University Transportation Research Center - Region 2

Final Report

Potential Hydrodynamic Load on Coastal Bridges in the Greater New York Area due to Extreme Storm Surge and Wave

Performing Organization: City University of New York (CUNY)

April 2018

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16. Abstract

This project makes a computer modeling study on vulnerability of coastal bridges in New York City (NYC) metropolitan region to storm surges and waves. Prediction is made for potential surges and waves in the region and consequent hydrodynamic load and scour at bridge piers in conditions of climate change/sea level rise (SLR) and change in hurricane patterns. In particular, two tasks are

- Computer modeling of storm surges and waves in the greater NYC area during hurricane Sandy, and the modeled results compare reasonably with field observation.
- Prediction of storm surges and waves in the region in conditions of SLR and change of hurricane patterns, and, on this basis, a preliminary estimate of hydrodynamic load and scour at selected bridges along the coastlines.

The study indicates that both rise in sea level and change in hurricane patterns could result in pronounced increase in hydrodynamic load and scour at bridge piers, and such increase should be taken into consideration in development of resilient coastlines.

17. Key Words
Climate change, sea level rise, Hurricane Sandy, NYC metro region, storm surge, wave, bridges, hydrodynamic load, scour

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I. Background, Problem, and Objective

Background As a consequence of global warming and climate change, sea-level rise has become an emerging threat to our coastal transportation systems. The global sea-level rise over next 100 years is projected to be in the range of 0.2 - 0.6 m, and this rise could be as high as 0.8 to 2 m by 2100 under unfavorable glaciological conditions (Pfeffer et al. 2008). Sea-level rise in the greater New York City (NYC) area is twice as fast as its global average (e.g., Stanley et al., 2004). Moreover, another important emerging threat is that the frequency of category IV and V storms in this area has greatly increased in the past three decades along with the ocean temperature (Gabriel et al. 2008), which has been manifested by Hurricane Irene and Hurricane Sandy in 2011 and 2012, respectively, one shortly after another.

The aforementioned threats result in a significant increase in chance of generation for extreme surges and waves of coastal water and thus risk for destruction of coastal infrastructure including transportation systems such as bridges (e.g., as indicated by the shallow water theory, a rise in sea level, or, a deeper water, implies a faster wave speed, and thus stronger momentum and more destructive). According to the National Bridge Inventory, there are over 300 bridges in NYC alone, with many of them having small vertical clearance and are now aging, plus that they were designed without any consideration of the two threats. It is anticipated that major bridges in the NYC metro region may not be at risk to extreme surges and waves, but a number of smaller yet important bridges could be in danger. Indeed vast destruction of infrastructure by extreme surges is a small probability event, nevertheless, once it happens, such destruction could be catastrophic. We have learnt such lessons, for instance, during Hurricane Katrina 2005, 2012 Hurricane Sandy, and 2011 Tōhoku Tsunami.

Problem of Study and Objctive This project studies potential storm surges and waves in conditions of sea-level rise and change of hurricane patterns as described above and consequent vulnerability of coastal bridges in the NYC metro region. In particular, this research targets at understanding how much the hydrodynamic load could be on the bridges in this region during future extreme storms.

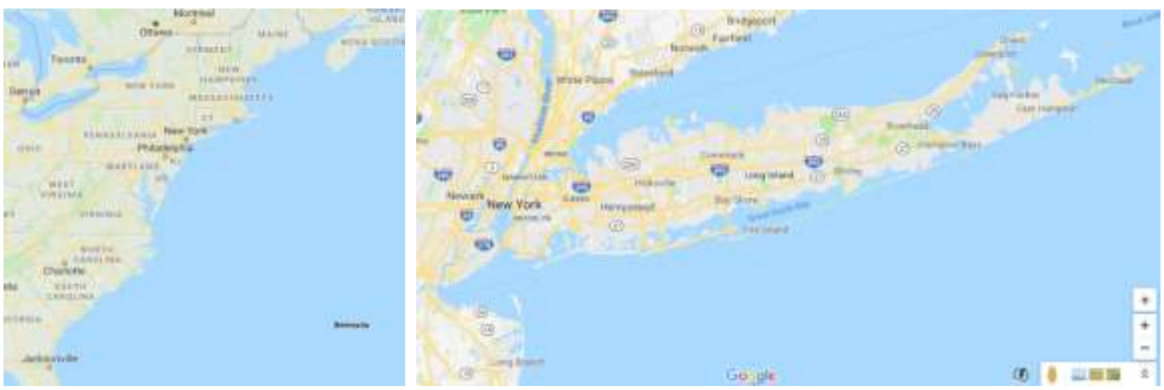
The objective of this research is to make a prediction of potential hydrodynamic load of extreme storm surges and waves on coastal bridges in the greater NYC area considering sea-level rise and change in hurricane patterns. The objective will be realized through two tasks:

