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ORIGINAL PAPER

Storm surge damage to residential areas: a quantitative analysis for Hurricane Sandy in comparison with FEMA flood map

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Abstract A quantitative assessment of storm surge damage is used to analyze structural vulnerability and evaluate the performance of flood risk mapping by the Federal Emergency Management Agency (FEMA). Using a survey of about 380 structures in heavily impacted Ortley Beach, New Jersey, following Hurricane Sandy (2012), we first assess component-level damage to each side and story of a structure based on a percentage scale. For each structure, these physical damage percentages are then integrated into a single indicator of overall damage—the economic loss ratio. These performance assessments are combined with building information to develop an integrated Geographic Information System database. This detailed database allows for a quantitative analysis of damage features and causes. Damage at the overall, story, side, and component levels all decrease as the distance to the coast increases, with most severely damaged houses concentrated in a near-shore region. Despite being heavily damaged however, this region was assessed as a low-risk zone according to FEMA's current flood risk map. In contrast, a neighboring inland region which experienced significantly less damage was assigned as a high-risk zone. The preliminary new FEMA flood map for the area is improved by increasing the risk category for the near-shore region, but the fundamental problem, likely induced by insufficient wave modeling, needs to be addressed further. This study demonstrates a method of quantitatively assessing and documenting storm surge damage and applying the damage information to evaluate flood risk maps.

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1 Introduction

Coastal exposure to hurricanes and especially their induced storm surge have dramatically increased in recent years due to property development and population increase (Kunreuther and Michel-Kerjan 2009). Flood risk management using quantitative approaches has long been addressed with the mapping of flood hazards being a fundamental step. In the USA, FEMA maintains and updates flood hazard data for coastal communities through the so-called Flood Insurance Rate Maps (FIRMs). Developed from hydrological/hydraulic analyses and topographic surveys, FIRMs delineate different flood risk zones and in each zone the base flood elevations (BFE; the level to which the house is recommended to be elevated). These flood risk zones and BFEs in turn dictate design requirements and insurance pricing (FEMA 2011).

Given the significant role of FEMA's flood map in decision-making, the accuracy of FIRMs has been evaluated in several studies. Douglass et al. (1999), for example, demonstrated how shoreline erosion along the Gulf of Mexico had influenced the boundaries of flood risk zones for Baldwin County in Alabama between 1970 and 1995. More direct evaluations of risk mapping have likewise compared assessed risk with observed post-event damage to structures. As early as the late 1970s, the observation of severe wave damage to structures outside the 100-year floodplain propelled FEMA to conduct wave run-up studies (Bellomo et al. 1999). More recently, following Hurricane Katrina of 2005, FEMA (2006) evaluated physical damage to Alabama, Louisiana, and Mississippi and found severe damage to structures outside flood risk zones, revealing that the real flood and wave effects were beyond the mapped flood domains. Hurricane Sandy (2012), which induced record-high storm surge and devastated coastal communities in the northeastern USA (NOAA 2013), is another significant event that can be used to evaluate the performance of FEMA's flood map by comparing estimated risk with observed damage.

Most existing methods for estimating post-hurricane damage are limited primarily to either qualitative or categorical damage assessments. Qualitative assessments tend to describe general damage conditions, evaluating damage outcomes according to structural failure/survival (FEMA 2006, 2009; Kennedy et al. 2011; Tomiczek et al. 2014) or by damage mechanism such as foundation scouring, wall cracking, frame failure, and roof sheathing damage (Dalrymple and Kriebel 2005; van de Lindt et al. 2007). Some quantitative but somewhat subjective approaches such as those used by FEMA roughly estimate the overall damage severity and cost of repair (U.S. Department of Homeland Security 2014). Methods are also developed to reduce personal bias by assigning categories for damage features or severity (Crandell 1998; Tezak and Rogers 2005; Robertson et al. 2007; Tomiczek et al. 2015). A more systematic way to quantify the damage, however, is by measuring the damage severity for various building components on a continuous numerical scale. These numerical damage scales at the component level can in turn be aggregated to obtain a single measure of overall building performance.

The purpose of this study is threefold. First, a field survey of heavily impacted Ortley Beach in New Jersey was carried out following Hurricane Sandy. This study performs a quantitative analysis to assess and document observed damage. Specifically, using pictures taken for each house in the study area, we estimate the percentage damage, on each side and story, of major structural components (including foundation, exterior wall and roof) and non-structural components (including wall siding, roof cover, windows, and doors) that contribute significantly to economic losses (Dhakal 2010). In addition, we aggregate component damage to calculate the loss ratio as the weighted sum of damage (using the economic values of components as weights) over the total value. The estimated damage and losses are integrated with additional building information into a comprehensive GIS-based database.

Second, using the developed database, we study damage features (e.g., the distribution of damage on various sides and stories of a building). Furthermore, we investigate the factors that contribute to damage (e.g., distance from the coast, ground elevation, elevation above ground, and year of built). Significant damage features at the building as well as component levels are quantitatively shown using fragility curves. In addition, we analyze the various contributions of different components to total economic losses. These analyses advance our understanding of surge damage.

Third, to evaluate the performance of FEMA's flood risk mapping in Ortley Beach, we overlay the assessed damage severities (loss ratios) of houses on both the current effective and preliminary FEMA flood maps. The statistics of damage in different flood risk zones are compared. In addition to flood zones, we also investigate the BFE assigned to each flood zone. Analyzing the performance of the houses in comparison with the estimated risk levels on the flood map can help reveal not only the accuracy of the flood map but also its role in the resulting damage in Ortley Beach from Hurricane Sandy.

Following this introductory section, Sect. 2 introduces the field survey following Hurricane Sandy of Ortley Beach and the collected data. Section 3 assesses physical damage, estimates loss ratios, and develops the GIS database. Section 4 analyzes the damage features and factors. Section 5 first introduces the FEMA flood zones in Ortley Beach and then evaluates the flood map using the case of Sandy. Finally, Sect. 6 summarizes the findings and comments on the implications to coastal risk mitigation.

2 Damage survey

Ortley Beach (also called Dover Beach South), located on the narrow Barnegat Peninsula that separates Barnegat Bay from the Atlantic Ocean, was one of the most affected coastal communities by Hurricane Sandy. A USGS tidal gauge station recorded a storm tide of 2.65 m in Ortley Beach during Hurricane Sandy (USGS 2012), and storm surge rather than wind or rain was the principle hazard responsible for the damage (Norman 2009; Blake et al. 2013). Following Sandy, a team of students and faculty from Princeton University and the University of Notre Dame surveyed a significantly damaged area in Ortley Beach, comprising nearly 380 structures (350 single-family structures, 22 multifamily structures, and 4 commercial structures). In addition to survey notes, the survey data include over two thousand photographs taken from various angles for the surveyed structures.

Two studies have discussed important damage features observed by the team in Ortley Beach. Hatzikyriakou et al. (2015) examined the performance of surge-susceptible structural components (foundation, exterior walls, and wall siding) and investigated the causes of damage including both building and environmental factors. They found that the damage varied greatly within the community, primarily depending on environmental factors such as distance to the shore, dune protection, shielding, and debris effects. Secondary contributors to damage were building features such as age, front door elevation, construction type, and materials. Tomiczek et al. (2015) classified the surveyed structures into damage states and correlated the damage state to local storm surge characteristics estimated from a hydrodynamic model. They found that local water velocity and shielding effects were the most important predictors of surge damage. Their findings are consistent with those of Hatzikyriakou et al. (2015), as the distance to the shore, dune protection, and shielding were the major environmental drivers of variation in surge and wave conditions from house to house in the community.

