Potential Losses in a Repeat of the 1886 Charleston, South Carolina, Earthquake

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A comprehensive earthquake loss assessment for the state of South Carolina using HAZUS was performed considering four different earthquake scenarios: a moment magnitude (**M**) 7.3 “1886 Charleston-like” earthquake, **M** 6.3 and **M** 5.3 events also from the Charleston seismic source, and an **M** 5.0 earthquake in Columbia. Primary objectives of this study were (1) to generate credible earthquake losses to provide a baseline for coordination, capability development, training, and strategic planning for the South Carolina Emergency Management Division, and (2) to raise public awareness of the significant earthquake risk in the state. Ground shaking, liquefaction, and earthquake-induced landsliding hazards were characterized using region-specific inputs on seismic source, path, and site effects, and ground motion numerical modeling. Default inventory data on buildings and facilities in HAZUS were either substantially enhanced or replaced. Losses were estimated using a high resolution 2-km × 2-km grid rather than the census tract approach used in HAZUS. The results of the loss assessment indicate that a future repeat of the 1886 earthquake would be catastrophic, resulting in possibly 900 deaths, more than 44,000 injuries, and a total economic loss of $20 billion in South Carolina alone. Schools, hospitals, fire stations, ordinary buildings, and bridges will suffer significant damage due to the general lack of seismic design in the state. Lesser damage and losses will be sustained in the other earthquake scenarios although even the smallest event could result in significant losses. [DOI: 10.1193/1.2083907]

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Figure 1. Damage on East Bay Street, Charleston, in 1886. Source: Stover and Coffman 1993.

INTRODUCTION

At 9:50 p.m. on 31 August 1886, one of the largest known earthquakes (approximate magnitude 7) to have occurred in eastern North America struck Charleston, South Carolina. It damaged or destroyed the large majority of buildings in Charleston (Figure 1) and killed 60 people (Bollinger 1977). Structural damage was widespread, extending as far as Alabama, Ohio, and West Virginia. The event was felt throughout the eastern United States and in such distant locations as Boston, Chicago, Milwaukee, Cuba, and Bermuda (Figure 2). Liquefaction was extensive in the epicentral area. Sand craterlets as large as 6.4 m in diameter were observed. In addition, lateral spreading was observed along the Ashley River. The maximum Modified Mercalli (MM) intensity was X (Bollinger 1977) (Figure 2). Summerville, which is now a rapidly growing urban area, was subjected to strong ground shaking that resulted in many houses either being displaced off their foundations, settled differentially, or having their chimneys destroyed. To this day, the source of the 1886 earthquake remains controversial (e.g., Bollinger et al. 1991). Due to a lack of surficial expression of the earthquake rupture, the identity of the causative fault has been debated among earth scientists for more than a century. Also, because the earthquake occurred prior to the advent of seismographic instrumentation, a precise measure of its magnitude has also been lacking. A wide range of values has emerged over time, from body-wave magnitude (m_b) 6.7 to surface-wave magnitude (M_S) 7.7 (Bollinger et al. 1991). The currently accepted magnitude of the 1886 earthquake is moment magnitude (**M**) 7.3±0.3 (Frankel et al. 2002), although a recent analysis suggests it may have been smaller at **M** 6.9±0.3 (Bakun and Hopper 2004).

Obviously a repeat of the 1886 earthquake or even a smaller, moderate-sized event could be catastrophic to South Carolina, particularly to the city of Charleston and the

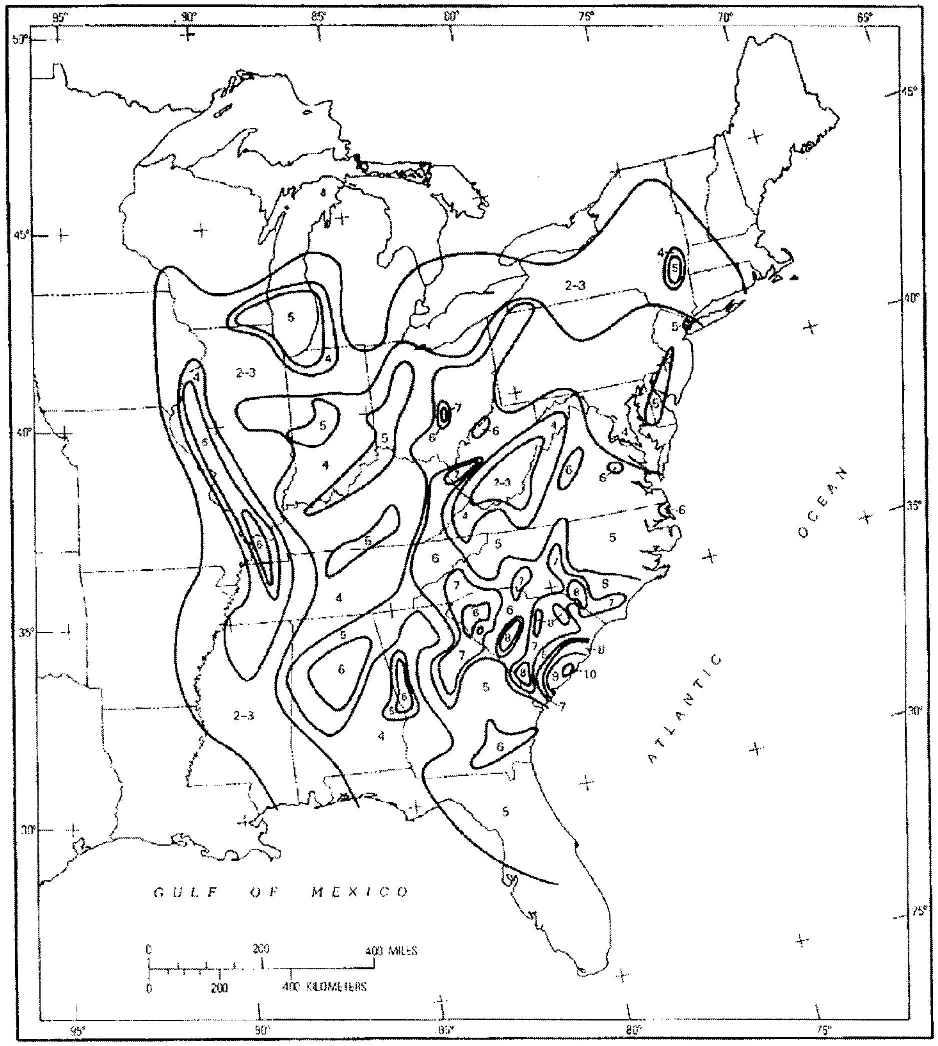

Figure 2. Isoseismal map of the 1886 Charleston earthquake. Arabic numerals refer to MM intensities. The initiation of minor damage corresponds to MM V. Source: Bollinger 1977.

surrounding areas. Based on the 2002 U.S. Geological Survey's National Hazard Maps (Frankel et al. 2002), the Charleston area is second only to the New Madrid zone in terms of hazard in the central and eastern United States.

In this paper, we present the results from a comprehensive, high-resolution earthquake loss assessment of South Carolina. The study was performed by a multi-organizational, multidisciplinary project team through funding support from the South Carolina Emergency Management Division (SCEMD), with partial funding from the Federal Emergency Management Agency (FEMA). The purpose of the study was to evaluate the potential losses from four earthquake scenarios using FEMA's loss estimation software HAZUS 99 (NIBS 1999). These results have provided a basis for the state to effectively plan and prepare for future damaging earthquakes, and also a means to raise public awareness of the state's earthquake risk. The state also hoped that this study will serve as a model on how to perform future comprehensive HAZUS studies. The four earthquake scenarios considered were an **M** 7.3 "1886 Charleston-like" earthquake, **M** 6.3 and **M** 5.3 events also from the Charleston seismic source, and an **M** 5.0 earthquake in Columbia. A specific objective of the study was to estimate as accurately as possible the potential earthquake losses by (1) characterizing the earthquake hazard input using state-of-the-art techniques and incorporating South Carolina-specific geologic, geotechnical, and seismological data, and (2) improving the inventory data either by replacing or modifying the default databases in HAZUS. Loss calculations were performed using 2-km $\times$ 2-km grid cells rather than the census tracts used in HAZUS. For South Carolina, there were 21,138 (2 km $\times$ 2 km) grid cells as opposed to 854 census tracts. These efforts resulted in one of the most comprehensive high-resolution loss estimations ever performed in the United States. In HAZUS terminology, this was a Level 3 HAZUS analysis (see following discussion).

The evaluation was carried out in seven tasks:

1. calculation of scenario earthquake ground motions
2. evaluation of liquefaction and earthquake-induced landslide potential
3. compilation and evaluation of building inventory
4. compilation and evaluation of lifeline and essential facility data
5. compilation and evaluation of hazardous materials (HAZMAT) data
6. evaluation of a dam database
7. HAZUS risk assessment

Papers describing in detail the major tasks were published in the *Proceedings of the 7th U.S. National Conference on Earthquake Engineering* (Bouabid et al. 2002, Silva et al. 2002, Graf et al. 2002, Siegel et al. 2002, Huyck et al. 2002, Bureau and Ballentine 2002). Additional analyses not described in those papers are described herein.