1) Computer modeling of storm surges and waves in the greater NYC area, and the modeled results compare reasonably with field observation.
2) Prediction of storm surges and waves in the region in conditions of SLR and change of hurricane patterns, and, on this basis, a preliminary estimate hydrodynamic load and scour at selected bridges along the coastlines.

Significance The project will be a first effort in the sense that it investigates potential hydrodynamic loads on realistic coastal bridges in a large coastal region, and it addresses a problem in the USDOT's goal and the UTRC's focus area on response to extreme events. This research will be preliminary due to restriction of funding and time, but it sets up a platform to further study vulnerability of coastal bridges and develop resilient transportation systems in the greater NYC area.

II. Area of Study and Relevant Data

In order to simulate storm surge and wave, which are generated by hurricanes, a large region of study is used, and it starts from Florida, US and ends at Prince Edward Island, Canada, ranging from latitude of 27.4 N to 45.8 N and longitude of 81.5 W to 60.1 W, as shown in Fig. 1a. The region of focus in which vulnerability of coastal bridges is examined is metro NYC region, as shown in Fig. 1b. In the region of study, nearshore water depth is mostly less than 30 m, and deep-ocean water depth is over 5,000 m.



(a) (b)

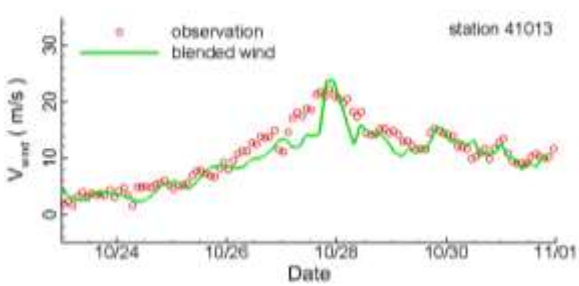
Figure 1. Region of study. (a) Whole region of study. (b) Area of focus.

The seashore boundaries are defined by the NOAA high-resolution composite vector shoreline, and, at the locations where small rivers are not included in the high-resolution dataset, NOAA medium resolution coastlines are used (NOAA CSC, 2017, NOAA SCR, 2017). The bathymetry data in shallow water zones comes from the National Geophysical Data Center (NOAA NGDC, 2017), while that in the deep ocean zones comes from the bathymetric data of ETOPO1 (NOAA ETOPO1, 2017), which is a 1 arc-minute global relief model of the Earth's surface that integrates land topography and ocean bathymetry.

The bathymetry data has resolution of about 100 m for majority of nearshore zones. NOAA's VDATUM is used to convert the bathymetric data to the common vertical datum NAVD88 (Parker, et al., 2003).

At the open boundary, mostly in deep ocean, water surface elevation is specified with the astronomic tides computed by software OTPS, and 13 tidal components of the water surface elevation are considered: eight primary (M2, S2, N2, K2, K1, O1, P1, and Q1), two long periods (Mf, Mm), and three non-linear (M4, MS4, and MN4) constituents (Edbert, et al., 1994). Since the contribution from small rivers is negligible during a storm surge event, only Delaware River and Hudson River are considered in the simulation. The water surface elevations downloaded from the United States Geological Survey (USGS) Current Water Data for the Nation (USGS CWD, 2017) are imposed. For waves, a non-reflecting boundary condition is imposed at the open boundary.

