9. EARTHQUAKES

A. Hazard Profile

i. Hazard Description

The infrequency of major earthquakes, coupled with relatively low-magnitude events in the past, has led to a public perception that New York City is not vulnerable to a damaging earthquake. While the city does not sit on a major fault system, it is susceptible to earthquakes that originate in or near the city. Population density, critical assets, and aging and interdependent infrastructure amplify the city's risk.

An earthquake is a sudden, rapid shaking of the earth caused by the breaking and shifting of rock beneath the earth's surface. Most earthquakes originate from faults, or a break in the rocks that make up the earth's crust, along which rocks on either side move past each other. As the rocks move past each other, they occasionally stick, causing a gradual buildup of energy. Eventually, this accumulated energy becomes so great that it is abruptly released in the form of seismic waves. These waves travel away from the earthquake's source (or focus) deep underground, causing the shaking (ground acceleration) at the earth's surface. The point on the earth's surface that is directly above the focus is the epicenter.

Ground acceleration caused by earthquakes has the potential to destroy buildings and infrastructure and can result in loss of life. In addition to these effects of ground acceleration, earthquakes can also trigger landslides and liquefaction under certain conditions. Liquefaction occurs when unconsolidated, saturated soils exhibit fluid-like properties due to the intense shaking and vibrations during an earthquake. Together, ground shaking, landslides, and liquefaction can damage or destroy buildings, disrupt utilities, trigger fires, and endanger public safety. Aftershocks are typically smaller than the main shock, and can continue over weeks, months, or years after the initial earthquake is felt.

ii. Severity

The terms "magnitude" and "intensity" are used to describe the overall severity of an earthquake. An earthquake's magnitude is a measurement of its total amount of energy and is expressed in terms of the Richter scale. Intensity measures the effects of an earthquake at a particular place and is expressed in terms of the Modified Mercalli scale.

Figure 1 compares the Richter scale magnitude and Modified Mercalli Intensity (MMI).

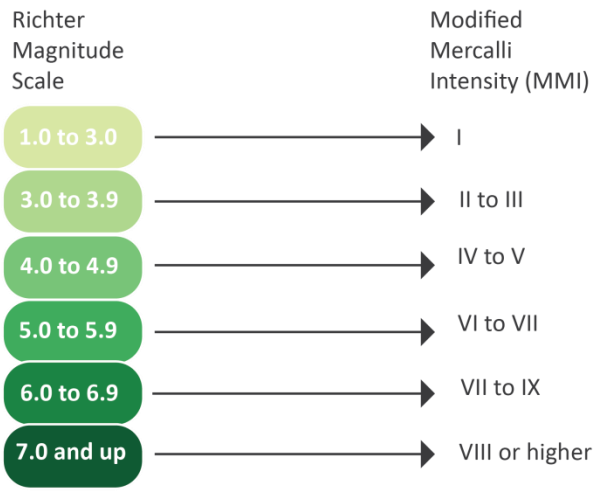


Figure 1: Richter Magnitude and Modified Mercalli Intensity Comparison

Table 1 describes the effects of intensity ratings. According to the National Climatic Data Center, the strongest earthquake near New York City occurred on August 10, 1884. It had a magnitude of 5.2 on the Richter scale and would have had an intensity of VI to VII on the MMI scale.

MMI	Damage/Perception
I	• Not felt except by a very few under especially favorable conditions
II	• Felt only by a few people at rest, especially on upper floors of buildings
III	• Felt quite noticeably by people indoors, especially on upper floors of buildings • Many people do not recognize it as an earthquake • Standing motor cars may rock slightly • Vibrations similar to the passing of a truck
IV	• Felt indoors by many, outdoors by few during the day • At night, some awakened • Dishes, windows, doors disturbed; walls make cracking sound • Sensation like heavy truck striking building • Standing motor cars rocked noticeably
V	• Felt by nearly everyone; many awakened • Some dishes, windows broken • Unstable objects overturned • Pendulum clocks may stop
VI	• Felt by all; many frightened • Some heavy furniture moved • Few instances of fallen plaster • Damage slight

MMI	Damage/Perception
VII	• Damage negligible in buildings of good design and construction • Slight to moderate damage in well-built ordinary structures • Considerable damage in poorly built or badly designed structures • Some chimneys broken
VIII	• Damage slight in specially designed structures • Considerable damage in ordinary substantial buildings with partial collapse • Damage great in poorly built structures • Fall of chimneys, factory stacks, columns, monuments, walls • Heavy furniture overturned
VIII	• Damage slight in specially designed structures • Considerable damage in ordinary substantial buildings with partial collapse • Damage great in poorly built structures • Fall of chimneys, factory stacks, columns, monuments, walls • Heavy furniture overturned
IX	• Damage considerable in specially designed structures • Well-designed frame structures thrown out of plumb • Damage great in substantial buildings, with partial collapse • Buildings shifted off foundations
X	• Some well-built wooden structures destroyed • Most masonry and frame structures destroyed with foundations • Rails bent
XI	• Few, if any masonry or frame structures remain standing • Bridges destroyed • Rails bent greatly
XII	• Total damage • Lines of sight and level are distorted • Objects thrown into the air