HAZUS

HAZUS is a tool that local, state, and federal government officials and others can use for earthquake-hazard mitigation, emergency preparedness, response and recovery planning, and disaster response operations (NIBS 1999). It incorporates approaches for (1) characterizing earthquake hazards including ground shaking, liquefaction, and landslides; (2) estimating damage and losses to buildings and lifelines; (3) estimating fires following an earthquake; (4) estimating casualties, displaced households, and shelter requirements; and (5) estimating direct and indirect economic losses. The output from this HAZUS evaluation can be used in a variety of ways:

- To assess the vulnerability of South Carolina's built environment to earthquakes of various magnitudes;

- To provide emergency managers at all levels with detailed estimates of damage and losses, information that can be used to identify resource requirements for effective, intergovernmental response and recovery operations;
- To specifically enable emergency managers to scale the mission requirements for "Emergency Support Functions." For example, the study provides the U.S. Army Corps of Engineers with estimates of the volume of debris that can be expected for different scenario earthquakes, information that can be factored into resource requirements for the agency's debris removal and disposal mission;
- To develop a statewide public awareness and education campaign that describes in detail the consequences of different scenario earthquakes;
- To support the development and prioritization of mitigation strategies in a long-term effort to reduce the vulnerability of South Carolina to earthquakes; and
- To promote business-government coordination and collaboration in preparing for a major earthquake in South Carolina. For example, the HAZUS output on the functionality of lifelines, including electric power, water supply, and transportation (notably the functionality of bridges) can be valuable information in carrying out a business impact analysis.

Three levels of data analysis can be performed using HAZUS based on user needs and resources: (1) default, (2) user-supplied, and (3) advanced data and models. Level 1 is the simplest analysis, and very approximate losses can be estimated based on the standardized methodology for estimating ground shaking, broad regional patterns (e.g., building types), and national census and inventory databases contained in HAZUS. Some types of analyses such as losses due to liquefaction and landslides cannot be performed at Level 1.

A Level 2 analysis requires more extensive inventory data and effort by the user. A Level 3 analysis incorporates results from seismic hazard, engineering, and economic studies using methods not included within HAZUS, such as calculating more precise estimates of seismic hazard based on local and regional data. For example, having a local or regional geologic map to derive site response categories (e.g., NEHRP or more site-specific) and amplification factors is essential for accurately estimating ground shaking. As will be discussed later, the uncertainty associated with ground motion estimates is the most significant contributor to the uncertainty in loss estimation.

HAZUS calculates losses at the centroids of census tracts. The composition of general building stock is also lumped at the centroid. A weakness in HAZUS is that for large census tracts, the precision of the loss estimates is reduced.

The HAZUS technology is built upon an integrated GIS platform that produces regional profiles and estimates of earthquake losses. The methodology addresses the built environment and categories of losses in a comprehensive manner. HAZUS is composed of seven major modules, which are interdependent and are shown in Figure 3. This modular approach allows different levels of analysis to be performed, ranging from estimates based on simplified models and default inventory data to more refined studies based on detailed engineering and geotechnical data for a specific study region; in this

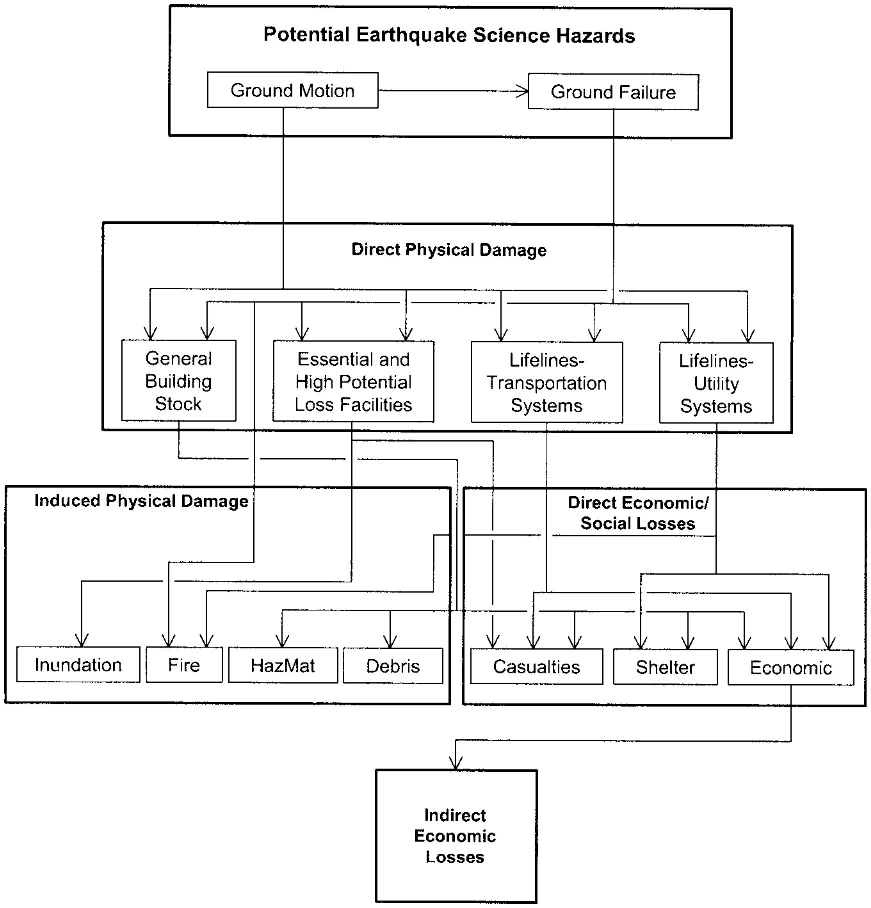

Figure 3. Flowchart of the HAZUS loss estimation methodology, modified after NIBS 1999.

case, the state of South Carolina. A brief description of each of the seven major modules is presented below. Detailed technical descriptions of the modules can be found in the HAZUS Technical Manual (NIBS 1999).

MODULE 1: POTENTIAL EARTH SCIENCE HAZARD (PESH)

The PESH module estimates ground motion and ground failure (landslides, liquefaction, and surface fault rupture) (Figure 3). HAZUS has the capability to estimate scenario ground motions in terms of spectral acceleration and peak horizontal ground acceleration based on the location, size, and type of earthquake. These ground motions are calculated using generic attenuation relationships for either the western or eastern United States. The ground shaking is estimated for either a uniform rock or soil site condition, and so unless specific geologic information is available, losses cannot be estimated for areas where both soil and rock site conditions exist. Probabilistic ground motions from the U.S. Geological Survey National Hazard Maps are also contained in HAZUS. User-provided ground motions are always desired because they can incorporate source, path, and site parameters that are region- and/or local-specific. For ground failure, permanent ground deformation and probability of occurrence need to be determined. User-provided input is required to estimate the ground failure hazard in HAZUS. In this study, the hazards were quantified specifically for the four scenarios and input into HAZUS.

MODULE 2: INVENTORY AND EXPOSURE DATA

Built into HAZUS is a national-level basic exposure database that allows a user to run a Level 1 analysis without having to collect any additional local data. The infrastructure within the study region must be inventoried in accordance with the standardized classification tables used by the methodology. There are four inventory groups: (1) general building stock, (2) essential (e.g., hospitals, police stations, fire stations, schools) and high potential loss facilities (e.g., dams, nuclear power plants), (3) transportation systems, and (4) lifeline utility systems (Figure 3). These groups are defined to address distinct inventory and modeling characteristics. In this study, inventory information related to the building infrastructure, essential facilities, transportation networks, and utility systems has been substantially enhanced.

The general building stock is classified by occupancy (residential, commercial, etc.) and by model building type (structural system, material, and height). The default mapping schemes are state-specific for single-family occupancy type and region-specific for all other occupancy types. The default exposure makes general assumptions regarding building age and type, appropriate for the region.

Default population data in HAZUS 99 is based on the 1990 U.S. census. In this project, however, the demographic information was updated using the 2000 census data. Estimates for building exposure were based on default values for building replacement costs (dollars per square foot) for each model building type and occupancy class, in addition to certain regional cost modifiers. The data were drawn from Dun and Bradstreet and RS Means and also updated to year 2000.