In order to simulate a storm surge during a hurricane, data for wind field, i.e., wind speed and pressure at water surfaces, is needed as external forcing. In this project, a blending of H*Wind and North American Regional Reanalysis (NARR) wind dataset of Hurricane Sandy is used (e.g., Powell, et al., 1996; NOAA NCEI, 2017). In view of its uncertainty and measurement errors, the data for air pressure and wind speed is further treated using an adverse-distance based weighting process to reduce its discrepancy from the wind data measured at 10 stations. Fig. 2 shows a comparison between the blended wind speed and pressure field and those obtained at a measurement station.



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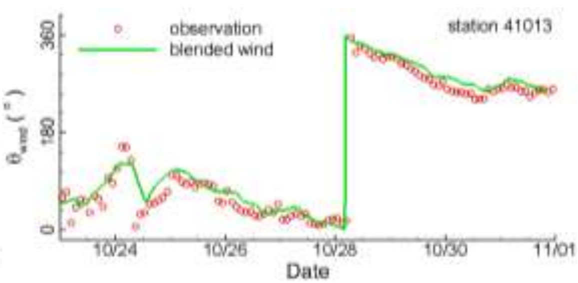

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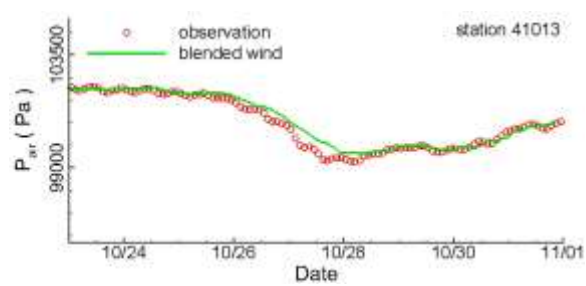


(c)

Figure 2. A comparison between observation data and blended wind data. (a) Wave speed. (b) Wave direction. (c) Air pressure.

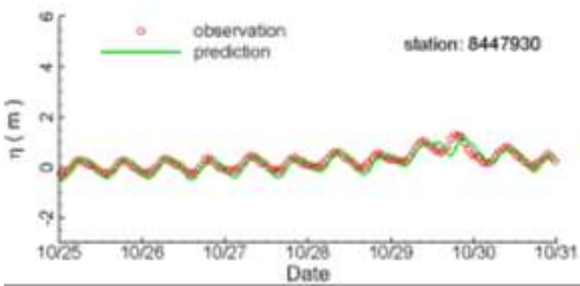
III. Model, Setup, and Calibration

The finite element coastal ocean model (FVCOM) in conjunction of a water surface wave model SWAVE is used to simulate storm surges and waves during hurricanes. FVCOM uses a triangular mesh in the horizontal direction and σ-layer in the vertical direction. The mesh covers the entire region of study, and its grid spacing is at size about 45 km in deep ocean and gradually refines to 200 m in coastal water, and then to about 10 m within rivers (Fig. 3) The mesh has about 160,000 nodes and 300,000 elements in horizontal plane, and 11 σ-layers in the vertical direction. In the computation, starting from the static status, the water body starts to flow because of the astronomic tides and the wind field. The time step is set as a large value for the first 5 days and 22 hours, and then reduced to 0.0625 s as a hurricane reaches the metro NYC region. In computation, the surface wind stress is calculated using $\tau = \rho_{air} C_d V_{wind}^2$, where ρ_{air} is the air density, V_{wind} is the blended 10-m wind speed, and C_d is the drag coefficient determined by (Sun, et al.,2013)

$$C_d = \begin{cases} 1.0 \times 10^{-3}, & 0 < V_{wind} \le 4.0\mathrm{m/s} \\ \left(1 + 1.5\dfrac{V_{wind} - 4.0}{27 - 4.0}\right) \times 10^{-3}, & 4.0\mathrm{m/s} < V_{wind} \le 27.0\mathrm{m/s} \\ 2.5 \times 10^{-3}, & V_{wind} > 27.0\mathrm{m/s} \end{cases} \quad (1)$$

Figure 3. Mesh for modeling of storm surge and wave.

