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EARTHQUAKE LOSS ESTIMATION FOR THE NEW YORK CITY AREA

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SUMMARY

A preliminary forecast of the type of losses that the New York City area could suffer after an earthquake is the subject of this paper. This research is funded by the Federal Emergency Management Agency (FEMA) and is coordinated by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). The initial stages of this study involved fact-finding and assessment, with the development of preliminary soil maps and building inventories. The primary objective of this study was to develop an initial risk characterization for Manhattan below 59th Street. Smaller regions within Manhattan and larger tri-State regions are also studied. The vehicle for performing these loss estimations has been a software tool entitled *Hazards US* (or *HAZUS*). The Federal Emergency Management Agency, through the National Institute of Building Sciences (NIBS) and RMS, Inc., developed the standardized earthquake loss estimation methodology and computer modelling program *HAZUS*, which can be used to quantify regional seismic risks and to form the basis for a more coordinated national loss program. The aim of this ongoing loss estimation project is to provide a framework for businesses and agencies to take mitigative action to reduce potential damage and losses which might be experienced in future earthquakes.

INTRODUCTION

The past several decades have witnessed a series of costly and damaging earthquakes. Although earthquake losses in the United States have been predominantly in California, several significant earthquakes have occurred and many more are projected in the areas that have been less active during the last century.

New York City's seismic risk exposure is of increasing concern. The New York City metropolitan area has been classified by the United States Geologic Survey (USGS) to belong to the moderate level for potential earthquakes. In order to be prepared for such natural disasters, it becomes essential to be able to estimate and predict the risk and losses associated with these potential seismic events. Risk is typically defined by three components: a hazard (the earthquake), the assets involved and the fragility of those assets. For New York City, the probability of a large earthquake is moderate, however it becomes an area of high risk because of its tremendous assets (nearly $1 trillion) and the fragility of its structures, which before 1996 have not been seismically designed as most are on the West Coast.

The present paper documents the findings of a preliminary study which focused on seismic risks in the New York City area. The vehicle for performing these loss estimations has been a software tool entitled *Hazards US* or *HAZUS* [NIBS, 1997]. The Federal Emergency Management Agency, through the National Institute of Building Science (NIBS) and RMS, Inc., developed a standardized earthquake loss estimation methodology and the corresponding computer modelling program *HAZUS*. It can be used to quantify regional seismic risks and form the basis for a more coordinated national loss program. *HAZUS* uses geographic information systems to model the local soil conditions and the built environment against the backdrop of possible natural disasters. The *HAZUS* methodology involves three basic components: classification of different systems for inventory (in this study, building types and soil information), methods for evaluating the damage and calculating losses, and databases of information on demographics, building information and the regional economy [NIBS, 1997]. An

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earthquake loss estimate can be performed using *HAZUS* for any location in the nation using only the methodology and default databases, however, more accurate loss estimates can be generated by collecting and incorporating additional (modified) information. The first step to perform a loss estimate in *HAZUS* is to select an area to be studied, which might be defined by political boundaries (for example, a census tract or county or city). Then a magnitude and epicenter location of a scenario earthquake are selected. This can be based on available knowledge of historic seismicity. Information on local soil conditions can be incorporated to facilitate the mapping of estimated shaking intensities and the probability of permanent ground deformation. Using building capacity and fragility curves, *HAZUS* estimates damages and loss from the given scenario earthquake. Given appropriately modified input information (e.g., the building stock and soil information), more accurate estimates of loss may be determined.

Seismic hazard in the northeast United States is a subject involving considerable uncertainty [Bernreutter *et al.*, 1984]. Earthquakes are not unknown in the New York City metropolitan area and events of up to a Modified Mercalli Intensity VII (MMI VII) have been observed in historical times (e.g., the December 18th, 1737 event, which reportedly caused chimneys to fall in New York City [Coffman and Hake, 1982]). Major events in the New York City area include the December 18th, 1737 (Mw=5) and the August 10th, 1884 (Mw=5.2) earthquakes. The 1884 earthquake is the largest and probably best documented event for the New York City area. The earthquake was a strong shock, centered off Rockaway Beach about 17 miles southeast of New York's City Hall, and felt over 70,000 square miles, from Vermont to Maryland. In New York City, the effects were moderate and varied, frightening many and causing only some non-structural damage, but no fatalities. Newspaper reports indicated falling chimneys and parapets, some broken windows and general alarm in all five city boroughs (especially Brooklyn, although at that time it was not yet a borough); in Manhattan, crockery and bottles rattled but generally did not fall [The New York Times and The Herald Tribune, 1884].