MODULE 3: DIRECT PHYSICAL DAMAGE

This module provides damage estimates for each of the four inventory groups based on the level of exposure and the vulnerability of structures (potential for damage at different ground shaking levels). The damage state probability in HAZUS is computed at the centroid of the census tract. For HAZUS, a technique using building capacity curves and building fragility curves based on the inelastic building capacity and site-specific response spectra was developed to describe the damage incurred in building components. Since damage to nonstructural and structural components occurs differently, the methodology estimates both damage types separately. Nonstructural building components are grouped into drift-sensitive and acceleration-sensitive components. Fragility curves for ground failure are also used to describe the probability of reaching different states of damage given permanent ground deformation.

For essential facilities, transportation and utility systems, and general building stock, damage state probabilities are determined for each facility or structural class. Damage is expressed in terms of probabilities of occurrence of specific damage states, given a level of ground motion and ground failure. Five damage states are identified: none, slight, moderate, extensive, and complete. The only exception is for pipelines, where damage is expressed in terms of breaks and leaks.

MODULE 4: INDUCED PHYSICAL DAMAGE

Induced damage is defined as the secondary consequence of an event. Fire following an earthquake and accumulation of debris are assessed in this module (Figure 3). Earthquake-induced flood inundation from tsunamis, seiches, or dam or levee failure, and hazardous materials sites for release potential are also assessed.

The fire following earthquake model encompasses ignition, spread, and suppression. The model provides estimates of number of ignitions, total burned area, population exposed to the fires, and building value consumed by the fire. The debris model estimates the amount of debris resulting from building damage for each census tract. The classes of debris are (1) brick, wood, and other, and (2) reinforced concrete and steel members. The model is empirically based and considers building type or general or specific occupancy class. For each source of flooding, the primary tool is an inundation map, which displays the area that will be impacted. The depth and velocity of flooding, the arrival time of the flood following the earthquake, and the probability of such an event occurring are also required to characterize the flood hazard.

MODULE 5: DIRECT SOCIAL LOSSES

HAZUS provides estimates of social losses in terms of casualties, displaced households, and short-term shelter needs (Figure 3). The output of the casualty module includes estimates for four levels of casualty severity (minor injury to dead) by time (2:00 a.m., 2:00 p.m., and 5:00 p.m.) for four population groups (residential, commercial, industrial, and commuting). The estimation of casualties is based on the correlation between building damage (both structural and nonstructural) and the number and severity of casualties. Collapses and partial collapses in large earthquakes will account for a proportionately large number of fatalities. Casualties, caused by secondary effects such as heart attacks or injuries while rescuing trapped victims, are not included.

Displaced households are estimated based on the number of structures that are uninhabitable, which in turn is evaluated by combining damage to the residential building stock with utility service outage relationships. The shelter model estimates the number of displaced households and the number of people requiring only short-term shelter.

MODULE 6: DIRECT ECONOMIC LOSSES

HAZUS provides estimates of economic losses including structural and nonstructural damage, costs of relocation, losses to business inventory, capital-related losses, income losses, rental losses, and cost of repair for lifelines. In general, input data consists of building damage estimates from the direct physical damage module. The damage estimates are in the form of probabilities of being in each damage state, for each structural type or occupancy class. To establish dollar loss estimates, the damage state probabilities must be converted to dollar loss equivalents.

Relocation costs may be incurred when the level of building damage is such that the buildings or portions of the building are unusable while repairs are being made. The relocation costs include disruption costs and rental of temporary space. Business inventories vary considerably with occupancy. In this model, the business inventory for each occupancy class is based on annual sales.

Business activity generates several types of income: (1) capital or property ownership; (2) profits, dividends, and earnings; (3) interest payments to loan institutions, rental and royalty payments; (4) proprietary income; and (5) labor. All these sources of business income are considered in the HAZUS calculations.

Direct economic losses for extended network lifelines depend on the locations of the various components and the models relating ground motion to damage. Losses are computed based on (1) probabilities of being in a specific damage state, (2) replacement value of the component, and (3) damage ratios for each damage state.

MODULE 7: INDIRECT ECONOMIC LOSSES

This module evaluates the long-term effects on the regional economy from earthquake losses. The outputs in this module include income change and employment change by industrial sector. Earthquakes may produce dislocations in economic sectors that do not sustain direct damage. All businesses rely on either regional customers to purchase their output or regional suppliers to provide their inputs and thus are potentially vulnerable to operational interruptions. The extent of indirect losses is dependent upon such factors as the availability of alternative sources of supply and markets for products, the length of production downtime, and deferability of production.

POTENTIAL HAZARDS

Three potential hazards associated with earthquakes were evaluated: ground shaking, liquefaction, and landsliding.

EARTHQUAKE GROUND SHAKING

A fundamental limitation encountered in the estimation of ground shaking in South Carolina is the lack of strong motion data in the entire central and eastern United States. The use of empirical attenuation relationships based on the recordings of strong motion is the traditional and most appropriate approach in estimating ground motions from future earthquakes. Such relationships are not available for the central and eastern United States. Hence, in this study, we have utilized a widely accepted state-of-the-art numerical ground-motion modeling technique. Ground motions were estimated for the four scenario earthquakes using the finite-fault and point-source versions of the stochastic numerical modeling approach (Silva et al. 2003). Statewide maps for surficial ground shaking in terms of peak horizontal acceleration (PGA), peak horizontal velocity, and 0.3- and 1.0-sec spectral acceleration were produced for each scenario by multiplying the stochastic model-computed rock motions by soil amplification factors. The ground motions are calculated on a 2-km × 2-km grid, thus the resolution is significantly superior to using census tracts.

An extensive effort was made to characterize the subsurface geology of the state for the purposes of quantifying the effects of soil on ground motions, through the use of amplification factors, and assessing the liquefaction potential. The type of geologic material, thickness, shear-wave velocities, and dynamic material properties of unconsolidated units were evaluated along with their respective uncertainties. For evaluating liquefaction, the degree of water saturation was also analyzed. Based on the characterization of the surficial geology, the state was divided into four site response categories: Blue Ridge/Piedmont, Savannah River, Myrtle Beach, and Charleston. Characteristic profiles were developed for each site response category using available subsurface and shear-wave velocity information, and considered a wide range of soil and rock conditions. Amplification factors were calculated as a function of site response category, spectral frequency, soil thickness, and input rock motion.

In the calculation of the scenario ground motions for the **M** 7.3 Charleston earthquake, the finite fault parameters were varied because of the considerable uncertainty regarding the source of the 1886 earthquake. The resulting calculated pattern of ground motions and probability of liquefaction were compared against the 1886 observations. Based on these comparisons, the final fault parameters were selected that resulted in the most favorable comparison to the 1886 earthquake. The rupture plane of the **M** 7.3 event was generally modeled as a north-northeast-trending strike-slip fault 100 km in length coincident with the Woodstock fault. The possibility that the fault was only 50 km long was also included in the ground motion estimates. The **M** 6.3 and **M** 5.3 Charleston scenario earthquakes were assumed to occur on the same fault source as the **M** 7.3 event but with smaller rupture dimensions. The **M** 6.3 rupture area was generally modeled as being 20 km in length and 10 km in width. The **M** 5.3 rupture area was assumed to have the dimensions of about 5 km × 5 km. Although the specific sources of earthquakes are unknown in the Piedmont, we assumed that the scenario earthquake in Columbia was an event that could occur along a segment of the Eastern Piedmont fault system with rupture dimensions of about 3 km × 3 km.

The resulting mapped peak horizontal accelerations for the **M** 7.3 scenario event were as high as 0.6 to 0.7 g on soil in the vicinity of the modeled rupture near Charleston (Figure 4a). For the **M** 6.3 and 5.3 Charleston scenarios, the highest peak horizontal accelerations are estimated to be greater than 0.3 g (Figure 4a) and 0.2 g, respectively. An **M** 5.0 earthquake in Columbia could result in peak values greater than 0.2 g.

LIQUEFACTION

The occurrence of liquefaction depends upon the susceptibility of the soil, the amplitude and duration of the ground shaking, and the depth of the water table. The evaluation of a soil's resistance to liquefaction involves the estimation of both the capacity to resist liquefaction and the demand placed on the soil by ground shaking.