In order to calibrate the modeling, a hindcase simulation for storm surge and wave during the Hurricane Sandy has been made. Comparison of simulation and measurement is made at 18 stations for water surface elevation and at 10 stations for wave. Fig. 4 shows an example of such comparison. Overall, the comparison at all stations is reasonable. In particular, the comparison with regard to water surface elevation and wave height is good, while discrepancy is relatively large in wave period. Such discrepancy in wind direction is attributed to its very strong transient, small-scale features that are difficult to capture with our current modeling capabilities.



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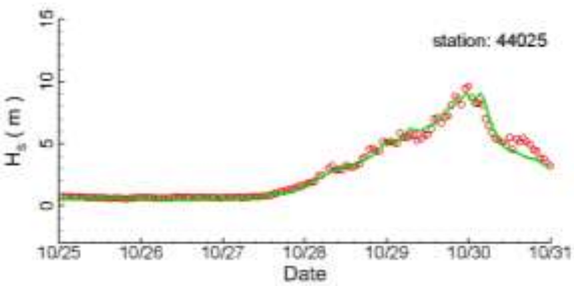

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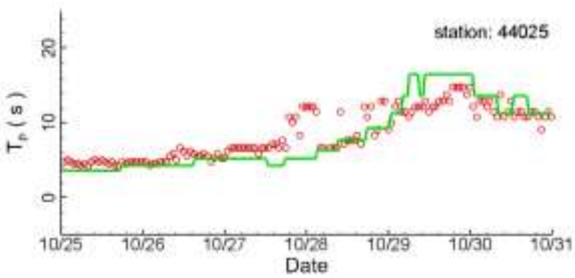


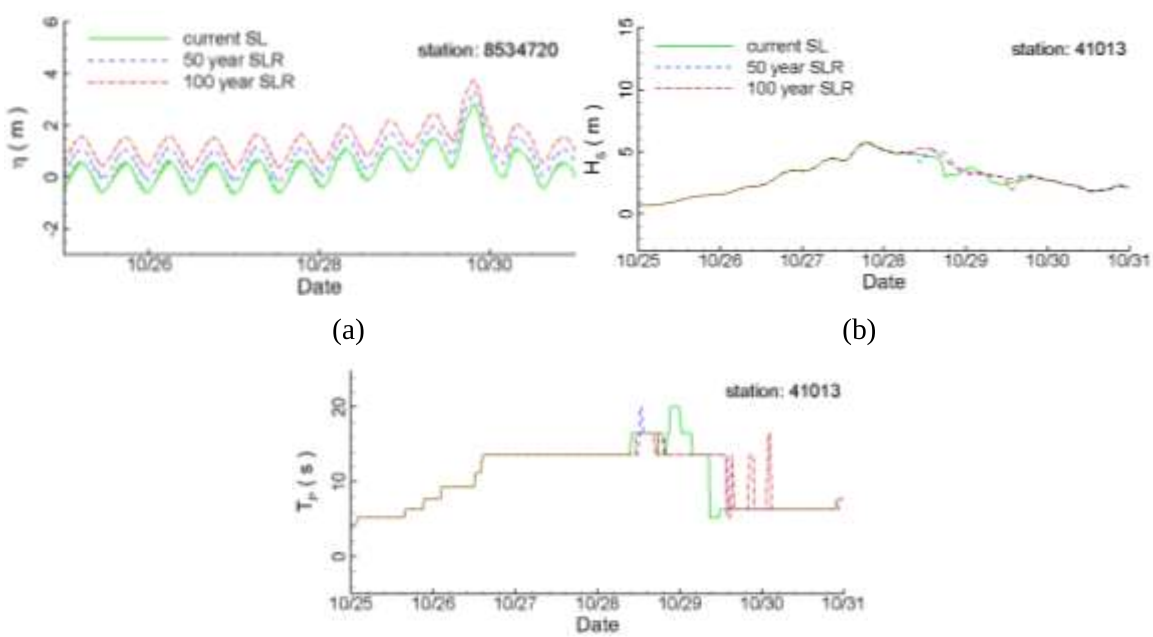
(c)

Figure 4. A sample comparison of prediction and measurement for storm surges and waves during Hurricane Sandy. (a) Surface elevation. (b) Wave height. (c) Wave period.