Table 1: MMI Scale Rating

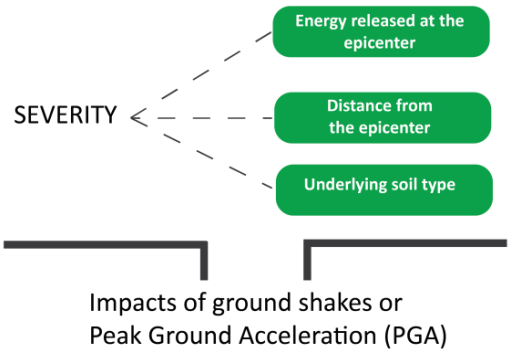


Figure 2: Earthquake Severity Factors

The severity of an earthquake also depends on the amount of energy released at the epicenter, the distance from the epicenter, and the underlying soil type. All these factors affect how much the ground shakes, known as Peak Ground Acceleration (PGA), during an earthquake, and what a building experiences, known as Spectral Acceleration (SA), during an earthquake (see Figure 2).

PGA measures the rate of change in motion of the earth's surface and expresses it as a percent of the established rate of acceleration due to gravity (9.8 m/sec^2). Figure 3 shows that PGA values of 3% to 4% of gravity have the potential to occur in New York City.

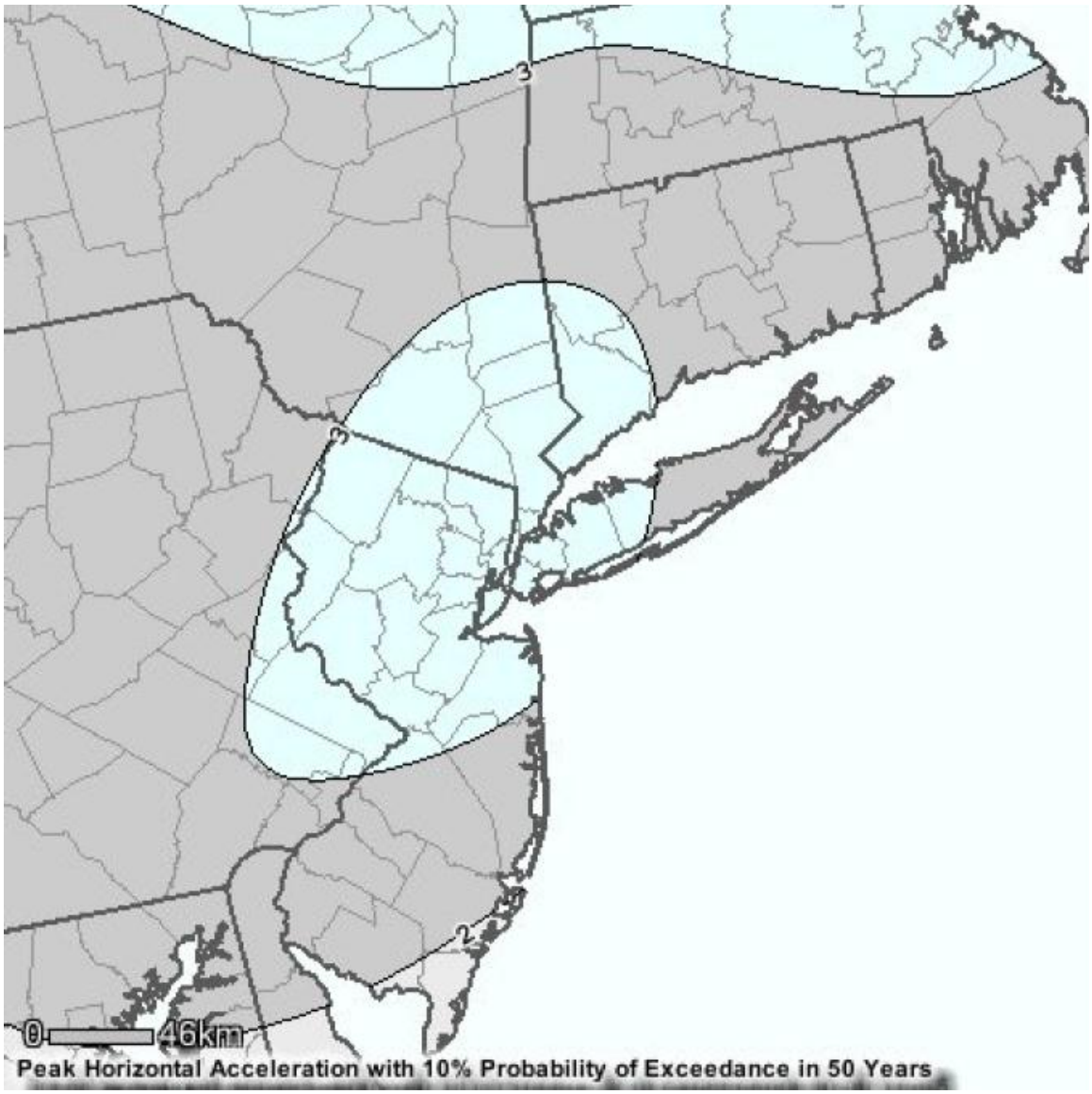


Figure 3: PGA in New York City (Source: National Seismic Hazards Maps, 2008)

An approximate relationship between MMI and PGA is shown in Table 2. The 3% to 4% PGA predicted above would result in an MMI intensity of IV (light perceived shaking and no damage).

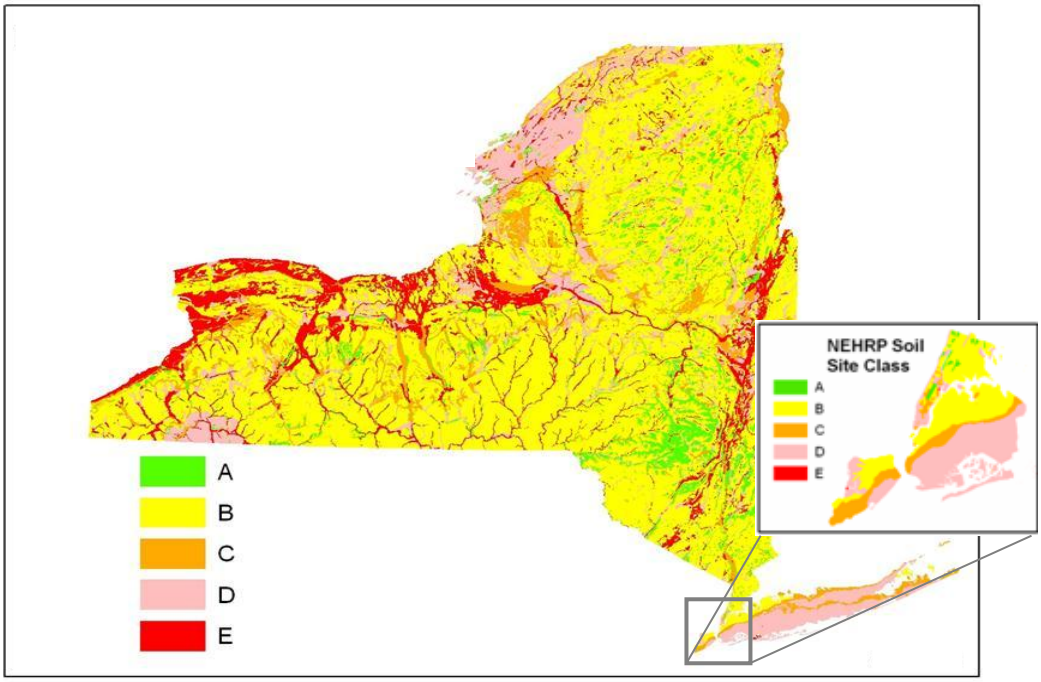
MMI	Acceleration (%g) (PGA)	Perceived Shaking	Potential Damage
I	< .17	Not felt	None
II	.17–1.4	Weak	None
III	.17–1.4	Weak	None
IV	1.4–3.9	Light	None
V	3.9–9.2	Moderate	Very light
VI	9.2-18	Strong	Light
VII	18–34	Very strong	Moderate
VIII	34–65	Severe	Moderate to heavy
IX	65–124	Violent	Heavy
X	> 124	Extreme	Very heavy
XI	> 124	Extreme	Very heavy
XII	> 124	Extreme	Very heavy

Table 2: Approximate Relationship between MMI and PGA

SA is approximately what is experienced by a building during an earthquake, as modeled by a particle mass on a mass-less vertical rod having the same natural period of vibration as the building. SA can be used as a better indicator of damage to specific buildings types and heights.

Soil type can also impact the severity of an earthquake at a given location. This is because seismic waves propagate from the epicenter and travel outward through the bedrock up into the soil layers. As the waves move into the soils, how stiff or soft the soil is affects the wave speed and velocity. In stiff or hard soil the wave generally will travel at a higher velocity. With soft soils, the wave will slow, traveling at lower velocities. With slower waves, the seismic energy is modified, resulting in waves with greater amplitude. This amplification results in greater earthquake damage.