HAZUS considers the potential for liquefaction (in terms of liquefaction-induced

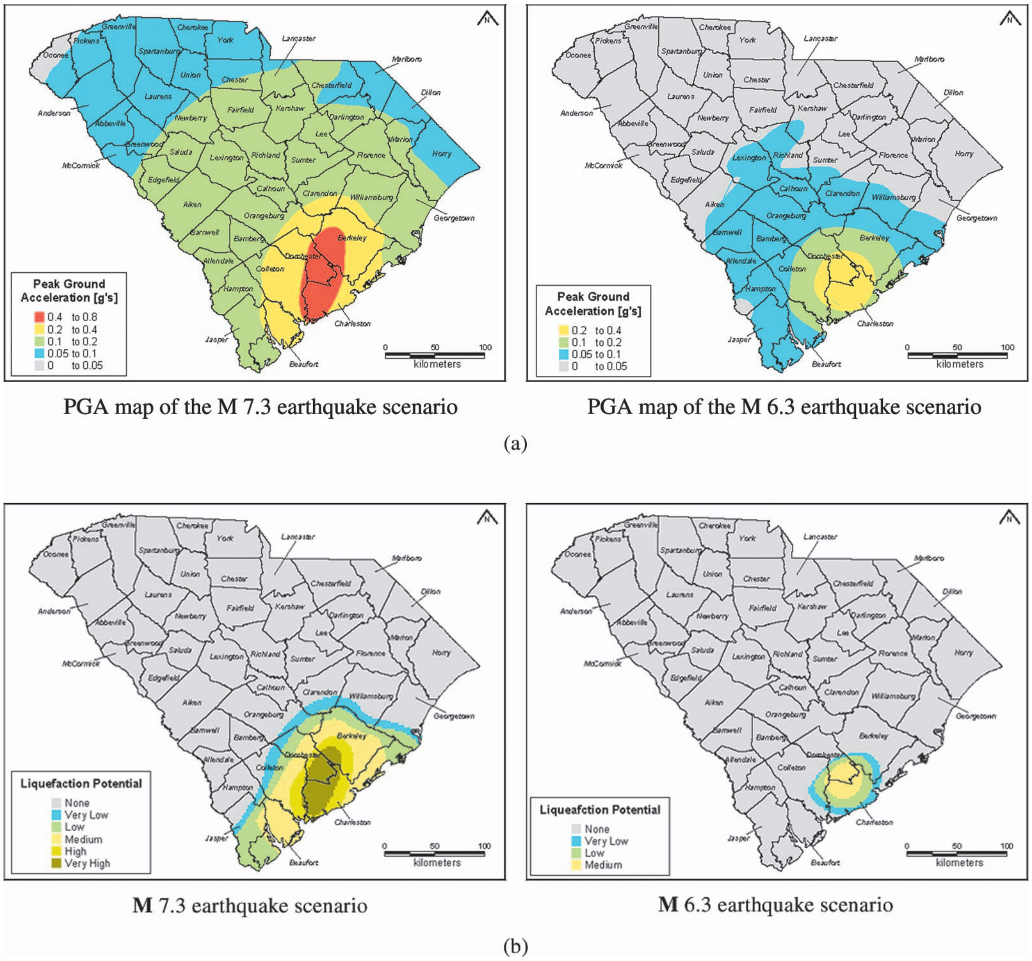

Figure 4. (a) Representative ground shaking maps used in the study, and (b) representative liquefaction potential maps used in the study. The actual maps used are much more detailed.

settlement and lateral flow) in assigning the potential for building and pipeline damage. For each of the four earthquake scenarios and characteristic geologic profile, the liquefaction demand in terms of an average cyclic stress ratio (CSR) within potentially liquefiable soil was calculated across the state at a 2-km × 2-km grid pattern (Silva et al. 2003). The liquefaction resistance of soil, as expressed by the cyclic resistance ratio (CRR), in the representative profiles was determined based on shear-wave velocity and the clay/silt content of the soil. The ratio of capacity (CRR) to demand (CSR) is termed the factor of safety against liquefaction. Liquefaction is predicted to occur when the factor of safety is at or below 1 and not to occur when it exceeds 1.

The initial step in modeling the observed liquefaction in 1886 was identifying the susceptible soils. Youd and Perkins (1978) categorized the susceptibility of soils according to age and depositional environment. In general, older soils have lower potential for liquefaction. In fact, essentially all documented liquefaction has occurred within soils of Pleistocene age or younger.

The results of the characterization and analyses indicate that greater amplification and liquefaction hazard are experienced in the Charleston region, as highlighted by the 1886 earthquake, than in other regions of South Carolina (Figure 4b; Silva et al. 2003). The greater liquefaction demand, as well as the common presence of loose sand deposits, results in a greater risk of liquefaction in the Charleston region. Considering the age of the residuum (weathered bedrock) in the Piedmont and Blue Ridge areas of South Carolina, the liquefaction hazard was considered very low (Figure 4b), and thus liquefaction-induced settlement and lateral spreading during an earthquake was considered very unlikely. However, younger sediments (e.g., loose Pleistocene and Holocene sands) along rivers and streams are considered susceptible to liquefaction.

EARTHQUAKE-INDUCED LANDSLIDING

In addition to the movement associated with liquefaction-induced settlement and lateral flow, there is also a potential for landslides in sloping terrain, where the additional seismic forces may temporarily exceed the slope strength. Specifically, the susceptibility of an area to earthquake-induced landslides is assigned based on the general steepness of slopes, the soil/rock type, and the groundwater conditions. Based on available information and a general characterization of the subsurface throughout the state, the landslide susceptibility was categorized based on the classification of Wilson and Keefer (1985), which is used in HAZUS.

INVENTORY DATA

The Project Team drew upon the expert opinion of local building officials and structural design professionals, visual surveys in Charleston and other urban areas, and records from the 1886 Charleston earthquake as a basis for updating structural vulnerability relationships within HAZUS. Key observations for the vulnerability of South Carolina's buildings include the following:

- Prior to the 1990s, very few buildings were designed for earthquake demands, and only a few jurisdictions systematically inspect construction.
- Until recently, unreinforced masonry (URM) bearing-wall construction was common throughout the state, including for schools, fire stations, and other important buildings. Charleston preserves many historic unreinforced masonry buildings that survived the 1886 earthquake.
- Most homes, small commercial buildings, and many public school buildings in South Carolina are wood-framed, many with masonry veneer.
- South Carolina has more "manufactured" housing per capita than any other state. Manufactured construction is also very common for schools.
- Medium to large commercial low-rise buildings are mostly light, steel-framed construction. There are very few concrete tilt-up buildings.

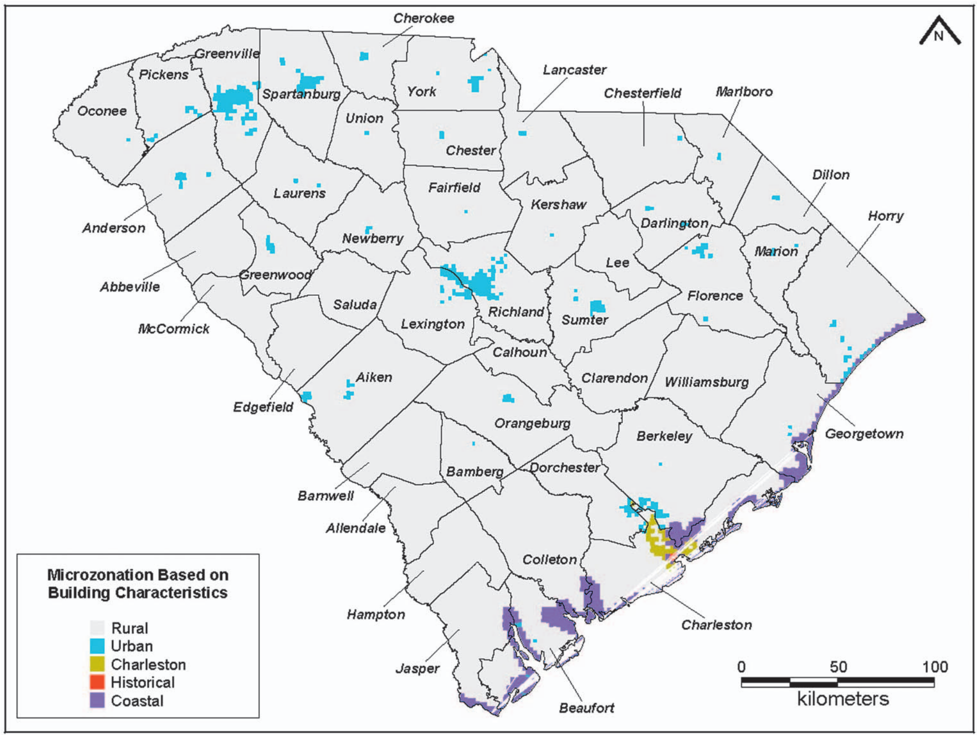

Figure 5. Microzonation map of the building inventory in South Carolina.

- Power generation facilities are generally designed for earthquakes. One exception may be substations, where equipment anchorage practice varies.
- Occupancy and vulnerability assignments were developed for four geographic sub-areas (Figure 5):

  1. Charleston's historical district,
  2. General urban areas (Charleston, outside of the historical district, and other areas statewide having a population density greater than 500 persons per square kilometer),
  3. General non-urban areas, and
  4. Coastal resort areas.