IV. Result and Discussion

IV.1 Effect of sea level rise

In this project, effects of rise in sea level is considered by changing sea level elevation while keeping all other parameters, such as coastlines, bathymetry, and astronomic tides, in simulation in the previous section on Hurricane Sandy. In particular, scenarios of SLR of 0.5 m and 1 m are considered, which roughly correspond to the estimated median values of SLR in the region of study in 50 and 100 years, respectively (Tang, et al., 2014). The simulation indicates that, at all 18 stations that recorded water surface, water surface elevation increases a as a result of SLR, roughly linearly, for instance, see Fig. 5a. In view that a higher surface elevation corresponds to a deeper water, and, according to the shallow water theory, a deeper water tends to lead to a faster surface wave speed (also roughly true for nonlinear, breaking waves) and thus stronger momentum of waves as they impact coastal structures. Therefore, from this regard, SLR increases risk of coastal bridges to damage. The simulation further indicates that waves also change as a result of SLR, however, no obvious pattern in change in wave height and direction is observed from the results at the 10 wave stations, and, in comparison with that at current sea level, it is could be in either way. As an example, the result in Figs. 5b and 5c shows the simulated wave field at one of the 10 wave stations, and it illustrates the features of such change.



(a) (b)

(c)

Figure 5. Effects of SLR on water surface elevation and wave. (a) Surface elevation. (b) Wave height. (c) Wave period.

In view of complicated behaviors of surges and waves at different sea levels, vulnerability of coastal bridges to impact of surges and waves due to SLR has to be analyzed individually. As indicated previously, there are numerous bridges over coastal waters in the metro NYC region, and, analysis of vulnerability of them takes a tremendous effort and needs a complete collection of relevant data. In this project, as shown in Table 1, nine bridges are selected for such analysis according to an earlier study by Shields (2012) on hydraulic vulnerability of brdiges in the region, which are located as in Fig. 6. Due to lack of data, configurations and sizes of these bridges are estimatesd by vision at them in Google Earth.

Table 1. Bridges selected for vulnerability study

No.	Bridge Name
1	Loop Parkway
2	Robert Moses Causeway over Fire Island
3	Robert Moses Causeway over Great South Bay
4	Meadowbrook Parkway over Sloop Channel
5	Meadowbrook Parkway over Fundy Channel
6	Meadowbrook Parkway over False Channel
7	West Shore Road over Mill Neck
8	Mill dam Road
9	Bayonne Bridge

Figure 6. Locations of bridges selected to be studied.

Drag exerted on a bridge pier is evaluated by an equation of FEMA 55 (FEMA, 2011):

$$F_{current} = \frac{1}{2} C_c \cdot \rho V_c^2 A_{pier} \quad (2)$$

where C_c is the drag coefficient (= 2.0 for square pier, 1.2 for round pier), ρ is water density, and V_c is the current velocity and is obtained from the simulation. $A_{pier} = D \cdot y_1$. y_1 is the flow depth directly upstream of the pier, which also obtained from the simulation. In this study, C_c is set as 2.0. In order to evaluate the breaking wave load on a bridge pier, the following formula from ASCE 7-05 is adopted (ASCE, 2006)

$$F_{wave} = \frac{1}{2} C_w \cdot \gamma \cdot D \cdot H^2 \qquad (3)$$

in which C_w is a coefficient (= 1.75 for round pier, = 2.25 for square pier) and is set as 2.25 in this project, γ is specific weight of the water (= 9,810 N/m^3), D is the pier diameter (=diameter of a circular section, =1.4 width of a square pier), and H is the wave height and it is extracted from the simulation. This project considers the load on a bridge pier as the sum of drag and wave force on it.