The National Earthquake Hazard Reduction Program (NEHRP) soil classification system describes how soils affect seismic waves. As shown in Figure 4, a map of the NERP soil classifications for New York State, Class A soils (on the map in green) tend to reduce ground motions, whereas Class E soils (shown in red) tend to further amplify and magnify seismic waves. New York City has a variety of NEHRP soil site classes ranging from hard rock to soft soil. Most of New York City is classified as Class B (rock) and Class D (soft to medium clays or sands).



A Very hard rock (e.g., granite, gneisses; and most of the Adirondack Mountains)
B Rock (sedimentary) or firm ground
C Stiff clay
D Soft to medium clays or sands
E Soft soil (including fill, loose sand, waterfront, lake bed clays)

Figure 4: New York State Soil Classifications (Source: NYS OEM 2014)

iii. Probability

The New York State Office of Emergency Management (NYS OEM) created county-specific seismic hazard maps that reflect the soil's ability to affect seismic waves and the resulting SA experienced by a building. The maps are based on the New York State Geological Survey shear-wave tests of the surficial soils. These maps facilitate a better understanding of local seismic hazards by identifying areas of higher vulnerability within the city. Figure 5, a USGS seismic hazard map for New York City, shows that SA values of 25% to 75% of gravity have the potential to occur in New York City. It presents the adjusted USGS 0.2 sec SA with a 2% probability of exceedance within 50 years.

Seismic hazard maps, or PGA maps, project the likelihood of an earthquake at a certain location over a given period. As shown in the USGS seismic hazard map for New York City, (Figure 5) a PGA value of 3% to 4% has a 10% chance of being exceeded over 50 years. Such an earthquake would likely produce light to moderate perceived shaking and little to no physical damage.

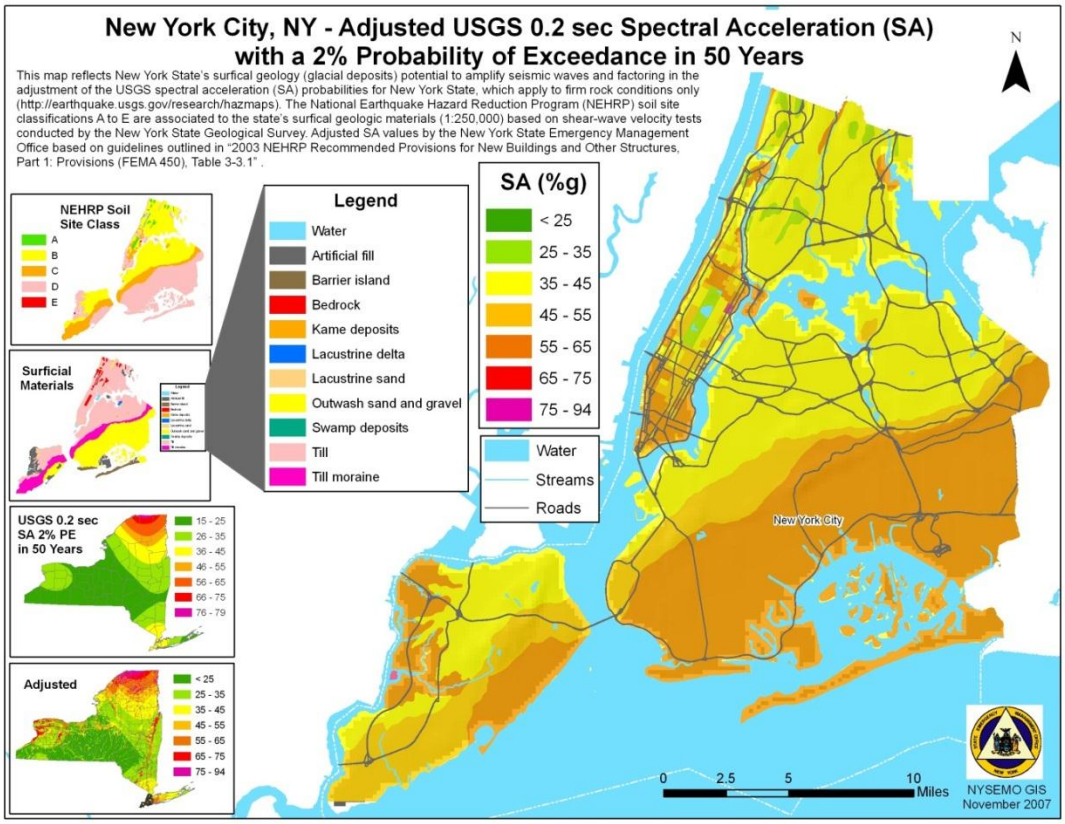


Figure 5: Adjusted USGS 0.2 Sec SA for New York City (Source: NYS OEM, 2011)

