decisions based on geohazards assessments. To meet these intents, a performance-

and risk-based engineering framework which considers life cycle costs is needed to address both new infrastructure components and the (often aged) legacy components. A design framework as shown conceptually in Fig. 36 can address both the individual component as well as the overall system needs, while planning for cascading hazards (Nikolaou et al., 2017). The GEER-organized efforts and presentation of data highlighted key flaws, demonstrating to stakeholders and the public that geotechnical engineers should be involved early in the decision-making process after major events such as Hurricane Sandy.

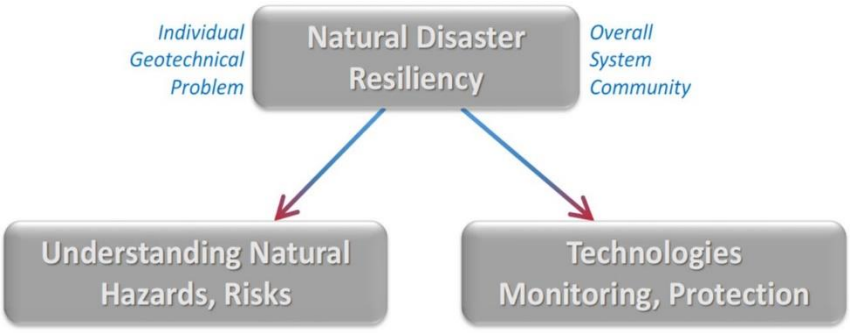


Figure 36. Framework for resilient-based design (Nikolaou et al., 2017).

CLOSING REMARKS

As indicated in reports prior to Hurricane Sandy (e.g., NYC Panel on Climate Change, 2009), extreme events have become increasingly frequent. In 2017 alone, the major Hurricanes Harvey, Irma, Jose, and Maria cost the U.S.A. an amount of $200B (Johnson, 2017), almost triple that of all 2012 hurricanes (with Sandy alone resulting in $65B in damages). The U.S. Global Change Research Program reports (USGCRP, 2018) that climate change may lead to U.S. economy losses amounting from hundreds of billions of dollars to up to 10% of its GDP by the end of the century. As our society indisputably lives in a "new norm of natural disasters" (O'Rourke, 2012), the new generation of geotechnical engineers is faced with the task of creating a new, risk-based mindset in geotechnical engineering design guidelines that will address the need for resiliency and sustainability against multiple natural hazards.

ACKNOWLEDGMENTS

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Many individuals and organizations contributed to the GEER work in the aftermath of Hurricane Sandy, with a complete list presented in the GEER report. These contributions are gratefully acknowledged. The authors would like to particularly acknowledge the contributions of all reconnaissance collaborators who volunteered their time on-site and during report preparation from MRCE, GMS, and other local engineering firms, as well as the public agencies of NY/NJ, especially the NYC Department of Buildings, NYS/NJ Departments of Environmental Protection, and the NJ Department of Transportation.

The selected actions related to recovery cover developments up to the end of year 2018. All opinions expressed are those of the authors and do not necessarily represent the opinions of these individuals and organizations.

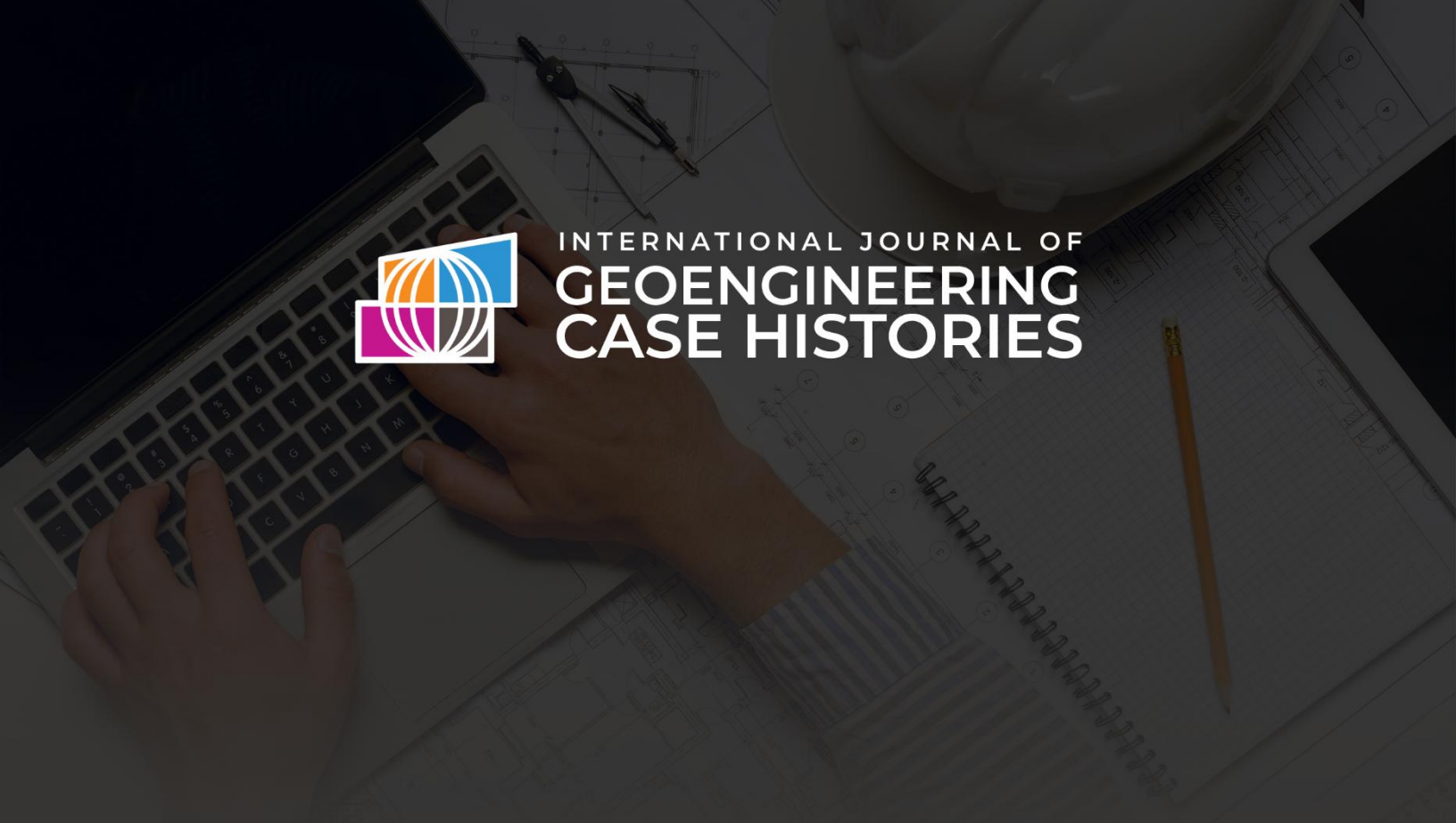
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