Scour at a bridge involves very complicated physical processes, and this project makes a preliminary estimate of local maximum scouring depth using HEC-18 (Arneson, et al., 2012) equation:

$$\frac{y_s}{y_1} = 2 \cdot K_1 \cdot K_2 \cdot K_3 \cdot \left(\frac{D}{y_1}\right)^{0.65} \cdot Fr_1^{0.43} \qquad (4)$$

where y_s is the scour depth, K_1 is a correction coefficient for pier nose shape, K_2 is a correction coefficient for angle of attach flow, K_3 is a correction coefficient for bed condition, and Fr_1 is the Froude number directly upstream of the pier. In this study, K_1 is set as 1.0, K_2 is set as 1.0, and K_3 is set as 1.1.

On the basis of the result from the simulation, together with formulas (2), (3), and (4), hydrodynamic load and scour at conditions of current sea level (CSL) and SLR are listed in Table 2. The table shows that, in general, scour increases at sea level becomes higher. An exception happens at Bridge #8. In addition, it shows that hydrodynamic load at the piers also increases with sea level, and, again, Bridge # 8 is an exception.

Table 2. Estimate of load and scour at a pier of the selected bridges in SLR conditions (Qu 2017).

No.	Scour Depth (m)			Impact Load (N)		
	CSL	50-yr SLR	100-yr SLR	CSL	50-yr SLR	100-yr SLR
1	4.4	4.6	4.7	55969	62835	70924
2	4.1	4.2	4.3	74398	83670	89263
3	2.6	2.7	2.8	38823	47629	57321
4	4.1	4.3	4.6	49681	57177	68244
5	4.1	4.3	4.5	35846	33104	45668
6	4.2	4.4	4.6	23058	29800	40386
7	1.9	1.8	1.7	16005	16488	16760
8	0.7	0.6	0.5	248	198	170
9	4.6	5.0	5.1	90213	106494	115422

IV.2 Effect of hurricane track

In general, potential of destruction of a hurricane strongly depends on its track and landfall location. In order to investigate the effects of the landfall and track, simulation has been made for hurricanes as a perturbation of the Hurricane Sandy. That is, in the simulation, the track of the original track of Hurricane Sandy is shifted to four locations and thus another four synthetic hurricanes are generated, and their tracks are shown as Track 1, 2, 3, and 4 in Fig. 7.

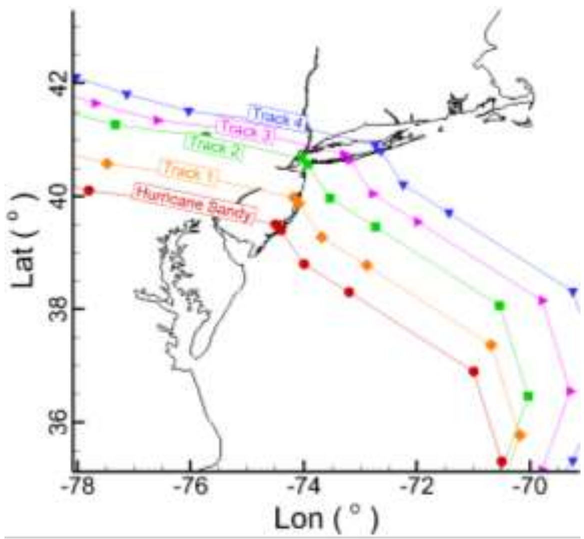
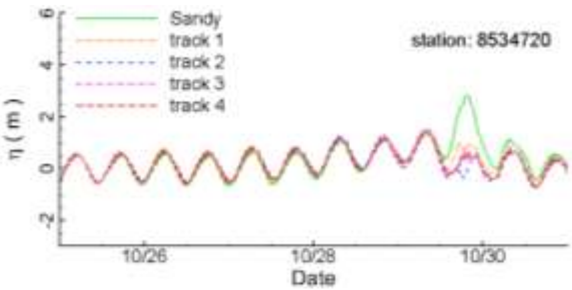
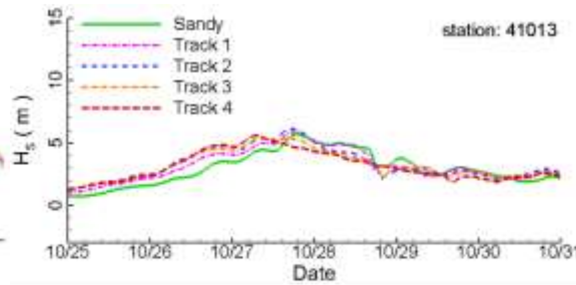