In this study, we perform a more quantitative assessment of the damage for Ortley Beach. Unlike the previous two studies, which describe the damage features by mechanisms or by damage state categories (i.e., failure/survival or a number of damage states), we quantitatively measure the damage percentage for each of the significant building components (foundation, exterior walls, wall siding, windows, doors, roof, and roof cover). Moreover, we assess the damage percentage to each component at each story and each side of a structure. The survey indicates that different sides and stories of a structure suffered different levels of damage due to the different surge/wave effects. Figure 1a, c shows examples in which ocean-facing side of a structure was significantly more damaged than other sides. Figure 1a–e shows examples of many structures suffering substantial damage to their first story while higher stories often performed well. Figure 1f shows an example in which all components of a house failed except that the roof was undamaged. Thus, this study documents the damage survey in Ortley Beach in the greatest detail. It can be used to study the damage features and causes more quantitatively than the previous two studies, and it can also be used to investigate the economic loss ratio, a practical indicator of overall damage that can be used to evaluate the performance of the FEMA flood map.

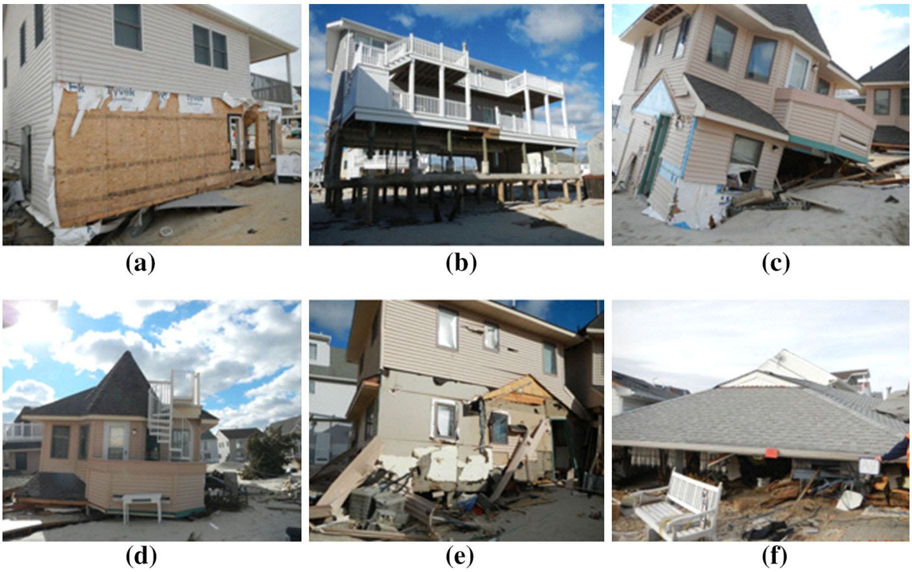


Fig. 1 Examples of different severity of damage to different stories and sides of structures in Ortley Beach

3 Damage assessment

3.1 Quantitative damage

Three semi-quantitative damage assessment approaches inspired our proposed damage assessment method. Applied Technology Council's scheme (ATC 2004) classifies overall damage severity into seven percentage ranges. Friedland (2009) proposed a wind and flood damage scale to classify the damage to components (roof, windows, foundation, and wall structure) into seven damage states. Tomiczek et al. (2015) extended the component damage classification of Friedland (2009) and proposed to use the maximum damage state of all components of a structure as an indicator of the overall damage to the structure. These three approaches have provided standard procedures for estimating damage. However, ATC's approach considers only the overall structural damage state while Friedland's approach estimates only the component damage state. Although the method of Tomiczek et al. (2015) links the component damage state to the overall structural damage state, the overall structural damage state may not always be well defined; for example, an overall damage state of 3 can be assigned to a structure with damage state 3 in foundation, wall, and windows as well as a structure with damage state 3 in only windows. In addition, none of the three approaches is quantitative enough to be applied to loss estimation.

We propose a more quantitative method to assess component damage on different sides and stories of a structure using a percentage scale. These damage percentages can be easily classified into the damage state categories. Furthermore, they can be aggregated into a more objective and practical indicator of the overall damage by using the economic values of the components as weights. In addition, the damage percentages can be aggregated to estimate damage to each component and to each side and story of the structure in order to better understand the damage mechanisms. Aggregating the percentages of damage to structural components at each side and story also reduces the potential bias in the overall damage estimation.

The main components we evaluate include foundation, exterior wall, wall siding, roof, roof cover, windows, and doors. Although the interior damage was not accessible during the damage survey, our assessment considers failures of the opening (cracking of walls, windows, and doors), which is directly correlated with water intrusion and thus interior damage (Mullens et al. 2006). We also consider damage to external attachments (such as attached garages and decks), which are integrated into the exterior wall damage. In addition, we take into account connection failure, especially those between foundations and walls. We classify connection failure into three categories (i.e., slight, moderate, and severe) and weigh the connection failure into the estimation of foundation damage.

A component is considered "damaged" if it appears to be altered from its state prior to Hurricane Sandy. Percentage damage to each side and story is assessed using multiples of 5 to reduce assessment error. If photographs of damage used in the evaluation are insufficient to clearly examine all parts of a structure, the parts of the structure that are not visible are assumed to be undamaged since the field survey focused on the damaged features. Damage criteria for each component are as follow:

- *Foundation* The estimated percentage of foundation damage on each side of a structure depends on the observed damage on the part of foundation above the ground, the performance of the superstructure, and the evidence of foundation failure (scouring depth, water marks around foundation, connection failure, pile out of soil, separation, differential settlement, and foundation cracking).

Table 1 Median, mean, and SD of the component damage percentage of the 376 surveyed buildings in Ortley Beach, NJ

Components	Median	Mean	SD
Foundation	27.5	42.04	26.32
Exterior wall	4.17	25.74	38.37
Wall siding	15.63	33.2	36.5
Window	23.68	35.73	35.78
Door	25	39.29	64.28
Roof	0	20.76	38.86
Roof cover	3.75	23.07	38.03

- *Exterior wall and wall siding* The estimation of damage to the wall siding/exterior wall on each side and each story is based on the percentage of surface area of the wall siding and exterior walls where the outermost layer/structural parts seem to be missing or damaged. If the wall on a side is inclined more than 20°, the exterior wall and wall siding on that side are regarded as 100 % damage.
- *Roof and roof cover* The estimation of damage to the roof/roof cover on each side is based upon the percentage of surface area of the roof cover/roof for which the shingles/structural parts seems to be missing or damaged. If a roof has collapsed, both the roof and roof cover are regarded as 100 % damage.
- *Window and door* The damage percentage of the windows/doors on each side and each story is estimated as the ratio of the number of damaged windows/doors to the total number of windows/doors. Glass failure is regarded as window damage.

Using photographs taken during the field survey, we assess component damage based on the above criteria multiple times to reduce potential errors. After all structures were evaluated by the primary investigator twice or more until the damage percentage agreed within a 5 % difference for each component, we randomly selected a number of structures and had another investigator assess the damage according to the same criteria. The damage percentage estimations for window and door were typically the same between the two investigators. The damage percentage for exterior wall, wall siding, roof, and roof siding typically deviated less than 5 %. The damage percentage for foundation deviated within 10 %.