The objectives of this study included performing *HAZUS* scenario runs in the New York City Area using default and modified (more accurate) soil and building information. NEHRP site categories [FEMA, 1998] were determined for all Manhattan census tracts south of 59th Street based on translating geotechnical boring data, including standard penetration tests (blow counts), into shear wave velocity profiles. *HAZUS* scenario runs were performed to examine the sensitivity of loss estimation to different soil conditions and different building inventories. Comparisons were made between default and modified scenarios. The project is currently acquiring additional boring data to improve the microzonation of soil conditions; it is also acquiring building information from local units of government and conducting a visual survey of selected census tracts within Manhattan to enhance that information. Ultimately, results from this ongoing loss estimation project will provide a framework for businesses and agencies to take cost-effective mitigative action to reduce potential damage and losses from future earthquakes.

STUDY REGIONS AND SCENARIO EARTHQUAKES

A *HAZUS* model requires a defined study area (composed of census tracts) and a scenario earthquake (defined at least by a magnitude and an epicenter location) [NIBS, 1997]. The basic geographic unit of analysis is a census tract, which is a homogenous unit of land containing approximately 2500 to 8500 families and typically only a few street blocks in size. The four separate study regions that were modelled (see Figure 2) within and around the New York City area include: a single census tract around Wall Street, a single census tract around Kips Bay, a collection of 132 census tracts in Manhattan below 59th Street and a collection of about 5,200 census tracts in the surrounding 31 county, tri-State region of New York, New Jersey and Connecticut. While the Wall Street census tract is representative of a commercial area, the Kips Bay census tract is representative of a residential area. The Manhattan study region below 59th Street provides a model of a medium-scale impact assessment on a series of census tracts (see Figure 2), whereas the tri-State study provides a large-scale impact assessment showing how a natural disaster can affect a large region.

For each study area, different inventory information was modelled and compared. For the Wall Street and Kips Bay census tract studies, four runs were considered: using default building and default soil inventories, using modified building and default soil inventories, using default building and modified soil inventories and using modified building and modified soil inventories. Modified building information was determined using visual inspection of the study regions, engineering judgement and the New York City Sanborn maps [Sanborn, 1998].

For each study area with a specific inventory case, six different earthquake scenarios were modelled and examined. Three scenario earthquakes, magnitudes 5, 6 and 7, were modelled at the fixed location of the 1884 historic earthquake. These scenarios were modelled to have an epicenter depth of 10 kilometers with a location about 20 kilometers from the center of the study region in southern Manhattan (Latitude 40.56°N, Longitude 74.00°W). An additional three scenario earthquakes, also magnitudes 5, 6 and 7, were modelled at locations that attempt to represent a constant probability for Manhattan at the exposure level of 2% in 50 years.

GEOLOGY AND SEISMICITY

One necessity for developing realistic earthquake loss estimation is an accurate soil profile of the region of study. For this research, geotechnical data consisting of standard penetration test (SPT) blow counts and standard soil descriptions from construction-related soil borings in New York City were used to assess the effect of near-surface geology on seismic ground-motion site-response (microzonation). In addition, information on depth to bedrock from older borings which do not contain information on the type of penetrated soils are also used for microzoning the shaking effects [Jacob, 1999]. The general objectives of seismic microzonation are generally to quantify urban seismic hazard and the risk (loss potential) by accounting for the local variations in shaking levels due to near-surface geological differences. These differences can influence the amplitudes and the spectral content of ground motions and, thereby influence the shaking levels of buildings and lifelines, and hence control the expected losses. The specific goals for this study are narrower than what is generally attempted during microzonation. This study is limited to determining the site classes A through E as defined in the 1997-Edition of the NEHRP Provisions for Seismic Regulations for Buildings [FEMA, 1997]. Knowledge of these site classes is required as input into the *HAZUS* earthquake loss estimation algorithm. Spatial resolution for *HAZUS* requires that a single site category be assigned to each census tract.