This approach allowed customizing and enhancing the default HAZUS databases for the building inventory in a way that better reflects the types and quality of building construction found in South Carolina. The customized inventory and vulnerability modeling were deemed extremely important because the distribution and characteristics of South Carolina's building are markedly different from the state or regional averages used in the default data provided with HAZUS, or from buildings in the seismically active western

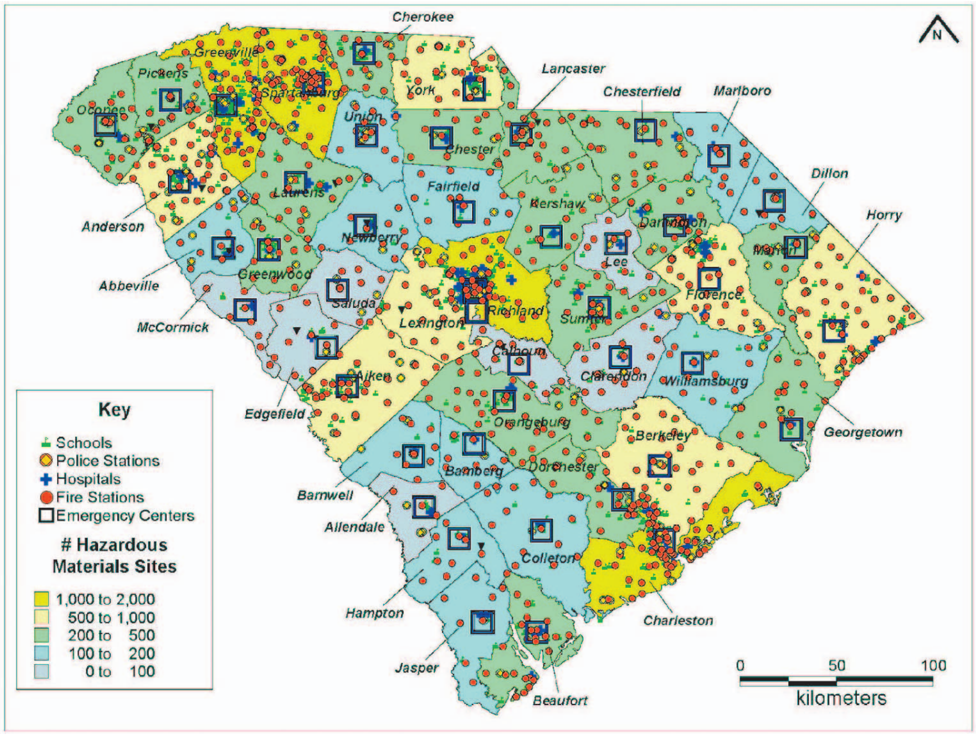

Figure 6. Map of essential facilities and HAZMAT sites in South Carolina.

United States. Within this process, the Project Team utilized six sources of information: (1) the 2000 Census data at a census block resolution level, (2) the 2000 occupancy square footage data processed by Dun and Bradstreet also at a census block resolution level, (3) collected assessor's files for Greenville and Berkeley counties, (4) historical demographic growth data to approximate the age of buildings, (5) county business pattern information from the U.S. Census Bureau, and (6) data reprocessed at the 21,138 (2 km × 2 km) grid cells.

HAZUS does not allow direct inspection or manipulation of damage relationships. Rather, the user assigns an appropriate HAZUS structural class with "seismic design level" and "building quality" modifiers. For each geographic sub-area, building values at risk from each occupancy class were distributed to HAZUS structural classes. Seismic design levels were specified, and seismic "quality" assigned. Age breakdowns were established where appropriate. As a result of the inventory revisions and the improved structural vulnerability modeling, the model input in HAZUS much more accurately represents the exposures and their damage potential. Based on these tasks, the information on the built environment was aggregated at the 2-km × 2-km grid for the state.

The most up-to-date site-specific data for essential facilities (Figure 6) and lifelines were also collected. Lifelines include water and sewage systems, electric power and communication systems, natural gas facilities (including pipelines), transportation systems, airports, and port and harbor facilities. Essential facilities include police and fire stations, hospitals, and emergency operations centers. Supplemental data were collected for all data types, summarized in Table 1. In the vast majority of cases, the HAZUS default data were substantially enhanced and replaced with better and more complete data sets. Very detailed HAZMAT materials databases were also collected from the South Carolina Department of Health and Environmental Control (Figure 6) and reformatted to adhere to a HAZUS format. The criteria for using data obtained from government sources hinged on whether the data could be used to supplement or supplant the HAZUS data, based on either its spatial resolution or its attribute data.

INVENTORY OVERVIEW

South Carolina has an area greater than 80,000 km^2 with about 1.3 million households in the state and a total population of about 4 million people. The 2000 population density distribution is shown in Figure 7. HAZUS estimates that South Carolina has about 1.5 million buildings, with a total building replacement value (excluding contents) of $168.8 billion (2000 dollars). Approximately 88% of the buildings (and 73% of the building value) are associated with residential housing.

For lifelines, the replacement value of the transportation and utility lifeline systems is estimated to be $26.6 billion and $17.2 billion, respectively. Finally, for essential facilities, there are 108 (31 large-sized, 45 medium-sized, and 32 small-sized) hospitals in the state, with a total bed capacity close to 15,000 beds. Furthermore, there are 1,588 schools and 4,455 relocatable school buildings, 880 fire stations, 205 police stations, 47 emergency operation facilities, and an additional 24 emergency response facilities.

LOSS ASSESSMENT

Table 2 provides an overview of the most significant losses that would be sustained in South Carolina in two out of the four earthquake scenarios considered in this study. The findings highlight several critical factors that have important implications for earthquake risk reduction, planning, preparedness, emergency response, and disaster recovery. Results indicate, not surprisingly, that the **M** 7.3 Charleston scenario would be by far the most destructive and disruptive to the state, followed by the **M** 6.3 scenario. Results from the **M** 7.3 scenario include the following:

- A daytime event will cause the highest number of casualties (Figure 8). Of the estimated 45,000 casualties, close to 9,000 or about 20 percent will be major injuries (injuries requiring hospitalization) or fatalities (about 900). Most of these casualties will occur in Charleston, Dorchester, and Berkeley counties.
- Nearly 70,000 households, or about 200,000 people, are expected to be displaced, with an estimated nearly 60,000 people requiring short-term shelter.
- Economic losses due to building damage alone are estimated to be over $14 billion (2000 dollars) (Figure 9), compared to almost $3 billion for the **M** 6.3 event. Losses to lifelines would result in an added $1.2 billion for the **M** 7.3 event.

Table 1. Sources collected for HAZUS input data

HAZUS Data Type	New Data Sources	Comments on Usage
Medical Care Facilities	South Carolina Department of Commerce (SCDOC), Department of Health and Environmental Control (DHEC)	Concrete shear-wall buildings or concrete frame buildings with unreinforced-masonry infill walls
Emergency Operation Centers	South Carolina Emergency Preparedness Division (SCEPD)	Replaced HAZUS inventory.
Fire Stations, Police Stations	South Carolina Insurance Reserve Fund (SCIRF), SCDOC	Low-rise unreinforced-masonry bearing-wall buildings—poor seismic design and typical seismic design
Schools	SCDOC, South Carolina Department of Education (SCDOE), University of South Carolina (USC), South Carolina State Budget and Control Board (SCBCB), Office of Research and Statistics (ORS), South Carolina Commission on Higher Education (SCCHE)	Replacement cost of $100-per-square-foot low-rise URM buildings without any special seismic design
Highways	Federal Highway Administration (FHWA)	Per lane mile cost of $70,000/km
Highway Bridges	South Carolina Department of Transportation (SCDOT)	Default NBI database updated with latest version
Railway Tracks	SCDOC	Many dismantled railways were removed from database
Railway Bridges	SCDOC	Bridges on dismantled railways were removed from database
Railway Facilities	SCDOC	Facilities on dismantled railways were removed from database
Bus Facilities	SCDOC	Replaced HAZUS inventory
Ports and Harbors Facilities	U.S. Army Corps of Engineers (USACE), SCDOC, Port of Charleston	The insured values of each terminal were used as a replacement cost. DOQs used to assess whether cranes were rail mounted.
Airport Facilities	South Carolina Department of Natural Resources (SCDNR), Federal Aviation Administration (FAA)	Public noncommercial assessed at $10 million; private landing strips estimated at approximately $100,000
Airport Runways	SCDNR, FAA	HAZUS default data accurate
Potable Water Pipeline Segments	SCDOC	Pipes installed during 1955 and earlier were classified as cast iron, or brittle; pipes installed after were classified as ductile iron, or ductile.
Potable Water Facilities	SCDOC	Average capacity was used to calculate the cost: wells, $150,000; on-ground wooden tanks, $13,000; elevated steel tanks, $1,000,000; on-ground steel tanks, $600,000. For water treatment plants, assigned $400,000 per millions of gallons processed daily.