Table 1 shows the basic statistics of the component damage. The median and mean of the foundation damage are the highest, but the standard deviation of the door damage is the highest. The median of roof and roof cover damage is small while their mean and standard deviation are relatively high, indicating that the roof damage is concentrated in a small number of houses due to collapsing. Table 2 shows the statistical correlation of the component damage. Overall, the damage percentages of components are highly correlated. Components that are connected with a load path transferring lateral and vertical loads (e.g., walls and foundations) are more correlated than those not connected by a load path (e.g., foundation and roof).

3.2 Economic loss ratio

In addition to component-level damage, the overall damage of a structure is an important indicator of the overall vulnerability of the structure. The visual measurement of overall structural damage may be relatively subjective. Instead, the economic loss ratio provides a more objective measure of overall damage calculated from component damage.

Table 2 Statistical correlation between the component damage percentages of the 376 surveyed buildings

Components	Foundation	Exterior wall	Wall siding	Window	Door	Roof	Roof cover
Foundation	1	0.87	0.9	0.83	0.79	0.79	0.8
Exterior wall	0.87	1	0.98	0.83	0.81	0.96	0.97
Wall siding	0.9	0.98	1	0.84	0.83	0.92	0.94
Window	0.83	0.83	0.84	1	0.85	0.77	0.79
Door	0.79	0.81	0.83	0.85	1	0.76	0.77
Roof	0.79	0.96	0.92	0.77	0.76	1	0.99
Roof cover	0.8	0.97	0.94	0.79	0.77	0.99	1

The loss ratio is defined here as the sum of losses of individual components divided by the total value of the components:

$$\text{Loss Ratio} = \frac{\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{n=1}^{N} C_{n,s,i} \times D_{n,s,i}}{\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{n=1}^{N} C_{n,s,i}}$$

where N is the number of considered components, S is the number of stories, I is the number of sides, D is damage percentage of the component, and C is the cost of repair (value) of the component. The component value is based on the RS Means (2013) online database, and it is assumed to be the value of the most common type of the component in the community because it is difficult to determine the component types for all houses.

In addition to the loss ratio of the overall structure, the loss ratio of a side or a story can likewise be calculated. When calculating the loss ratio for a structure's first story, we consider damage to windows, doors, wall siding, and the exterior walls of the first floor in addition to the structure's foundation. For the second floor, we include windows, doors, wall siding, and the exterior walls of the second floor plus the roof and roof cover.

The total loss in value of a house can be calculated by multiplying its property value by its loss ratio. Note that this calculated loss would be smaller than the real cost of repair because our loss ratio emphasizes structural damage and ignores factors such as market inflation, FEMA's zoning requirements for elevating severely damaged structures, and content loss. However, this estimation of the direct economic loss is an effective approach to link building's component damage to overall structural damage. It is also more useful than a damage state for a homeowner to make reconstruction/repair and insurance decisions. Moreover, insurance claim data indicating the actual economic losses can be used to evaluate our loss estimation and extend it to estimate the real cost of repair.

3.3 Database

We integrate the damage survey data (over 2000 photographs for nearly 380 buildings), our physical damage assessment (estimated damage percentage for each component on each side and each story of each building), and estimated loss ratios into a comprehensive GIS-based database for Ortley Beach. The data can be easily aggregated to study damage at component, story, side, or building level. For example, Fig. 2 shows the spatial distribution in Ortley Beach of the percentage damages at the component level for foundations, exterior walls, and wall siding, respectively. The severity of component damage clearly decreases as the distance to the coast increases. The severe component damage is prevalent near the coast because many houses in the front rows were separated from their foundations by

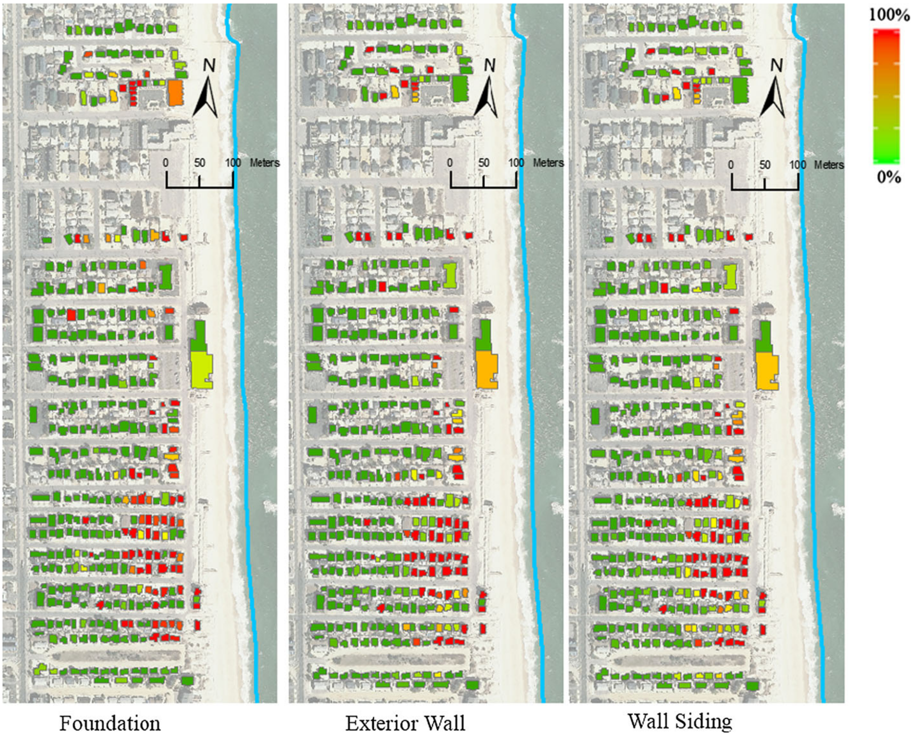


Fig. 2 Spatial distribution of the damage percentage for foundation (*left*), exterior wall (*middle*), and wall siding (*right*) of all surveyed buildings (the *blue curve* indicates the coastline)

strong surge and wave forces and waterborne debris impact. As discussed further in the following sections, the overall loss ratio at the building level also tends to decrease with increasing distance from the coast. In a few cases, houses far from the coast (e.g., beyond 200 m) suffered significant damage because of local debris impact.

In addition to the damage and loss ratio data, the database also includes related information for each house, such as house characteristics, age, and ground and front door elevations, as well as the waterborne debris damage and structural shielding effects estimated by Hatzikyriakou et al. (2015; Debris damage is classified into different levels of severity from 0 (no damage) to 3 (severe damage) and structural shielding is coded "yes" if the front structure did not suffer substantial damage). Table 3 lists the main attributes of the developed GIS database. The framework of the database is constructed to be general enough for documenting hurricane damage to residential structures, i.e., for both wind and surge damage. Further analysis using the database to investigate Sandy's damage to Ortley Beach and related FEMA insurance issues is discussed in the following two sections.

4 Analysis of structural damage and vulnerability

The detailed damage information of the database allows us to characterize damage features such as failure mechanisms and the relative severity of damage to various components, sides, and stories. Furthermore, we can investigate the damage factors, quantify the

Table 3 Main attributes in the developed GIS-based database

Built environment		
Distance to coast	Ground elevation	Distance to neighbors
Row number	Debris impact	Shielding effect
Building characteristics		
Front door elevation	Year of built	Number of stories
Elevation above ground	Building type	
Component types		
Foundation	Exterior wall and siding	Roof and roof cover
Window	Door	Connection
Component characteristics		
Material	Foundation type	Failure mode
Wall inclination		
Component damage percentage at a side and a story		
Front side (ocean-facing)	Left side	Right side
Back side	1st, 2nd or 3rd story	
Loss ratio		
Overall loss ratio	Loss ratio of first story	Loss ratio of second story
Loss ratio of four sides	Overall losses	

vulnerability of structures and components through fragility analysis, and estimate the relative contributions of component damage to the total loss. Such analyses, as illustrated in this section, advance our understanding of the performance of coastal structures during historical storm surge events (Sandy in this case) and provide quantitative information for developing effective strategies to mitigate future risk.