The analog information of a total of 150 geotechnical borings in lower Manhattan (below 59th Street) was entered into digital spreadsheets. Data included casing and SPT blow counts and standardized descriptions of the stratigraphic materials encountered as a function of depth. A locally derived relation (Equation 1 and Figure 1) was used to translate the measured SPT blow counts into shear wave velocity versus depth profiles [Jacob, 1999].

$$V_s\,({}^{ft}\!/\!_{s}) = (220 + 3 \cdot N) \cdot D^{0.3} \qquad [1]$$

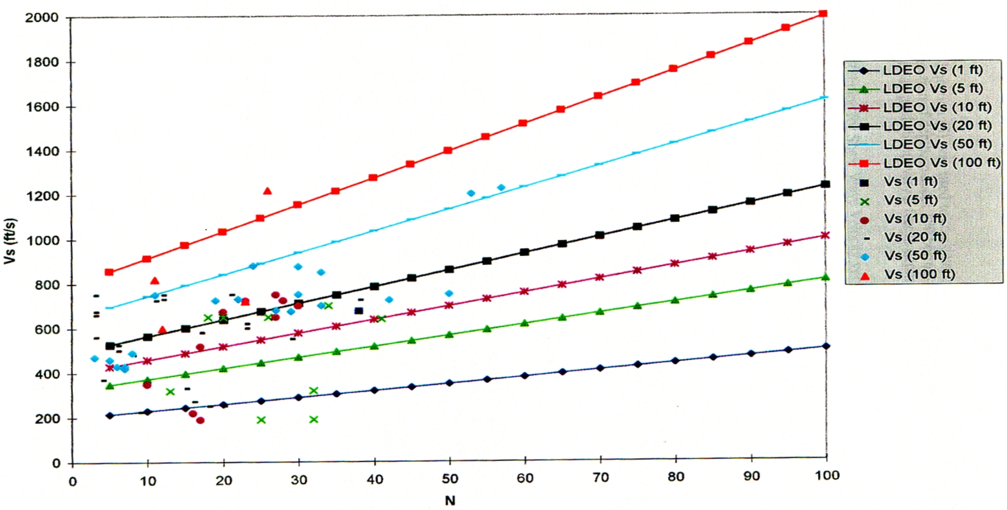


Figure 1 – Shear wave velocity (ft/s) versus Standard Penetration Test (SPT) blow counts N, with depth, D (feet) as a parameter. The plot compares calibration data for New York City soils (individual depth-coded points) to the generalized relation (solid lines) used in this study (See Equation 1) [Jacob, 1999]

Equation 1 is based on the few locally available calibration borings relating SPT counts, N to shear wave velocity, Vs and depth, D (feet). The shear wave velocity (Vs) depth profiles were then used to determine the NEHRP site classes for each boring site. At more than 200 older boring sites, where only depth to bedrock but no soil properties are known, analysis was proceeded differently. First an average relation of shear wave velocity versus depth for lower Manhattan was derived from a subset of borings using the N to Vs conversion described in Equation 1 [Jacob, 1999]. Only about 50 of the 150 available geotechnical soil borings (i.e. those which reach bedrock) were used for this purpose. For these borings, the nominal average relation for shear velocity versus depth for soils in southern Manhattan was determined (Equation 2), whereby any figures after the decimal period are insignificant.

$$V_s\ (\text{ft}/\text{s}) = 435.11 + 11.08 \cdot D\ (\text{ft}) \quad [2]$$

In fact, the scatter is very large (about a factor of 2 up and down from the mean) since this average relation does not attempt to differentiate between the different soil materials and densities encountered. Then, at the more than 200 bedrock boring sites without soil information, the average relation (Equation 2) was used as nominal velocity input for the soil profiles down to bedrock or 100 feet (which ever depth is less). For sites with soil profiles less than 100 feet thick, an average Vs for rock of 5,000 feet per second was used for the remaining depth interval in rock down to 100 feet below grade [Jacob, 1999].

Since in Manhattan south of 59th Street (as opposed to "upper" Manhattan) bedrock is rarely near the surface, the majority of sites were determined to be class D or C sites (Figure 2) in NEHRP site classification terminology (dense and stiff soil and soft rock). This reflects the fact that most sediments in lower Manhattan are quite deep and are soft because they are predominantly of post-glacial Holocene and Recent estuarine origin (organic clays, salts and fine sands). Often they directly overlie very hard meta-sedimentary to crystalline rocks, with medium-hard sediments rarely present [Jacob, 1999]. No sites belonged to the stiffest site class A (very hard rock), but a fair number to B (firm rock), and several to class E with very deep soft soils.