According to the New York State Hazard Mitigation Plan (SHMP), New York State can expect a damaging earthquake about once every 22 years, and these events are more likely to occur within one of three regional areas. These regional areas are the North and Northeast third of the state (the North Country/Adirondack Region, including a portion of the Greater Albany-Saratoga region), the Southeast corner (including the greater New York City area and western Long Island), and the Northwest corner (including the city of Buffalo and vicinity). The SHMP references a New York State Geological Survey (NYSGS, study by W. Mitrovonas, entitled "Earthquake Hazard in New York State," which states, "…at present an earthquake of magnitude 3.5 to 4 occurs, on the average every three years somewhere in the State. Such earthquakes do not cause any appreciable damage (except for cracks in plaster, perhaps) but are large enough to be felt strongly by many people near the epicenter."

Although New York City has a low risk of damaging earthquakes, overall seismic risk is higher because of the city's tremendous assets, concentration of buildings, and construction types (most buildings have not been seismically designed). Furthermore, a

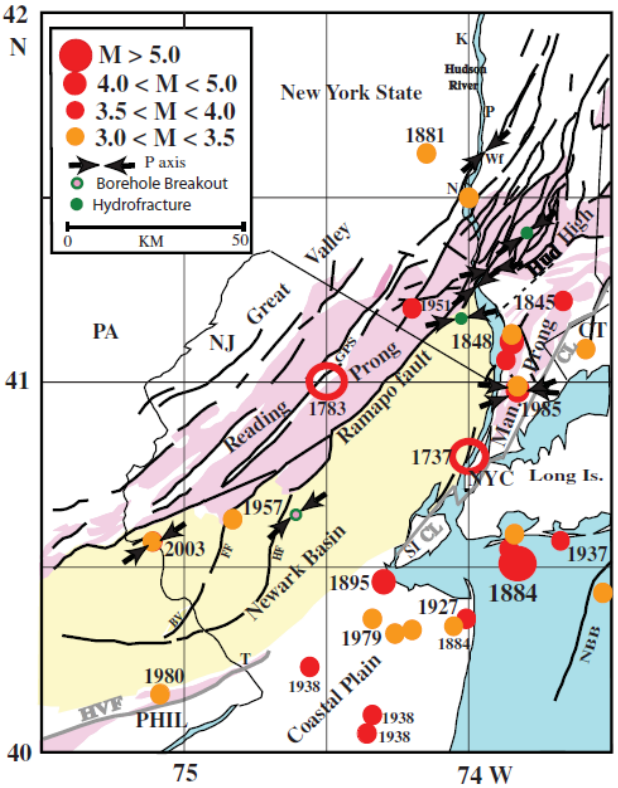


Figure 6: Earthquakes in the Greater New York/Philadelphia area 1667 to 2004, Graded by Magnitude

2001 analysis by the Federal Emergency Management Agency (FEMA) ranks New York City as the 11th most at-risk U.S. city for earthquake damage.

The risk of earthquakes in the New York City area might be greater than once believed. According to a 2008 study by Columbia University's Lamont-Doherty Earth Observatory, there are subtle but active faults in the area. Although New York City is not located along a major fault, the existence of many smaller yet active faults may increase the probability of a large earthquake. The Lamont-Doherty Earth Observatory located hundreds of small events, which included magnitude 3 earthquakes that occurred from 1677 to 2007 (see Figure 6). The smaller earthquakes tended to occur along a series of small, old faults in harder rocky soil. The study asserts that these faults are still active and capable of producing severe earthquakes. According to the study, the probabilities of occurrence in a 50-year period would be 7% (magnitude 6) and 1.5% (magnitude 7).

iv. Location

According to the U.S. Geological Survey (USGS) Earthquake Hazards Program, around 90% of earthquakes occur at the boundaries where the earth's tectonic plates meet, although it is possible for earthquakes to occur entirely within plates. New York City is located well within the North American plate, far from the plate boundary, which is located approximately 2,000 miles east in the Atlantic Ocean. Seismic research is being conducted into the causes of earthquakes in regions far from plate margins. Regardless of where they are centered, earthquakes can affect locations beyond their point of origin.

Earthquakes are possible in any of New York City's counties. However, the risk of earthquakes is not the same throughout the city, as evidenced by higher SA values in certain areas. These areas would likely experience more damage depending on their proximity to an earthquake's epicenter. Figure 7 shows the distribution of historical earthquake epicenters throughout New York State. Even if the greatest damage occurs

outside the metropolitan area, earthquakes that occur in the northeast region can still affect New York City (see Table 3). For example, two earthquakes that recently occurred (one in Virginia in 2011 and one in Canada in 2013) were felt in the city.