4.1 Damage features

The overall damage features in Ortley Beach have been discussed by Hatzikyriakou et al. (2015) and Tomiczek et al. (2015) (see Sect. 3.1). Here, we focus on more detailed features revealed by our quantitative database. Storm impact on a structure differs at different stories, mainly due to the different effects of wind and storm surge. In the case of Hurricane Andrew (1992), which was a strong wind event, upper-level damage (e.g., roof) was much more severe than lower-level damage (Crandell et al. 1993). On the contrary, more severe lower-level damage (e.g., foundation damage) was observed in Hurricane Opal (1995), as it induced intensive storm surges (Crandell 1998). As for Hurricane Sandy, we apply our database to quantitatively assess the performance of different stories by comparing the loss ratio of the first story to that of the second story. As shown in Fig. 3a, almost all houses suffered significantly higher damage to the first story than to the second story; the data (objectively) indicates that Sandy was more of a surge event than a wind event. (Only one structure had higher damage in the second story; it is located in the middle of the study area, and its roof appears to be affected by windborne debris.)

Connection failure has been widely observed in post-hurricane investigations (Eamon et al. 2007; van de Lindt et al. 2007). Our study also finds that most of the connection failures occur at the connections between walls and foundations, contributing significantly to the damage to the first story. A surge induces not only horizontal loads but also vertical

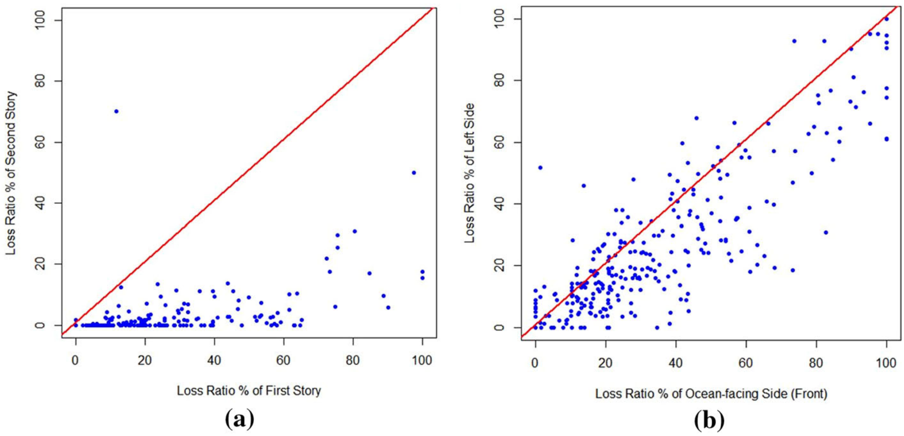


Fig. 3 Analysis on the story and side effects on damage to all surveyed buildings. **a** Loss ratio of first story versus loss ratio of second story; **b** loss ratio of the front side (facing the ocean) versus loss ratio of the *left side*

loads due to buoyancy. Therefore, in addition to shear failure (i.e., siding failure along the plane of foundation), this upward force can also fail the house by pulling it up from its foundation. It is thus critical to strengthen the connections between walls and foundations to resist surge damage.

The vulnerability of a structure also differs on different sides. The direct impact from a surge acts on the wall facing the ocean, resulting in higher damage of the exterior wall, windows, and doors on that side. Foundation scouring also occurs more often on the side facing the ocean as the water erodes the base of a structure and washes away the soil underneath it (Crandell 1996). Thus, as Fig. 3b shows in a majority of cases the ocean-facing front side has a higher loss ratio than the left side (or other sides; not shown). The results support the intuition that reinforcing the oceanfront side of the structure will effectively improve the overall strength of the structure subjected to storm surge. For example, it would be beneficial to construct the oceanfront wall with higher construction material standards (e.g., higher strength wood and/or durable concrete), retrofit windows, doors and foundation with reinforced waterproof covering, and reinforce and weld the connections between the wall and foundation.

4.2 Damage factors

During storm surge, built environment features such as the distance to the ocean, location (e.g., row number), ground elevation, and shielding and debris effects of surrounding buildings can affect storm surge risk to individual structures. In addition, building characteristics such as building age, house elevation, and construction type further influence the vulnerability.

In Fig. 4, we investigate how various environmental features and building characteristics affect the overall loss ratio of buildings. As shown in Fig. 4a, the study area in Ortley Beach has 20 rows with the distance of structures from the coast ranging from 95 to 366 m. Distance and row are highly correlated, and damage decreases quickly as the distance and/or row increases. Structures with moderate and severe damage are clustered within 190 m

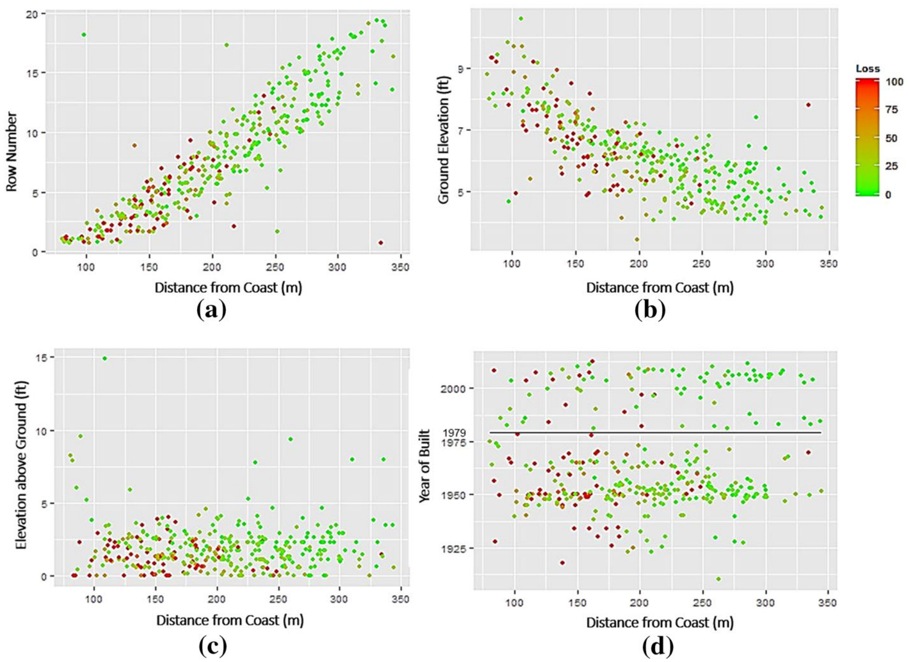


Fig. 4 Variation of overall loss ratio (in a continuous *scale*) of surveyed buildings with: **a** distance versus row; **b** distance versus ground elevation; **c** distance versus front door elevation above the ground; **d** distance versus year of built (1979 is the year when the first FIRM of Ortley Beach was released). (Distance from coast was measured in GIS; ground elevation was obtained from 1-m Lidar digital elevation models (DEM; USGS 2013); elevation above the ground was measured during the damage survey; and building age was obtained from the property tax data of Toms River, NJ)

(6 rows) from the coast, and almost all houses that are beyond 240 m (10 rows) from the coast suffered light or no damage. Ground elevation is not found to be an important factor (Fig. 4b). The effect of ground elevation is not influential to damage because in this study area the ground elevation is inversely correlated with the distance to the ocean (i.e., front rows are on higher ground), and front houses near the coast suffered substantial damage due to large surge and wave impact. This phenomenon suggests that distance to coast/row number is a dominant damage factor compared to the ground elevation.