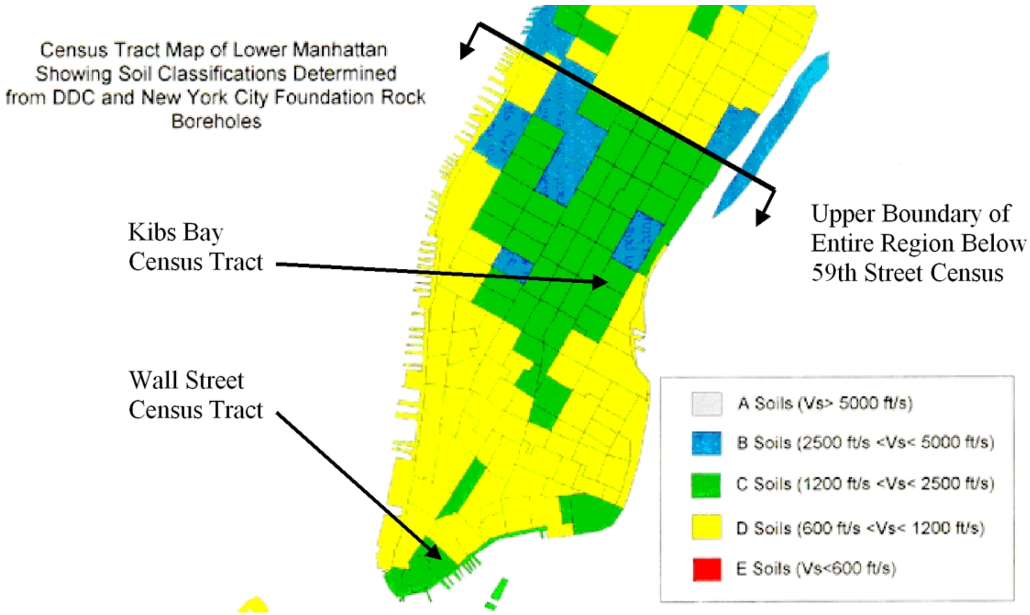
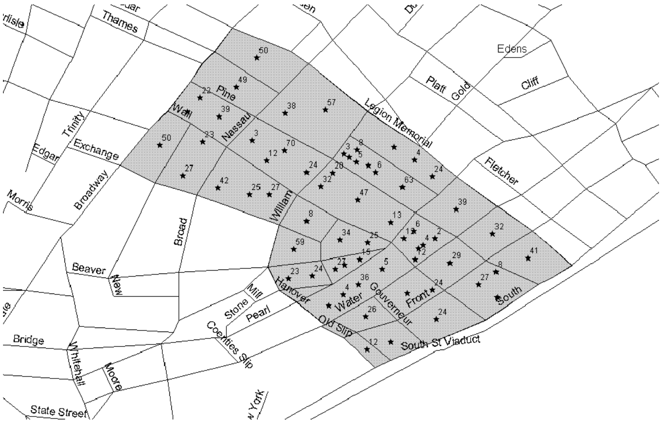


Figure 2 – NEHRP Soil Classifications by Census Tract of Lower Manhattan [Jacob, 1999]

STUDY REGIONS OF LOWER MANHATTAN

The first area of study is a single census tract containing Wall Street (see Figures 2 and 3) with a land area of 0.06 square miles and a population of 154 inhabitants. The Wall Street census tract is representative of a predominately commercial area. Figure 3 shows the Wall Street census tract (shaded) with each building marked by a star and labelled with the number of stories for each building. This demonstrates a unique characteristic of New York City, where certain areas have a considerable percentage of tall buildings.



	HAZUS DEFAULT	WALL STREET
Age		
Pre 1950	0%	0%
1950-1970	0%	50%
Post 1970	100%	50%
Quality		
Code	25%	75%
Inferior	75%	25%
Superior	0%	0%
Seismic Design Level		
Low	0%	75%
Moderate	0%	25%
High	100%	0%
Building Height		
Up to 3 Stories	100%	5%
4-7 Stories	0%	14%
Above 8 Stories	0%	81%

Figures 3 and 4 – Wall Street Census Tract (shaded) with Building Location and Number of Stories for each Building and Wall Street Census Tract: Building Assumptions, [Nordenson *et al.*, 1999].