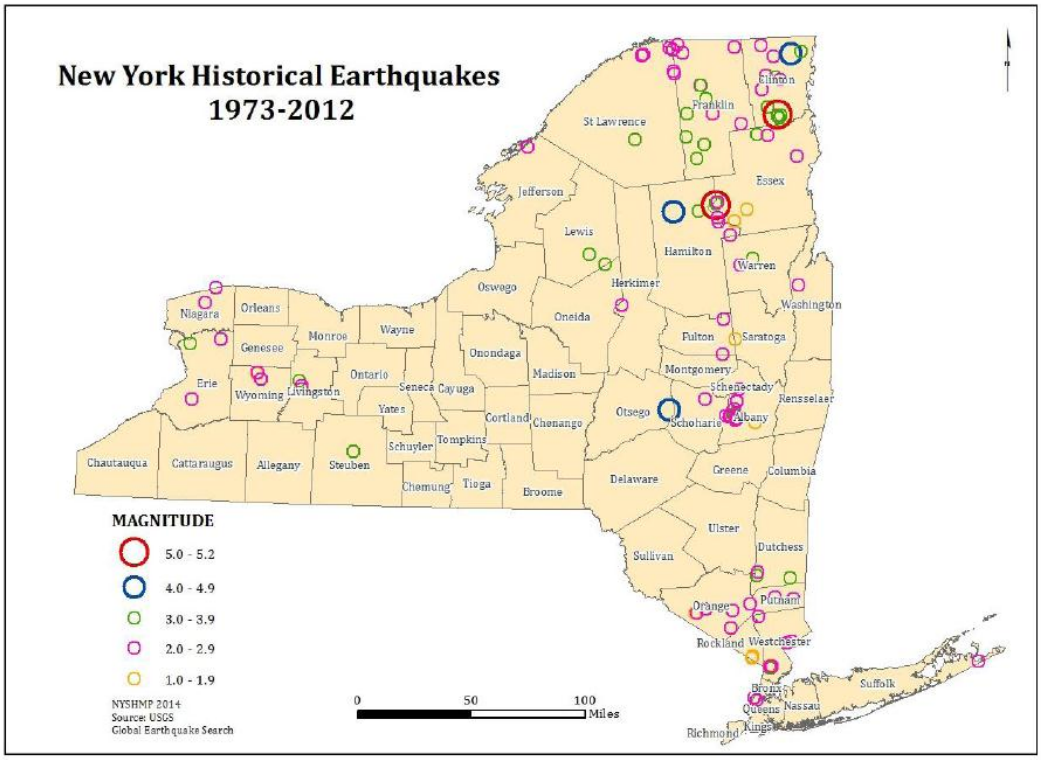


Figure 7: New York State Historical Earthquakes 1973-2012

Areas with large numbers of unreinforced masonry buildings are also vulnerable to earthquakes. This building type is not as sturdy and does not absorb energy as well as other structure types such as wood, steel, or reinforced concrete. Brooklyn has the largest number of unreinforced masonry buildings (see Built Environment, below). According to the New York City Area Consortium for Earthquake Loss Mitigation (NYCEM), 79% of all buildings in Manhattan are unreinforced masonry buildings. Neighborhoods in Lower Manhattan—such as Soho, Greenwich Village, Chinatown, Little Italy, and Noho—have many unreinforced masonry buildings. In addition, both the Upper West Side and Upper East Side have many unreinforced masonry buildings. The 125th Street fault runs from 125th Street and Broadway east, crossing the East River and running between Wards and Randall's Island through an area with large numbers of unreinforced masonry buildings.

v. Historic Occurrences

More than 400 earthquakes with a Richter magnitude greater than 2.0 are on record in New York State between 1700 and 1986, but many more have occurred. Stronger earthquakes are rarer. From 1973 to 2012 there were only two damaging earthquakes in the state with intensity of 5 or greater on the MMI Scale.

Many smaller earthquakes have been felt in New York City. For example, in 2001 an earthquake with a 2.4 magnitude occurred in the Upper East Side near the 125th Street fault. The earthquake only caused minor damage, but it was the first one on record in Manhattan.

Six earthquakes felt in New York City between 1737 and 2013 are described in the table below; all of them have magnitude values of 3.5 and higher on the Richter scale.