Having an adequate elevation above ground (front door elevation minus ground elevation) is considered to be an effective mitigation strategy for storm surge (e.g., Aerts et al. 2014; Klima et al. 2011). Houses with low elevation above ground are expected to suffer higher damage if exposed to the same hazard as higher houses. As Fig. 4c shows, the majority of houses with moderate or severe damage in the study area have an elevation that is less than 2 ft above the ground. Houses with an elevation that are more than 4 ft above the ground suffered limited damage even if they are near the coast. These observations suggest that if a house is elevated high enough above the ground with an open foundation (e.g., elevated on piles, piers, or columns), its vulnerability to damage would be reduced significantly. However, because most houses in Ortley Beach were built using closed foundations with continuous perimeter walls (e.g., slab foundations) and a front door elevation that was lower than 4 ft above the ground, those structures were exposed directly to storm surge and wave impact.

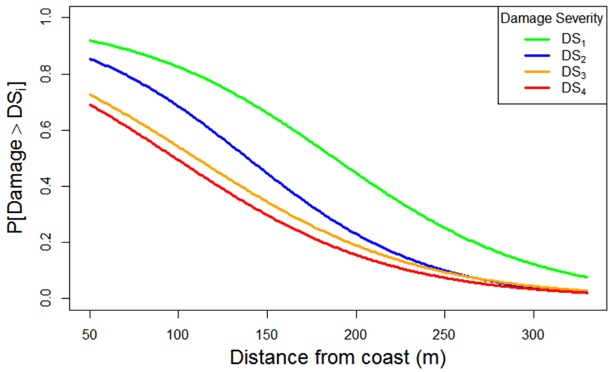


Fig. 5 Building fragility curves giving probability of exceeding damage state i, denoted by DSi (DS1: 20 % damage; DS2: 40 %; DS3: 60 %; DS4: 80 %) as a function of distance from coast, based on the data of all surveyed buildings in Ortley Beach

Building age was found to be an important damage predictor for major components, especially wall siding (Hatzikyriakou et al. 2015), as old structures often lack continuous load paths to transfer forces effectively (FEMA 2013). As shown in Fig. 4d, the year of construction for surveyed structures varies from 1910 to 2010. The majority of the buildings were built between 1945 and 1975, and their age is almost uniformly distributed over the area. Since the release of the first FIRM in 1979 enhanced the building standards for Ortley Beach, the year of construction may be classified into two groups with a cut point of 1979. The proportion of the buildings built after 1979 with very severe damage is lower than that of buildings built before 1979, indicating that the enhancement of the building standard was effective. However, the distance to the coast is still a dominant damage predictor compared to the year the structure was built.

The above analysis suggests that both built environment features and building characteristics affect building vulnerability and both need to be considered in assessing the resistance of structures to storm surge (i.e., the ability to remain undamaged under storm surge impact). However, as the distance from the coast is a dominant damage predictor in this case, we present the (relative) structural vulnerability in the area under Sandy's surge with fragility curves showing the probability of exceeding a given damage state as a function of distance from the coast, shown in Fig. 5. Four damage states of loss ratio (indicated as DSi) are considered: 20 % (DS1), 40 % (DS2), 60 % (DS3), and 80 % (DS4). Damage exceeding DS1 (light damage) is likely to occur even beyond 200 m (with a probability of over 0.5). The probability of damage exceeding DS2 (moderate damage) reduces more quickly as the distance to the coast increases. Severe damage (exceeding DS3 or DS4) is not likely to occur beyond 200 m (with a probability of about 0.2), even under the extreme surge case of Hurricane Sandy.

4.3 Component vulnerability

Hatzikyriakou et al. (2015) discussed the importance to statistically analyze component vulnerability using characteristics of the built environment such as the distance of a structure from the coast. As an improvement over their analysis (of failure/survival damage states), we consider damage severity of components and develop fragility curves giving the probability of exceeding a given component damage state as a function of the distance

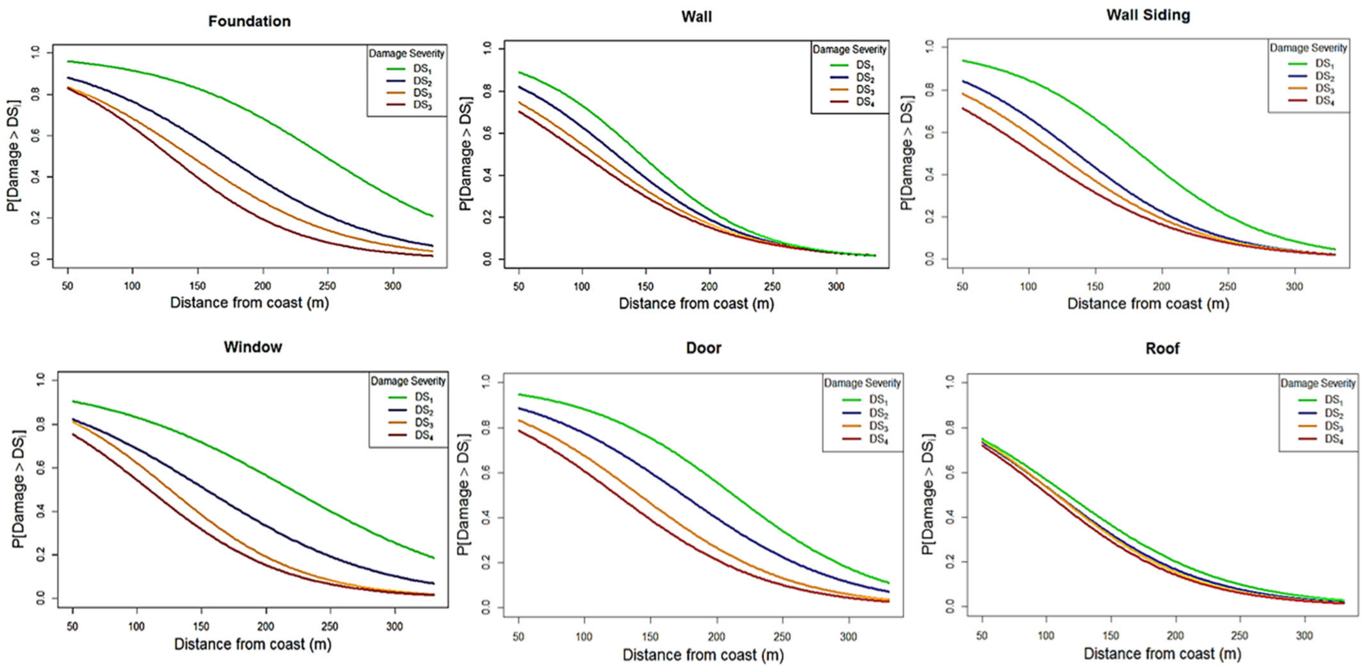


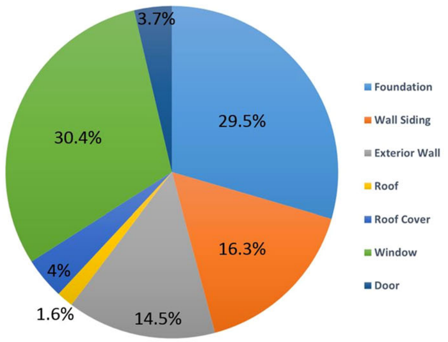
Fig. 6 Component fragility curves giving the probability of exceeding damage state i, denoted by DSi (DS1: 20 % damage; DS2: 40 %; DS3: 60 %; DS4: 80 %) as a function of distance from coast, based on the data of all surveyed buildings in Ortley Beach

from the coast. Similar to the case for overall structural damage, four damage states, 20 % (DS1), 40 % (DS2), 60 % (DS3), and 80 % (DS4), are considered for each component.