HAZUS uses building square footage to calculate economic losses for buildings from a scenario earthquake. For the Wall Street census tract, a comparison of building area by general occupancy type shows significant differences in the building area of the *HAZUS* default inventory with the actual. The *HAZUS* default inventory assumes 20 million square feet of building area for 710 buildings. The Wall Street census tract actually contains about double the square footage (40 million square feet) for only 63 buildings [Sanborn, 1998]. The default *HAZUS* inventory characterizes Wall Street as a census tract with a large number of low-story buildings, when it actually contains a small number of very tall buildings [Nordenson *et al.*, 1999]. Figure 4 displays the HAZUS default assumptions for these four categories and the corresponding building assumptions made by the authors.

In addition to building square footage, *HAZUS* makes some other building assumptions to estimate economic loss from earthquakes (Figure 6). This includes assumptions on the percent distribution of buildings in each census tract by age, quality, seismic design level and building height [NIBS, 1997]. The fourth building assumption that *HAZUS* uses to estimate losses is the percent distribution of buildings by height. Taller buildings have in general relatively longer natural periods, which means that they will have a relatively lower response when compared to shorter buildings. This can be inferred from the response spectrum plotted in Figure 5 (it should be pointed out that this statement is strictly qualitative). Eventually, a lower response will lead to less damage and loss. As a result, the height of a building becomes a very important factor in determining potential damage and losses. By refining the building inventory with the correct building height distribution, it is possible to get a more accurate estimate of loss [Nordenson *et al.*, 1999]. For the Wall Street census tract, the default *HAZUS* estimate is that 100% of the buildings are under 4 stories. However, the actual count of buildings indicates that only 5% of the buildings are under 4 stories. Approximately 14% of buildings are between 4 and 7 stories and 81% are above 7 stories [Sanborn, 1998]. Comparing the distribution of building heights, it becomes obvious that using the actual distribution of building heights is extremely important to estimate reliably the overall structural damage (rather than using the default distribution provided by *HAZUS*) [Nordenson *et al.*, 1999].

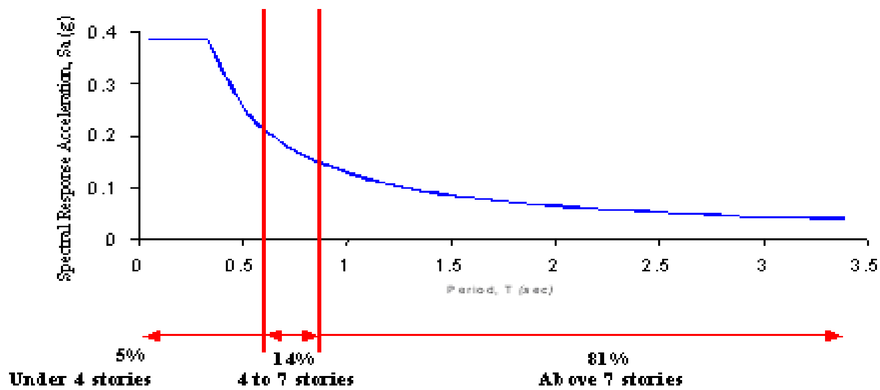


Figure 5 — Wall Street Census Tract: Actual distribution of building heights plotted versus a typical response spectrum (buildings represented by their fundamental natural periods) [Nordenson *et al.*, 1999]

Figure 6 shows the structural and total economic losses for the Wall Street census tract for the various cases considered. The economic losses are shown for different inventory information (default and modified soil and building information) and for different scenario earthquakes (magnitude 5, 6 and 7 earthquakes at a fixed location and at a constant probability) [Nordenson *et al.*, 1999].