Date	Location	Richter Magnitude	Description
December 18, 1737	Citywide	5.2	Bells rang, several chimneys fell
September 2, 1847	Citywide (offshore)	3.5	No reference and/or no damage reported
August 10, 1884	Citywide	5.2	Chimneys and bricks fell, walls cracked
July 9, 1937	Brooklyn	3.5	No reference and/or no damage reported
April 20, 2002	Plattsburgh, NY	5.1	Vibrations felt in New York City
August 23, 2011	Virginia	3.5	Vibrations felt in New York City
May 17, 2013	Quebec	5.1	Vibrations felt in New York City

Table 3: Earthquakes that Affected New York City with a Magnitude of 3.5 or More between 1737 and 2013

B. Vulnerability Assessment

i. Social Environment

Unlike other natural hazards, earthquakes often occur with little or no warning, placing the population at risk. Since earthquakes have not occurred as frequently as other natural hazards, the risk to public safety may be higher since the general public may not be as prepared or know how to respond. A high-magnitude earthquake could cause significant casualties, financial losses, and disruptions in critical facilities and services.

In addition, earthquakes can disrupt emergency and medical services, putting individuals that depend on these services at even greater risk. Some of the long-term health risks that earthquakes pose include post-traumatic stress disorder and other mental health problems such as depression and anxiety.

Earthquakes can impact the economy. They can cause significant economic losses, including losses from repair and loss of rental income. They can displace and disrupt

business operations and utility operations, and they can impair people's ability to generate income due to disruptions brought on by the event.

ii. Built Environment

A building's construction is a key factor in determining how well it can withstand the forces produced by earthquakes. Unreinforced masonry buildings are most at risk because the walls are prone to collapse in an outward fashion. Steel and wood buildings have a greater ability to absorb the energy from an earthquake. Wood buildings with proper foundation ties rarely collapse in earthquakes.

Masonry buildings make up roughly 48% of the all buildings in New York City. The greatest number of masonry buildings are in Brooklyn (178,920), followed by Queens (115,062), the Bronx (54,434), Manhattan (28,762), and Staten Island (8,870). Therefore, it is likely that Brooklyn, Queens, and the Bronx would sustain the most building damage during an earthquake. This estimation is refined further in the HAZUS-MH analysis presented below.

The 1968 Building Code contains seismic provisions that, in effect, require designers to increase the load the building can withstand. Department of Buildings (DOB) has addressed structural vulnerability for earthquakes in the revised 2008 New York City Construction Codes. The Construction Codes not only make buildings stronger, but also more flexible. For example, the soil type and building foundation will be taken into account, and seismic detailing is required to ensure the joints and connections of a building hold up during an earthquake. Inspections are also required during construction to ensure seismic features are built correctly. Furthermore, as they are in the old code, critical facilities—such as firehouses and hospitals—will be designed under the revised code to not only survive an earthquake, but also remain open and functional afterwards. (For more information on the New York City Construction Code, see Risk Assessment Section 3: New York City's Hazard Environment.)

Upstate dams and aqueducts are also a concern and could incur serious damage from an earthquake, affecting the water supply to New York City. In addition, the Indian Point nuclear facility is located 24 miles north of the city and sits above two active seismic zones. These zones are capable of generating a magnitude 6 earthquake, which may increase the risk of harmful radiation exposure.

HAZUS-MH Earthquake Summary

HAZUS-MH was used to estimate losses and structural vulnerability for earthquakes in New York City. HAZUS-MH earthquake scenarios were completed using HAZUS-MH v2.1 (with ArcGIS 10.0). As with all HAZUS-MH modeling represented in this report, default buildings and essential facilities data were replaced with Level II local data. In addition, the local National Earthquake Hazards Reduction Program (NEHRP) soils data was loaded to further improve the accuracy of the results. No modifications were made to the existing HAZUS-MH damage functions relating to earthquake building damage.

For the hazard definition, a set of probabilistic scenarios were modeled to focus on damage to buildings. The probabilistic earthquake model in HAZUS-MH allows for the output of annualized dollar losses (the average annual loss expected based on the probability of occurrence of a wide range of potential earthquake events). In addition, a wider range of output is available for a suite of return periods. This method looks at expected damages based on the probability of occurrence in a given year (for example, a 100-year return period correlates to an event that has a 1% chance of occurring in any given year). Potential damages were calculated for return periods of 100, 250, 500, 1,000, and 2,500 years (see Table 4 and Table 5).

Return period (years)	Chance of occurrence in any given year (%)
100	1
200	0.5
250	0.4
500	0.2
1,000	0.1
2,500	0.04

Table 4: Return Periods for Probabilistic Modeling for Earthquakes

As is the case with every HAZUS-MH model, there are limitations to the data generated. The overall damage state categories for the HAZUS-MH earthquake module are None, Slight, Moderate, Extensive, and Complete. Included below is a graphic depiction of structural damage states (see Figure 8).