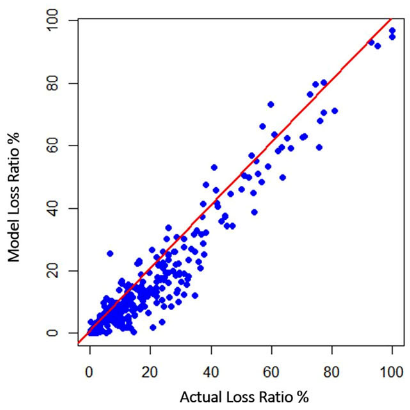
As shown in Fig. 6, the probability of foundation damage is generally higher than that of wall damage. Furthermore, the probability of foundation damage exceeding DS1 is relatively high over a large distance from the coast while the probability of exterior wall damage exceeding DS1 reduces quickly as the distance increases. It is likely due to the fact that for structures relatively far from the coast, foundations may be still vulnerable to failure due to scouring (Hatzikyriakou et al. 2015) while surge velocity is too low to cause significant damage to exterior walls. The similar probability of exterior wall damage exceeding DS1, DS2, DS3, and DS4 (especially when distance is beyond 200 m) implies that exterior wall damage is not likely to occur far inland. Although the shape of the fragility curves for higher damage states for exterior walls and wall siding are similar, the probability of exceeding DS1 for wall siding is higher than for exterior walls because surge with low velocity may still damage siding with inundation. The fragility curves for windows and doors are higher than those for exterior walls but similar to (or slightly higher than) those of wall siding, as windows and doors are on the wall but they are more vulnerable to surge and wind. The roof fragility curves converge because the roof had limited damage in this surge event except for houses that were completely destroyed (i.e., roof damage is close to either 0 or 100 % in most cases). (The light damage curve is slightly higher due to limited wind and windborne debris damage to the roof of structures not being greatly affected by the surge.)

4.4 Component losses

In addition to different damage severities, components contribute to the overall loss differently due to the variable costs of repair. To better understand these differences, we break down the overall loss ratio into component loss contributions. As shown in Fig. 7a, windows and foundations take the highest loss proportions among all components, as they are both vulnerable and expensive to repair. If we aggregate exterior walls and wall siding as a single component, this subassembly becomes the largest contributor to overall losses,



(a)



(b)

Fig. 7 Analysis of component losses based on the data of all surveyed buildings in Ortley Beach. **a** Loss contributions of main components to the overall loss; **b** comparison of the actual loss ratio and the model loss ratio estimated from linear regression; model loss ratio (%) = 3.42 + 0.37 × foundation damage (%) + 0.47 × wall damage (%) + 0.12 × roof damage (%), with R^2 of 0.97

slightly higher than that of windows and foundations. Doors are a small proportion because we have limited number of doors, and the resistance of doors is much higher than that of windows. Roof and roof covers make up the smallest proportion since wind damage was minor in the case of Hurricane Sandy.

Thus, damage to exterior walls (including siding) and foundations largely determine the overall damage/loss due to storm surge, considering windows are on the wall and thus window damage is highly correlated with wall damage (see Table 2). However, roof damage indicates the presence of wind effects. Although limited in this event, these effect may be important in other hurricanes in which wind damage is substantial (e.g., FEMA 2009; Crandell 1998). Therefore, a multi-variable linear regression may be developed to relate the overall loss ratio of a structure to wall, foundation, and roof damage. Indeed, such a regression can be developed with a high statistical confidence (R^2 value of 0.97) for the surveyed data for Ortley Beach (Fig. 7b). Although this empirical regression is based on one surge event and a single community, this method to correlate component damage to overall losses may be further applied and evaluated in future damage assessments. A simpler regression can also be obtained using, for example, only foundation damage as the indicator of overall losses, since the damage among all components are indeed highly correlated due to correlation in both load and resistance (Table 2). Such a fit to our surveyed data for Ortley Beach has moderately lower confidence (with an R^2 of 0.87; not shown). Such an approximate relationship may be useful to quickly estimate the loss from only the information on foundation damage, which may be detected quickly from airborne and mobile LIDAR and remote sensing data (Hatzikyriakou et al. 2015; Friedland 2009).

5 Evaluation of the FEMA flood map

Based on the analysis of Sandy-induced storm surge damage to coastal structures in Ortley Beach, in this section we assess the performance of FEMA's flood risk mapping. The accuracy of flood mapping depends on hydrological, hydraulic, and terrain information (Maidment 2009). Analyses considering surge, wave, wave run-up, erosion, and frontal sand dune are used to determine the risk zones and base flood elevation (BFE) in Flood Insurance Rate Maps (FIRMs; Algeo and Mahoney 2011). Coastal changes such as coastal erosion, vegetation growth, and man-made development can affect hydrological processes (Farrell et al. 1999; FEMA 2013; Crowell et al. 2007). However, it is challenging to keep the national flood map updated. For example, FEMA has not performed scientific hydraulic and coastal modeling analyses for Seaside Heights in Ocean County, New Jersey, since 1983 (FEMA 2014). Furthermore, as mapping is primarily based on simulation and modeling, uncertainties exist when compared to real flood events (Shan et al. 2009). Although these and other potential issues with current FIRMs have been recognized, there is limited if any external literature beyond FEMA using real damage data to evaluate FEMA's flood maps. Such evaluation is crucial to determining potential problems with existing estimation of the coastal risk. We begin by briefly introducing the FEMA flood map for Ortley Beach.

5.1 Flood map for Ortley Beach

FIRMs delineate the boundary of flood zones to provide a technical basis for the design of coastal structures in storm surge zones (FEMA 2013). In each flood zone, the local BFE consists of a still water height estimated from hydrodynamic and hydraulic studies and a wave crest elevation estimated from wave modeling (Bellomo et al. 1999). The first FIRM for Ortley Beach was released in 1979 and updated over the years. In the following discussion, the current map refers to the currently effective FIRM, which was released in September 2006 (and was in effect in 2012 when Sandy happened). The preliminary new FIRM was released in March 2014 and is currently under review; it is expected to be finalized and released at the end of 2015. The flood zones on the current effective and new FIRMs for Ortley Beach are defined below (according to FEMA 2011 and FEMA 2013b) and displayed in Fig. 8a, b.