Cost Structural Damage
(in thousands of dollars)

Earthquake with Fixed Location	5.0M	6.0M	7.0M
Default Soil and Default Bldg	3,369	41,249	187,388
Modified Soil and Default Bldg	1,701	26,079	151,426
Default Soil and Modified Bldg	772	82,287	283,809
Modified Soil and Modified Bldg	218	46,296	228,635

Earthquake with Constant Probability	5.0M	6.0M	7.0M
Default Soil and Default Bldg	3,369	4,488	21,104
Modified Soil and Default Bldg	1,701	2,476	9,779
Default Soil and Modified Bldg	772	4,188	43,167
Modified Soil and Modified Bldg	218	1,430	19,834

Cost Total Loss
(in thousands of dollars)

Earthquake with Fixed Location	5.0M	6.0M	7.0M
Default Soil and Default Bldg	59,322	412,136	1,713,500
Modified Soil and Default Bldg	24,530	260,632	1,403,898
Default Soil and Modified Bldg	13,735	445,526	1,651,316
Modified Soil and Modified Bldg	4,068	272,707	1,307,527

Earthquake with Constant Probability	5.0M	6.0M	7.0M
Default Soil and Default Bldg	59,322	32,969	151,485
Modified Soil and Default Bldg	24,530	15,605	62,739
Default Soil and Modified Bldg	13,735	18,431	203,018
Modified Soil and Modified Bldg	4,068	6,236	79,541

Total Loss Per Square Foot
(in dollars)

Earthquake with Fixed Location	5.0M	6.0M	7.0M
Modified Soil and Modified Bldg	0.10	6.89	33.02

Earthquake with Constant Probability	5.0M	6.0M	7.0M
Modified Soil and Modified Bldg	0.10	0.16	2.01

Figure 6—Wall Street Census Tract: Damages for Different Scenario Earthquakes and Building Inventory and Soil Information, [Nordenson *et al.*, 1999].

For a 5.0 magnitude earthquake at the 1884 historic epicenter, the Wall Street census tract has an estimated $59.3 million total loss using the *HAZUS* default inventories. As the default building inventory and soil information are modified to represent the actual site conditions, the estimated total loss becomes $4 million. Refining the *HAZUS* default information changes the loss estimate by a factor of about 15 for a 5.0 magnitude earthquake. As the magnitude of the earthquake increases from 5.0 to 7.0, the general trend is the same, however the loss ratio of completely default information to completely modified information decreases from 15 to about 1 or 2 (depending on whether it is a fixed location or constant probability earthquake). Therefore, to get an accurate estimate of loss, especially for smaller earthquakes, it is extremely important to have accurate building and soil information. Similar studies were conducted for other census tracts in Manhattan (like the purely residential Kips Bay area labelled in Figure 2) and similar results were observed [Nordenson *et al.*, 1999].

Another area of study is the entire Manhattan region below 59th Street (see Figure 2), which includes 132 census tracts, with a land area of 10.71 square miles and a population of 550,000 inhabitants. The Manhattan region below 59th Street includes both residential and commercial census tracts with 44,762 buildings, containing approximately 914 million square feet of floor area. The default *HAZUS* soil type for all of the Manhattan census tracts below 59th Street is Class D, indicating that it is a moderately stiff soil. As shown in Figure 2, the actual soil class varies throughout Manhattan below 59th Street. By refining the soil information, a more accurate estimate of losses is expected.

In Figure 7, the economic losses are shown for different inventory information (default and modified soil information) and for different scenario earthquakes (magnitude 5, 6 and 7 earthquakes at fixed location and constant probability). For the Manhattan region below 59th Street, only default building inventory information was used [Nordenson *et al.*, 1999].

Cost Structural Damage
(in thousands of dollars)

Earthquake with Fixed Location	5.0M	6.0M	7.0M
Default Soil and Default Bldg	86,399	1,140,683	5,386,804
Modified Soil and Default Bldg	69,630	539,581	4,299,301

Earthquake with Constant Probability	5.0M	6.0M	7.0M
Default Soil and Default Bldg	86,399	145,883	648,811
Modified Soil and Default Bldg	69,630	95,513	385,950

Cost Total Loss
(in thousands of dollars)

Earthquake with Fixed Location	5.0M	6.0M	7.0M
Default Soil and Default Bldg	1,339,320	11,460,330	44,882,943
Modified Soil and Default Bldg	952,801	5,488,060	37,168,731

Earthquake with Constant Probability	5.0M	6.0M	7.0M
Default Soil and Default Bldg	1,339,320	1,188,883	4,870,706
Modified Soil and Default Bldg	952,801	712,884	2,803,283

Figure 7 — Manhattan below 59th Street: Damages for Different Scenario Earthquakes and Soil Information, [Nordenson *et al.*, 1999].