Figure 7. Tracks of hurricanes.

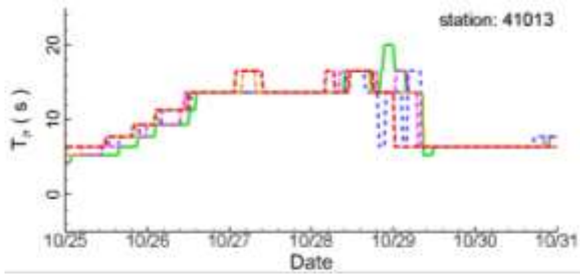
Simulation has been made in condition of different hurricane tracks shown in Fig. 7. In general, hurricane tracks have significant effects on surface elevation and wave, and Fig. 8 shows an example of such effects. The simulation also indicates that the track affects flow at different location not at a same degree, and this is attributed to the fact that the surges and waves generated by a hurricane are very complicated and highly nonlinear in behaviors.



(a)



(b)



(c)

Figure 8. Effects of hurricane tracks on water surface elevation and wave. (a) Surface elevation. (b) Wave height. (c) Wave period.

On the basis of the simulated results and also according to formulas (2), (3), and (4), the scour and load at piers of the selected bridges are estimated as in Table 3. The table indicates that, in comparison with that associated with the Hurricane Sandy, hurricane track plays an important role on the scour at piers. This is also true with regard to hydrodynamic load on bridge piers. The load at some piers, e.g., that of Bridge #1, 2, 3, 4, and 5, has doubled roughly. With this regard, in comparison with what shown in Table 2, a hurricane track could play much more significant change in the load that SLR.

Table 3. Estimate of load and scour at a pier of the selected bridges in condition of different hurricane tracks (Qu 2017).

No.	Scouring Depth (m)		Impact Load (N)	
	Original Track	All Track	Original Track	All Track
1	4.4	4.5	55969	130046
2	4.1	4.7	74398	152047
3	2.6	3.4	38823	73529
4	4.1	4.5	49681	76427

5	4.1	4.4	35846	67157
6	4.2	4.4	23058	38780
7	1.9	2.3	16005	19609
8	0.7	0.8	248	11117
9	4.6	5.8	90213.8	166598

V. Concluding Remark

This project makes a computer modeling prediction of storm surge and wave in NYC metro region, and then presents a study on resulting vulnerability of coastal bridges in this region. In particular, first, as a calibration and validation, FVCOM-SWAVE is used to simulate storm surges and waves during Hurricane Sandy, and reasonable comparison with field measurement is obtained, which is an encouraging achievement in view that the simulation involves a substantial amount of work and as well as complicated phenomena (especially the wind field of Hurricane Sandy). On this basis, prediction is made for future storm surges and waves in conditions of SLR and different tracks of hurricanes. Then, the predicted flows are used to estimate scour and hydrodynamic load at bridge piers in the region. It is concluded that both SLR and hurricane tracks can introduce significant changes to scour and load at the piers.

The results reported in this report are adopted from Qu (2017), and more details are available in it. It is indicated that, while the hindcast modeling of surges and waves during Hurricaen Sandy and prediction of them in the future are intensive and complete, the vulnerability study of this project, in particular, scour and load, is preliminary. We shall conduct further investigation with this regard on the basis of the predicted future storm surge and waves, and all results will be published once they are available.

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