Table 1. **(cont.)**

HAZUS Data Type	New Data Sources	Comments on Usage
Wastewater Pipeline Segments	SCDOC	For wastewater treatment plants, the linear equation was used to estimate the replacement cost of each facility ($800,000 per millions of gallons processed daily). Lift stations assigned $100 per gallon a minute processed.
Wastewater Facilities	SCDOC	259 sewage treatment facilities and 2,318 lift stations collected within the state
Oil Pipeline Segments	NPMS, SCDNR	Increased spatial accuracy from national database
Oil Facilities	Energy Information Administration—Geographical Information Systems for Natural Gas (EIAGIS-NG)	HAZUS default data accurate
Natural Gas Pipelines	EIAGIS-NG, South Carolina Public Service Commission (SCPSC)	Transmission pipelines in the state are welded-steel with arc-welded joints
Natural Gas Facilities	EIAGIS-NG, SCPSC	Equipment and piping in this facility were anchored and the facility had back-up power
Natural Gas Distribution Lines	EIAGIS-NG, SCPSC	Half plastic and half steel. Assumed that all of the pipelines were ductile.
Electric Power Facilities	EIAGIS-NG, Federal Energy Regulatory Commission (FERC)	Largely braced steel-frame structures with tall exhaust stacks. Determined to be of low seismic design and poor construction. High-voltage substations and electric power plants were anchored. Moderate-sized substations were found to have unanchored components.
Communication Facilities	USC	Initial HAZUS database contained 487 communication facilities, reducing to 202 key facilities led to more reasonable results.
Communication Distribution Cables	SCDNR	HAZUS default data accurate
Hazardous Materials	DHEC	Many locations updated and facilities added

- About $10.9 billion or about 77 percent of the total economic losses will occur in the Tri-County region (Charleston, Berkeley, and Dorchester counties).
- The building damage (Figure 10) alone will cause over $4.2 billion in losses due to business interruption in the state. These losses correspond to rental income losses, lost business income, wage losses, and expenses associated with reloca-

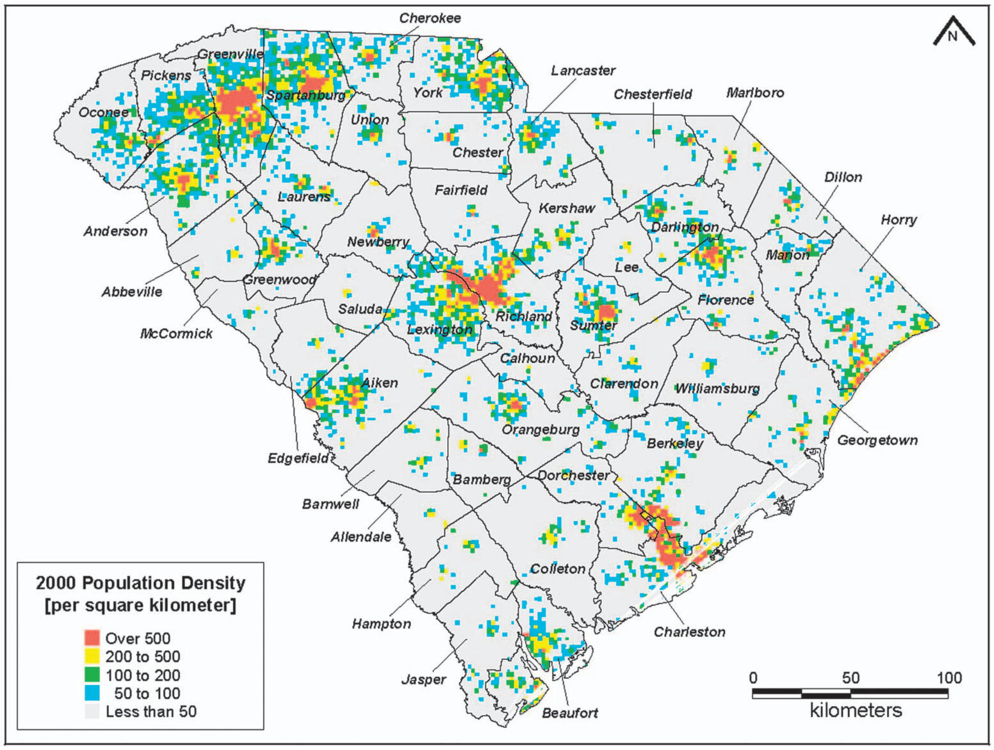

Figure 7. 2000 population density distribution in South Carolina.

tion. Secondary business interruption losses related to lost revenues to suppliers and wholesalers are not included.

- Schools and fire stations are particularly vulnerable to damage. More than 220 schools (not considering the extensive damage to the relocatable school buildings) and 100 fire stations will experience significant damage. These losses are due to insufficient seismic building code standards and the vintage of the building stock, the majority of the structures in the state. This situation may lead to issues with respect to providing reliable shelters for immediate use in emergency response and sheltering, and with respect to responding effectively to the 250 fires expected from this scenario. Schools are expected to suffer significant damage in the case of the **M** 6.3 scenario, as well.
- Of the 47 emergency operation centers, 10 are expected to suffer at least moderate damage.
- There could be safety issues related to school children, teachers, and other persons in school buildings. The catastrophic failure or partial collapse of one or more school buildings during school periods could greatly increase the casualty

Table 2. Overview of results for key parameters in the case of **M** 6.3 and **M** 7.3 earthquake scenarios

Category	Description of Parameter	**M** 6.3	**M** 7.3
Hazards	Peak ground acceleration (PGA)	Maximum of 0.39 g	Maximum of 0.64 g
	Lateral spreading (inches)	Maximum of 20 in.	Maximum of 92 in.
Critical Facilities	# Schools with at least moderate damage	116	404
	# Hospitals with at least moderate damage	9	30
	# Fire stations with at least moderate damage	75	298
Lifelines	Damage to potable water pipes (diameter> 12″)	7 breaks & 25 leaks	496 breaks & 654 leaks
	# Treatment plants with at least moderate damage	2	16
	# Bridges with at least moderate damage	120	761
	# Airports with at least moderate damage	2	8
	# Power facilities with at least moderate damage	17	63
Building Damage	# Bldgs. slight/moderate	136,100	331,700
	# Bldgs. at least extensive	25,600	172,100
	Capital stock loss ($M)	2,210	14,060
	Income loss ($M)	710	4,290
	Total ($M)	2,920	18,340
Shelter	# Displaced households (1 household ~3 people)	7,250	69,150
	Short-term shelter (# people)	5,170	59,190
Fire	Number of potential fires	42	255
Debris	Total weight [million tons]	5.2	36.0
Casualties	Nighttime Event - Minor	2,660	29,732
	-Major	470	6,165
	-Deaths	38	573
	Daytime Event -Minor	2,961	36,227
	-Major	562	7,951
	-Deaths	55	891

estimates. Restoration of the schools for the emergency sheltering of the homeless and other contingency service will be demanding.

- Hospitals will suffer significant building damage that would likely result in more than 30 hospitals out of the 108 (about 30%) being nonfunctional. Over half of these affected hospitals may experience extensive damage. The **M** 6.3 event will result in about 10 hospitals suffering considerable damage. Since most of this damage will be concentrated in the Tri-County area, the region may be faced with the serious issue of how to provide the needed care to existing patients and potentially thousands of earthquake victims from the affected communities.
- Close to 800 bridges are expected to suffer enough damage to make them inaccessible, thus hampering even further the recovery efforts. In addition, certain

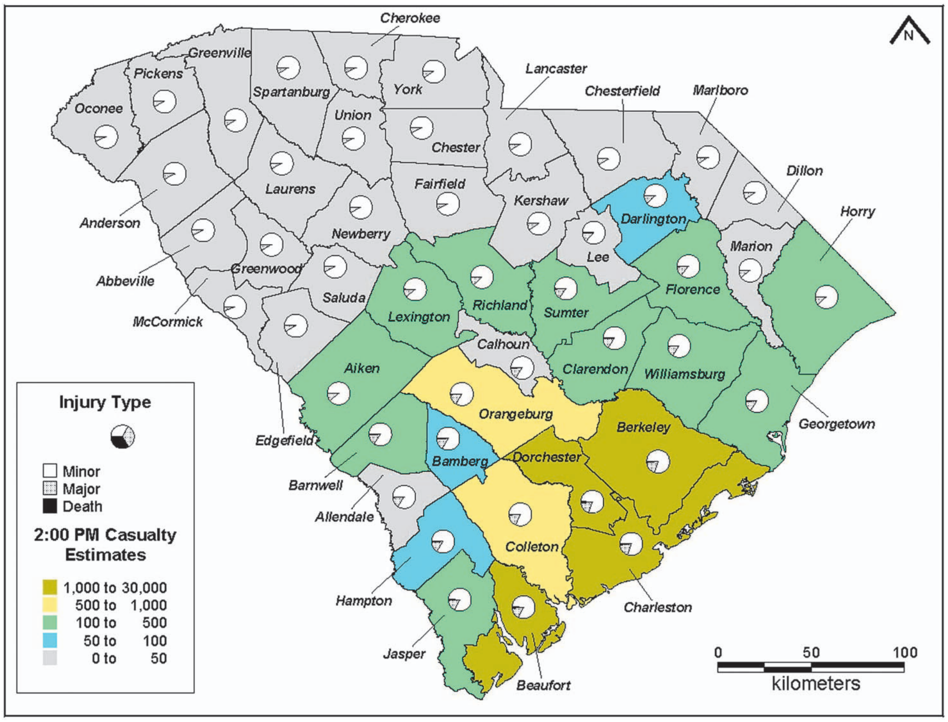

Figure 8. Casualty estimates for the **M** 7.3 earthquake scenario.

communities in the greater Charleston area that are only accessible by bridge routes may be cut off.