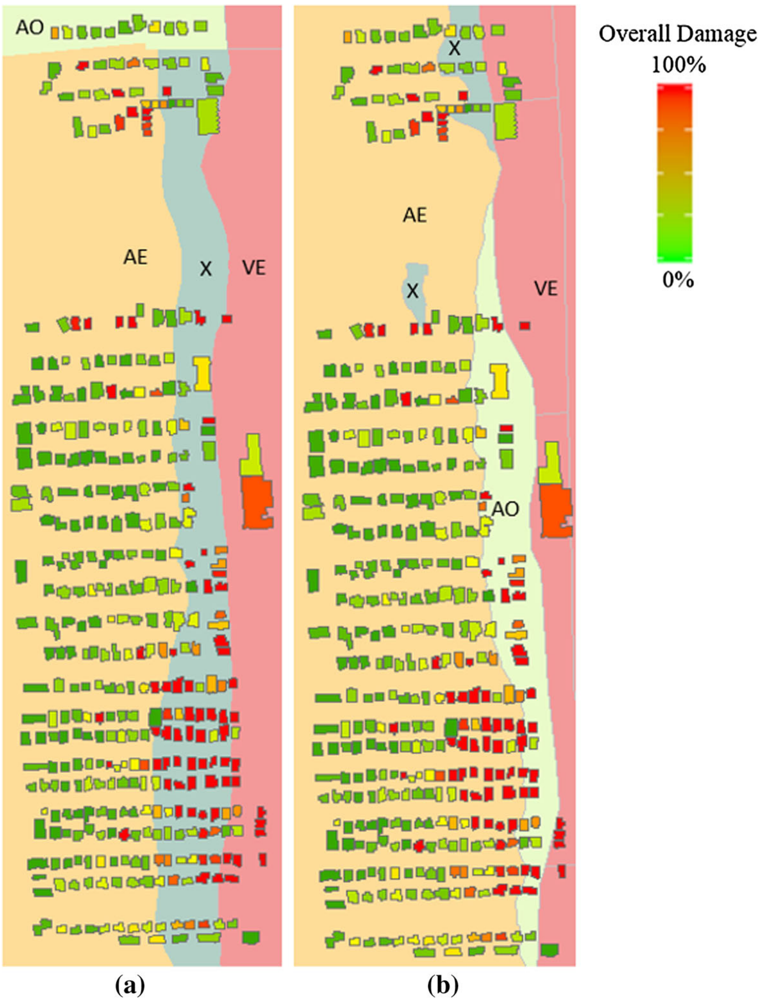
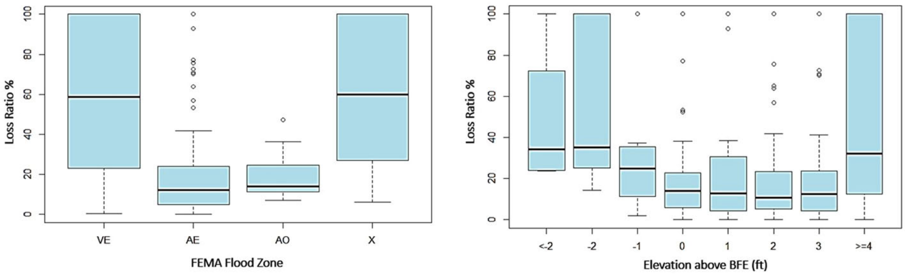


Fig. 8 Loss ratio of Ortley Beach houses (*blocks*) overlaid on FEMA flood zones (*shades*) for: **a** current effective FIRM and **b** preliminary new FIRM. The loss ratio ranges from 0 % (*green block*) to 100 % (*red block*; measured by the *color bar*). Flood zones of FEMA include (in order of high to low risk): VE zone (*red shade*), AE zone (*yellow shade*), AO zone (*light green shade*), and X zone (*blue shade*)

- *VE zone* is subject to inundation risk of 1 % annual chance (100-year flood) and wave risk of over 3 ft. All properties that exist in this region must purchase mandatory flood insurance. Any new structure built in this area or any home that undergoes at least 50 % structural damage must raise the house so that the bottom of the lowest horizontal structural member (LHSM) of the building is at or above the BFE (current: 10–12 ft; new: 12–16 ft).
- *AE zone* is subject to inundation risk of 1 % annual chance and wave risk of 1–3 ft. Homeowners are required to purchase flood insurance. It is required that all homes with 50 % or greater structural damage be raised to a level such that the LHSM is at or above the BFE (current: 6 ft; new: 7 ft).
- *AO zone* is subject to inundation by the 1 % annual flood event but to only shallow flood level of 1–3 ft. Mandatory flood insurance is required for all homeowners in this area. The BFE is not specified in the current map and is 1 foot in the new map.
- *Shaded X zone* is either the area in a 0.02 % annual flood plain (500-year flood), area of 100-year flooding with average flood depths of less than 1 ft, area of 100-year flooding where the drainage area is less than 1 square mile, or area protected from a 100-year flood by a levee. Flood insurance is available but not mandated. There is no specified BFE for this zone, so there are no standard heights a house must be raised to.

5.2 Evaluation of flood map

To compare the actual damage from Sandy and the flood risk indicated by the FEMA flood map, we overlay our estimated loss ratio for the Ortley Beach houses on the current FEMA flood map and new preliminary FEMA flood map, as shown in Fig. 8a, b, respectively. In Fig. 8a, the three main zones on the current FIRM, VE (red shade), X (blue), and AE zones (yellow), are distributed in order from the coast to inland, indicating a decreasing and then increasing risk from the coast to inland. However, surge damage from Sandy in Ortley Beach continuously increases (from green to red footprint blocks) as one approaches the coast, and severely damaged houses are concentrated in front rows facing the beach. Surprisingly, most of these front row homes are located in the low-risk X zone on the current effective FEMA map. This is in contrast to less damaged inland structures which are located in the higher-risk AE zone (Fig. 8a). Specifically, among the 74 houses that suffered severe damage (>70 %), 47 belong to the X zone in the current flood map. This underestimation of relative flood risk in the X zone is possibly due to high ground elevation and existence of sand dunes (FEMA 2013). We suspect that the wave effect was not sufficiently accounted for by FEMA so that the estimated flooding depended mainly on the ground elevation, which happens to increase toward the coast in this area. (FEMA would classify a zone as low-risk as long as the estimation of 100-year flood level does not reach the ground elevation.) Also, the current map may have considered Ortley Beach being sufficiently protected due to the presence of a coastal dune, which completely failed during Hurricane Sandy (Hatzikyriakou et al. 2015). This observation is in stark contrast to some other areas where the dune system successfully resisted surge/wave forces and the community suffered far less damage from Sandy, such as the nearby Seaside Heights (Hatzikyriakou et al. 2015; FEMA 2013a). Nevertheless, if the dune system cannot be reinforced over time to maintain its capacity of surge/wave protection, it should not be accounted as a risk reduction factor. Indeed, the dune in Ortley Beach had been significantly eroded before Sandy's arrival, as the Toms River Township seldom reinforced the dune there according to our interview with residents living in Ortley Beach. As a result,



(a) **(b)**

Fig. 9 Statistical distribution, as shown by the *box plot*, of the loss ratio of Ortley Beach houses on FEMA's current flood map. **a** Loss ratio distribution of the houses in different flood zones; **b** loss ratio distribution of the houses with different front door elevations above the BFE. The *central black line* is the median (50 %); the *upper* and *lower* boundaries of the box are *upper* (75 %) and *lower* (25 %) quartiles. The *two vertical lines* extending from the central box to the lowest level within 1.5 IQR of the lower quartile and the highest level within 1.5 IQR of the upper quartile (IQR is defined as the difference between the *upper* and *lower* quartiles); outside data are outliers shown by the *points*

since flood insurance is not mandated and there is no mitigation requirement for the X zone, the severely impacted homes in Ortley Beach were not motivated to mitigate risk or purchase insurance before Hurricane Sandy, leading to the significant damage and difficulty in repair/reconstruction.