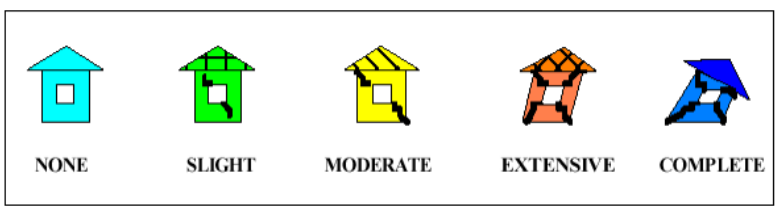


Figure 8: HAZUS-MH Earthquake Damage States (Source: HAZUS-MH Earthquake User Manual Figure 9.17)

Recurrence Interval	Construction Type	Total Buildings	Slight	Moderate	Extensive	Complete	Total Damaged	% of Buildings Damaged
100-year	Unreinforced Masonry	189,362	5	1	0	0	6	0.00%
	Other Construction	884,025	4	1	0	0	5	0.00%
	Total	1,073,387	**9**	**2**	**0**	**0**	**11**	**0.00%**
250-year	Unreinforced Masonry	189,362	3,140	1,101	129	24	4,394	2.32%
	Other Construction	884,025	2,664	446	37	4	3,151	0.36%
	Total	1,073,387	**5,804**	**1,547**	**166**	**28**	**7,545**	**0.70%**
500-year	Unreinforced Masonry	189,362	11,265	4,787	796	88	16,936	8.94%
	Other Construction	884,025	14,750	2,723	220	1	17,694	2.00%
	Total	1,073,387	**26,015**	**7,510**	**1,016**	**89**	**34,630**	**3.23%**
1,000-year	Unreinforced Masonry	189,362	21,284	11,106	2,476	360	35,226	18.60%
	Other Construction	884,025	45,333	10,892	1,148	30	57,403	6.49%
	Total	1,073,387	**66,617**	**21,998**	**3,624**	**390**	**92,629**	**8.63%**
2,500-year	Unreinforced Masonry	189,362	35,559	25,856	8,526	2,058	71,999	38.02%
	Other Construction	884,025	123,753	43,713	7,389	512	175,367	19.84%
	Total	1,073,387	**159,312**	**69,569**	**15,915**	**2,570**	**247,366**	**23.05%**

Table 5: Earthquake Damage by Return Period

Definitions of structural damage states for a single building class (in this case, Type W1-wood, light frame) are included here for reference:

Slight: Small plaster or gypsum board cracks at corners of door and window openings and wall-ceiling intersections; small cracks in masonry chimneys and masonry veneer.

Moderate: Large plaster or gypsum board cracks at corners of door and window openings; [[small diagonal cracks across shear wall panels (stucco and gypsum)]]; large cracks in brick chimneys; toppling of tall masonry chimneys.

Extensive: Large diagonal cracks across shear wall panels or large cracks at plywood joints; permanent lateral movement of floors and roof; toppling of most brick chimneys; cracks in foundations; splitting of wood sill plates and/or slippage of structure over foundations; partial collapse of room-over-garage or other soft-story configurations; small foundations cracks.

Complete: Structure may have large permanent lateral displacement, may collapse, or be in imminent danger of collapse due to cripple wall failure or the failure of the lateral load resisting system; some structures may have slipped and fallen off foundations; large foundation cracks.

Table 6 and Table 7 describe the potential impact of a variety of earthquake scenarios if the epicenter were located at the historic August 10, 1884 location in New York City. This model was taken from the NYCEM study published in 2003.

Richter Scale	Building Damage (billion)	Income Loss (billion)	Total (billion)	Hospitalization (people)	Shelter Required (people)	Fires	Buildings Completely Damaged	Debris (million tons)
5	$4.4	$0.4	**$4.8**	24	2800	500	45	1.6
6	$28.5	$10.8	**$39.3**	2,296	197,705	900	2,600	31.9
7	$139.8	$57.1	**$196.8**	13,171	766,746	1,200	12,800	132.1

Table 6: Summary of Deterministic Results of NYCEM Study (Source: NYCEM, 2003)

Return Period	Building Damage (billion)	Income Loss (billion)	Total (billion)	Hospitalization (people)	Shelter Required (people)	Fires	Debris (million tons)
100-year	$0.1	$0.1	**$0.2**	0	0	0	0.2
500-year	$6.1	$2.0	**$8.1**	28	575	50	3.1
2,500-year	$64.3	$20.4	**$84.8**	1,430	84,626	900	34.0
Annualized Losses	$0.1	$0.1	**$0.2**	N/A	N/A	N/A	N/A

Table 7: Summary of Probabilistic Results of NYCEM Study (Source: NYCEM, 2003)

iii. Natural Environment

Earthquakes can severely damage the natural environment, including loss of aesthetic value, due to destruction of trees and parks. They can also have secondary impacts—including fires caused by gas pipe explosions, broken water pipes, hazardous waste releases, or landslides—that could harm the natural environment.

iv. Future Environment

Earthquakes can compromise infrastructure, and New York City's aging infrastructure may amplify the structural impacts of earthquakes in the future.

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