- A good portion of the Charleston region is susceptible to liquefaction. However, ground failure effects contribute only about 5% to building losses. Ground failure effects, on the other hand, are more significant in the Charleston area for pipelines, roads and runways.
- More than 36 million tons of debris will be generated, including an estimated 10 million tons of Category II debris, which includes concrete and steel—materials that require special treatment in "deconstruction" and disposal. Debris disposal, therefore, may pose a major challenge in the recovery phase. This total does not include biomass.
- In potable water pipes greater than 12 inches, more than 1,100 repairs will be needed, or about a repair for every 2 km of these pipes. Over half of these are expected to be breaks. Widespread water failure may drain water within minutes or hours from the distribution system, thus preventing adequate water supply for fire suppression. In addition, about 80% of the urban households in the affected area will be deprived of water. It will take weeks, if not months, to restore the

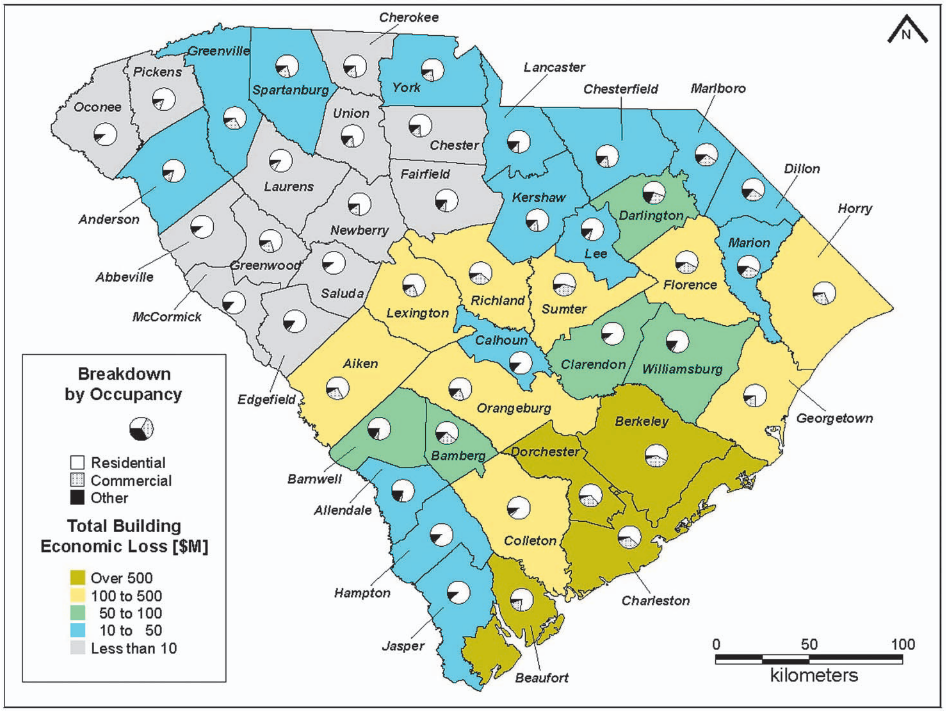

Figure 9. Distribution of the building-related economic losses for the **M** 7.3 earthquake scenario.

serviceability of the water systems. Therefore, significant external augmentation would be required to provide and sustain such a high repair level.

- Of all the utility systems, electric power is arguably the most critical, as many other lifelines depend on it. It is expected that about 63 electric power facilities (51 substations out of the total of 380 and 12 power plants out of the total of 53) will suffer at least moderate damage and nearly 300,000 households will be without power right after the earthquake.

In the event of an **M** 6.3 earthquake in Charleston, approximately 136,000 buildings will sustain slight to moderate damage, and 25,000 will be extensively damaged. Total building loss including capital stock and income losses will approach $3 billion. Approximately 30 to 60 people will be killed and from 2,000 to more than 3,000 people will suffer minor to major injuries.

In the **M** 5.3 Charleston scenario earthquake, the losses and casualties decrease significantly. Injuries will number less than 100 with no estimated deaths. Total loss to buildings will be about $230 million.

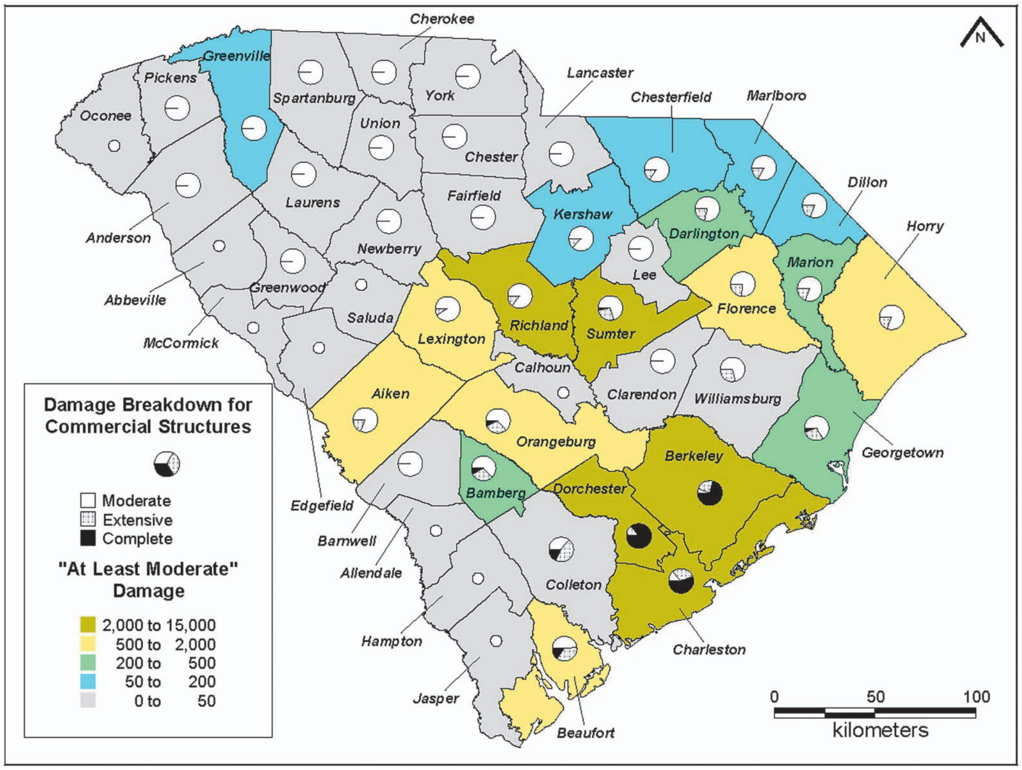

Figure 10. "At least moderate" damage distribution map of commercial structures from the **M** 7.3 earthquake scenario.

If a small earthquake of **M** 5.0 were to occur in Columbia, approximately 2,600 buildings would sustain slight or moderate damage with a total loss of $310 million. Fewer than 10 people will be injured and only with minor injuries.

UNCERTAINTIES AND LIMITATIONS

A limitation of HAZUS and this analysis is that the influx of tourists into the state, particularly during the summer months, is not explicitly accounted for in our loss estimates. If a large earthquake were to occur in the summer, the losses and casualties could be significantly higher. The effects of dam failures were also not addressed in this analysis and this could result in even greater losses.

Subsurface conditions can vary significantly within the grid spacing used in this study, and while the near-surface conditions of South Carolina have been extensively characterized in some isolated areas, very little high-quality subsurface data is available for much of the state. Therefore, in consideration of the statewide nature of this study and the level of detail involved in the characterization, some simplification based on engineering judgment was necessary. The simplifications applied in this study were needed

Table 3. Sensitivity analyses

Parameter	Scenario 1 Improved Hazards & Inventory	Scenario 2 Improved Hazards$+1\sigma$ & Inventory	Scenario 3 Improved Hazards but Default Inventory	Scenario 4 Default Hazards and Improved Inventory
PGA_{max}	0.64 g	1.31 g	0.64 g	1.28 g
Economic Loss [$B]	14.45	25.87	13.19	19.33
Minor Injuries [Nighttime Event]	24,878	47,575	13,566	29,315
Major Injuries [Nighttime Event]	5,338	10,397	2,829	6,306
Deaths [Nighttime Event]	518	941	240	606

to create a practical model and were intended to result in conservative estimates within the HAZUS model, and thus were considered appropriate for the purposes of this study.