For a 5.0 magnitude earthquake at the 1884 historic epicenter, the Manhattan region below 59th Street has an estimated $1.34 billion total loss. As the default soil information is modified to represent the actual site conditions, the estimated total loss reduces to $952 million. Refining the *HAZUS* default information for soil reduces the loss estimate by a factor of about 1.4 for a 5.0 magnitude earthquake. As the magnitude of the earthquake increases from 5.0 to 7.0, the general trend is the same, however the loss ratio of default soil information to modified information decreases from 1.4 to about 1.2 [Nordenson *et al.*, 1999]. To get an accurate estimate of loss, especially for smaller earthquakes, it is very important to have accurate soil information. As determined in the Wall Street and Kips Bay studies, it is extremely important to have accurate building and soil information. This Manhattan study below 59th Street, however, only used modified soil information. Figure 8 shows the total damage by census tract in lower Manhattan for a constant probability 7.0 magnitude earthquake.

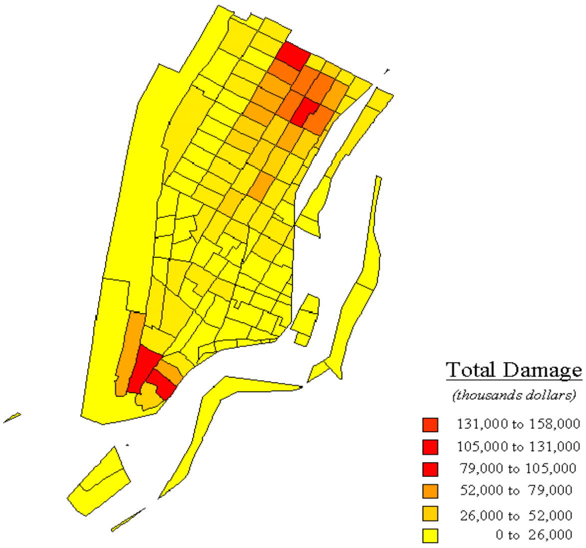


Figure 8 —Total Damage by Census Tract in Lower Manhattan for a Constant Probability 7.0 Magnitude Earthquake at the Historic 1884 Location, [Nordenson *et al.*, 1999].

The total economic loss to the 132 Manhattan census tracts below 59th Street increases as the magnitude of the earthquake increases. The general trend shows that the loss difference between the default and modified site information decreases as the magnitude of the earthquake increases.

A TRI-STATE STUDY REGION (NY, NJ AND CT)

The final area of study is a 31 county, tri-State region of New York, New Jersey and Connecticut, which includes 5,238 census tracts, with a land area of 12,990 square miles and a population of 20 million inhabitants and a building inventory valued near $1 trillion. The tri-State region contains both residential and commercial census tracts with 4 million buildings, containing approximately 16 billion square feet of floor area. The default *HAZUS* soil type for all of the tri-State region census tracks is Class D, indicating that it is a moderately stiff soil. Only the default soil and building information was used for this scenario.

For magnitude 5, 6 and 7 earthquakes at the constant probability locations (used for the individual census tracts earlier), the tri-State region has estimated total losses of $7.6 billion, $13.72 billion and $42.4 billion respectively. As the magnitude of the earthquake increases from 5.0 to 7.0, the obvious trend is that the total damages increase [Nordenson *et al.*, 1999].

FUTURE WORK AND CONCLUSIONS

The preliminary results of this research indicate that to produce a realistic loss estimation, it is of paramount importance to establish better estimates for soil conditions and building inventory for the entire New York City area. This is apparent because of the dramatic differences in total loss estimates between runs done with default values and runs done with improved estimates of soil conditions and building inventories. Although differences are more dramatic for smaller magnitude events, the effect of switching to better estimates of building inventory can be as important as the effect of switching to better estimates of soil conditions.

Future work for this research is recommended to develop a more accurate loss estimate. Suggested future work includes providing better data for building age, type, quality, height, square footage, and seismic design level and performing sensitivity analyses to determine their relative importance. A higher density of soil information is attempted to avoid the need for interpolation over large distances. It is recommended that the soil and building inventory information for the entire New York City area be updated. Another task for future work includes developing more accurate fragility curves (used to estimate probabilistic damage states) for the type of buildings unique to the New York City area, because parts of New York City have the unique characteristic of a considerable percentage of tall buildings. Ultimately, the aim of this loss estimation research is to provide a framework for businesses and agencies to take mitigative action to reduce potential damage and losses which might be experienced after an earthquake.

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