To summarize the effect of the flood zones on the current map, we compare the statistical distribution of the loss ratio in different flood zones in Fig. 9a. It is striking that the distribution of the loss ratio in the X zone is similar to that in the VE zone. Although there are several areas of significant damage in AE zone, the loss ratio in AE and in AO zones is significantly lower than that in the X and VE zones. The average loss ratio in the X zone (mean 63 %; median 59.9 %) is as large as that in the VE zone (65 %; 58.9 %) and is much larger than that in the AE zone (21 %; 12.2 %) and AO zone (19 %; 13.9 %). Although Hurricane Sandy was an extreme event and some damage might not have been avoided, the loss ratio should be weighted toward the high-risk region or relatively uniform if the spatial distribution of risk was accurately estimated and corresponding mitigation actions were taken.

To further investigate this issue, we also study the effect of BFE. Figure 9b shows the distribution of the loss ratio of the houses with different front door elevations above the BFE on the current map. The current flood map reasonably reflects the high risk for houses with elevation lower than the BFE and moderate risk for houses with elevation slightly higher (0–3 ft) than the BFE. Outliers of significant damage exists for houses with elevation slightly higher than the BFE; more significantly, the distribution of the loss ratio of the houses with elevation greater than 4 ft above BFE is surprisingly high and comparable to those for the houses with elevation lower than 2 ft under BFE. The median loss ratio for houses with an elevation of at least 4 ft above the BFE is as high as 32.2 % (mean is 48.2 %), compared to 34.4 % (mean 48.1 %) for an elevation of at least 2 ft below the BFE.

To examine why the elevation above BFE does not inversely correlate with the damage, we list, in each risk zone, the number of houses with different elevation differences between the front door and BFE in Table 4. More than half of the houses in the VE zone are below the BFE, plus the fact that the residential houses in VE zone are relatively old

Table 4 Distribution of the number of houses with different elevation differences between the front door and BFE in the various risk zones of the current effective FIRM

Elevation difference	Flood zone			
	VE	AE	AO	X
<−2	2	2	0	0
−2	4	4	0	0
−1	7	35	0	0
0	4	36	0	3
1	3	48	0	0
2	2	59	0	0
3	0	41	0	0
4	0	16	0	1
>4	2	8	11	87

(built between 1928 and 1952, resulting in high losses in this zone under this extreme event (Fig. 8a). The majority of the houses in the AE zone are above the BFE, and thus, limited damage was observed in this zone (Fig. 8a). As the AO zone has a BFE of only 1 foot, all of the houses in this zone have a front door elevation greater than the BFE; as shown in Fig. 8a, these houses were only moderately damaged. The most problematic zone is the X zone. Although almost all houses in this zone are higher than the BEF by more than 4 ft, many houses in this zone were totally destroyed (Fig. 8a). This severe destruction occurred because the X zone does not have a BFE (denoted as 0 ft), and the houses were not required to be elevated. The reason that they are much higher than the BFE is that their ground elevation is already several feet above the BFE. Thus, although the large losses for houses with the front door elevation much lower than the BFE (left end of Fig. 9b) is mainly due to the homeowners' ignorance of the risk in the VE and AE zones in Ortley Beach, the large losses for houses with the elevation much higher than the BFE (right end of Fig. 9b) can be at least partially attributed to FEMA's significant underestimation of the risk for the near-shore region (specified as the low-risk X zone).

These analyses show that the current FEMA flood map may not reflect the actual spatial distribution of risk and that updating is necessary. Indeed, FEMA has conducted more detailed hydrological and hydraulic studies and wave analysis to update the flood map. To evaluate the new preliminary flood map, we also overlay our estimated damage for Ortley Beach on the new map (Fig. 8b). The main zones in the new map are VE (red shade), AO (light green), and AE zones (yellow), distributed generally in order from the coast to inland. The risk is still indicated to first decrease and then increase from the coast to inland, but the X zone is almost totally removed and most houses in the current X zones (87 out of 91) would be located in higher-risk zones. Specifically, 61, 22, and 4 houses in the X zone would be moved to the AE, AO, and VE zones, respectively, and these houses would be mandated to purchase insurance and required or motivated to take mitigation actions. However, although the AO zone is assigned a higher flood risk than the X zone, wave effects are not considered in this zone either. Sandy's case indicates that this AO zone (including 22 houses) in the new map will be subjected to wave impact. Indeed, as this AO zone is located in front of the AE zone, its houses will shade the houses in the AE zone (subjected to wave impact risk by definition) from wave impacts. Thus, FEMA's new map has improved the risk classification by moving the X zone houses to higher-risk zones, but the potential effect of waves is still not well represented.

6 Conclusions and recommendations

Damage induced by Hurricane Sandy to approximately 380 coastal structures in Ortley Beach is assessed quantitatively. A detailed GIS database is established, incorporating building and environmental information, estimated physical damage, and economic loss ratio. The database is used to analyze damage features, key damage factors, as well as structural and component vulnerability. Overall damage features can be assessed at the building, side, and story levels. For example, the analysis quantitatively shows that the ocean-facing side and the first story of the building suffered significantly greater damage than other sides and higher stories, due to the effects of surge/wave impact in this event. Among the various factors contributing to structural damage, the distance to the coast is found to be most dominant, as it is highly correlated with the dissipation of waves and shielding effects of near-shore structures. The elevation of the structure above the ground is found to be of secondary importance; a near-shore structure has a relatively high chance of survival if it is elevated high enough from the ground (>4 ft in this case). The age of the structure also has some effect: houses built after 1979 (when the first FEMA flood map was released for the area) performed better than older houses. Among the various structural components, foundations are the most vulnerable to storm surge, followed by exterior walls. Also, because the magnitudes of damage to different components are highly correlated, the overall damage and loss ratio may be estimated from the damage severity of foundations, walls, and roofs (or only from that of foundations in a surge event). Similar to overall damage, minor component damage especially to foundation is likely to occur over the entire coastal area, but moderate or severe component damage is concentrated near the coast.

The database is then used to evaluate the performance of the FEMA flood map. It is found that FEMA significantly underestimated the storm surge risk to structures near the shore relative to structures further inland. The low-risk X zone in the current flood map is located in front of the higher-risk AE zone, while in reality most severely damaged buildings are concentrated in this near-shore X zone and buildings in the relatively inland AE zone performed significantly better. The difference in damage in these two neighboring regions is induced by two factors: (1) waves were indeed stronger in the near-shore region (even though it is on a higher ground) plus the near-shore buildings shade the inland buildings from wave impacts and (2) unlike their inland neighbors in the AE zone, the near-shore buildings in the X zone were not motivated to take risk mitigation actions or required to purchase flood insurance. This finding highlights the importance of accurately defining coastal flood maps for mitigating flood risk. This analysis also demonstrates a method to evaluate the spatial distribution of the risk on the flood map; the flood map for other areas affected by Hurricane Sandy and other historical storms should be similarly investigated to provide information for updating the flood map. Our study also notes that the preliminary new FEMA flood map is improved by removing the X zone from our study area, but a near-shore region is still assigned a no-wave-risk AO zone, in front of the wave-susceptible AE zone; further improvements should be made in wave modeling.

Finally, this study provides recommendations for building design and FEMA's policy making. Concerning building design, it is critical to strengthen the connections between foundations and walls in order to reduce separation failure due to surge/wave impact. In coastal planning, a minimum distance from the coast may be required in building construction and reconstruction. Old buildings (pre-FIRM) near the coast should be strengthened or elevated to meet or exceed the BFE even if they were not severely damaged during Hurricane Sandy. To further improve the accuracy of the flood map in representing the spatial variation of the risk, FEMA may consider subdividing the risk zone into more BFE categories for minimum design requirements. Overall, the database and analyses in this study can be used by policy makers in Ortley Beach and similar communities to more effectively relocate their resources for community recovery and risk mitigation.

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