It is important to emphasize that the loss estimates coming out of HAZUS are best-estimate (median) values, and the uncertainties in the resulting earthquake losses are large as with any loss assessment. There are several sources of uncertainties, including, for example, those derived from the use of building fragility curves. The accuracy of loss estimates can be improved by inputting the most accurate inventories of infrastructure, as was done in this study, rather than relying on the national default databases provided in HAZUS. The largest source of uncertainty, however, with the most significant impact on losses, are those associated with the estimates of ground shaking. It is typical that one standard error in modeled eastern U.S. ground motions results in a factor of two or more uncertainty in the median value. For a median peak horizontal acceleration of 0.40 g, which was a typical value for the Charleston area in the 1886 scenario, the value could be as low as 0.20 g and as high as 0.80 g at the 16th and 84th percentiles, respectively. (Note, for example, that there is still a 16% chance that the value of 0.80 g will be exceeded.)

To evaluate the impact of the improved seismic hazards input including ground shaking and their uncertainties and the enhanced inventory data on the HAZUS results, we have performed some sensitivity analyses varying the inventory and ground motions. The analyses are for the four counties that will be most significantly impacted by a repeat of the 1886 earthquake: Charleston, Dorchester, Berkeley, and Colleton. In Table 3, we summarize four HAZUS scenarios that were calculated: (1) our base case using the hazard inputs and revised inventory developed in this study, (2) the base case scenario but using the 84th percentile (one sigma) ground motions with the associated liquefaction, and landsliding estimates calculated in the study, (3) a scenario using the default inventory contained in HAZUS 99 but with our improved seismic hazard input, and (4) a scenario with the HAZUS 99-calculated ground shaking (no liquefaction and landslides) and our improved inventory. Relative to our base case (Scenario 1), the overall losses almost double with the doubling of the ground motions in Scenario 2 (Table 3). This factor of two uncertainty in losses is extremely significant because the large uncertainties in ground motion prediction are the current state-of-the-practice as described above. Although the economic losses only show a small decrease in Scenario 3 relative to our base case Scenario 1, deaths and injuries appear to be almost a factor of two too low. We attribute this decrease to the building stock, which is actually more vulnerable to damage and collapse (more URM) than assumed in the default inventory in HAZUS 99. Finally, based on our analysis, HAZUS 99 overestimates the ground shaking hazard as characterized by the default peak horizontal acceleration of 1.28 g (Table 3). With the improved inventory and default ground shaking, economic losses and death and injuries are severely overestimated. Given the large uncertainties in any loss assessment, we strongly recommend that sensitivity analyses be performed where the ground motion inputs to HAZUS are varied to evaluate the impact on the estimated losses.

IMPACTS FROM THE HAZUS RESULTS

Upon completion of the HAZUS evaluation, SCEMD presented the study results to local, state, and federal agencies and began improvements to the South Carolina Earthquake Plan. The plan assigns responsibilities and actions to each of the state agencies and organizations to provide effective response after a damaging earthquake. The earthquake plan has three components: (1) The basic plan contains the responsibilities, operational concepts, and functional task assignments along with the **M** 7.3 Charleston earthquake scenario loss estimation that includes liquefaction probability and isoseismal maps; (2) Emergency Support Function (ESF) (federal, state, and county support groups within the respective Emergency Operations Center) annexes describe the enhanced concept of operations, actions, and responsibilities specific to earthquakes; and (3) sections of the plan provide specific planning guidance for earthquake response actions and include items and topics such as the county situation report, earthquake phased checklist, rapid response teams overview, critical resource needs assessment, probability of liquefaction areas, etc.

SCEMD exercises the plan annually at the state and county levels. Following each exercise, SCEMD makes changes as appropriate to broaden and improve the plan and to improve the State Emergency Operations Center plan and activities. Examples of improvements to the plan as a result of this study included (1) aerial reconnaissance to enhance road and bridge assessment for bridge engineering inspections and input for ingress and egress analyses; (2) a disaster transportation route management system: SCEMD purchased software that, using HAZUS data, quickly identifies alternative routes to specific locations. SCEMD also will use the combination of HAZUS and the route management system to develop planned emergency ingress and egress routing maps; and (3) earthquake operational areas: SCEMD designed this strategy to deploy response assets to areas isolated due to severe road and bridge damage. The plan contains 18 operation areas most prone to severe damage. Detailed maps of those areas are in the plan.

RECOMMENDATIONS FOR COLLECTING INVENTORY DATA

We believe the inventory data collection for this loss assessment was a significant achievement. In a pre-9/11 environment, the Project Team obtained detailed data for every lifeline and transportation component type, statewide. This yielded valuable data collection, processing, and even modeling techniques specific to HAZUS. Following are suggestions for modifying HAZUS GIS data during a Level 2 or Level 3 analysis. Where applicable, suggestions have been updated for HAZUS-MH (multiple hazards).

HAZUS accommodates updates to all base data, damage functions, and parameters either through the interface or through the underlying databases. With the option to update any data set, users need a systematic method for prioritizing data collection. The decision to update a specific component should depend on whether the given component is a primary contributor to losses, whether the default HAZUS database is complete and comprehensive and whether better data are readily available. A matrix ranking these three parameters helps assess update priority by data type. For example, power substation voltage is an important parameter, but data are difficult to obtain. Railroad facility data are also difficult to collect, but damage to railroads represents a small portion of the total loss. These circumstances justify less effort to collect data for railroad facilities, but it may be worthwhile to explore data sources for power substation voltage. Additional high-priority items include cranes at port facilities, electrical substations, regional cost modifiers, and building replacement costs.

Various federal, state, and local agencies collect and maintain inventory data. These data sets are useful for loss estimation within HAZUS and as supplementary data for emergency response. Reviewing the metadata helps to assess data applicability for a specific project. Contacting the agency that distributes the data helps confirm data applicability. There may be errors in metadata, and descriptions of data are frequently easy to misinterpret. This is a good opportunity to discuss the project, so that the agency knows how the data is being used.

Default replacement cost should be reviewed and updated when necessary. Improved replacement cost estimates can be found by contacting external sources or refined from defaults in HAZUS. The size of a facility can also be used to refine the default replacement cost. Users updating HAZUS should be aware that when detailed information is collected, the default cost may no longer be representative.

High-resolution remote sensing data provides a georeferenced photographic backdrop that allows an analyst to adjust location or key attributes in a HAZUS database. This data may prove useful for various specific facilities where accurate square footage, height, or location justifies the additional effort.

Once additional data are collected, it must be reviewed for completeness and accuracy. Analysts can assure that updated facilities are in the right place in the world by overlaying the data with other layers from HAZUS or commercial databases. Geocoding facilities or using online map sites to obtain coordinates provides a cross-check for specific facilities. Projection problems like DATUM shifts are common.

Qualitative review of the data is also important. The density of facilities and infrastructure correlate closely with population density. Most types of facilities occur in every county and every major city within a study area. Spatial databases correlate. For example, rail facilities are on train tracks and major bridges are on highways. Utility pipelines are often collocated. A visual review of the data leads to the discovery of data processing or reliability issues.

The accuracy of HAZUS loss estimates is dependent on the quality of the underlying data. As the user adjusts the default parameters for a specific study site or imports additional data, the accuracy of the estimates generally increase. HAZUS will provide estimates as delivered, based on national data sets that come with the software package. In most cases, these data sets originate from agencies other than FEMA, and the intended use of the data was not loss estimation. Users should become very familiar with the default data, the detail of the data, and assess the applicability to loss estimation independently. The components analyzed by HAZUS vary greatly in their contribution to loss. Collecting GIS data for a specific data type can be simple or extremely difficult. Given these complexities, HAZUS users should proceed with updating data very cautiously and check their work after every step, and independently with hand calculations.

CONCLUSIONS AND AUTHORS' PERSPECTIVE

A repeat of the 1886 earthquake may cause the state to be overwhelmed by widespread damage as well as the disruption of lifelines. The picture for Charleston is particularly severe. Fires may spread unfought since water pipeline ruptures will inhibit suppression. Damage to emergency services including police, fire, and hospitals, will be extensive. Access by bridges may be limited. Statewide losses could be of catastrophic proportions, and our assessment does not include the impact of an 1886 repeat on neighboring states in what will be a regional disaster.

The impact from this event demonstrates the scope of the problem and reinforces the need to implement structural and nonstructural mitigation measures as a central feature in long-term initiatives to reduce seismic risk. Affected communities will be coping with the trauma and demands of immediate response and early recovery. Early federal assistance, along with first-tier support drawn from the non-affected regions, will be of highest priority. Still, a well-coordinated, preplanned response involving all levels of government, along with the private sector and other groups, will be required to deal effectively with the consequences of an event of this magnitude. Establishing centralized communications, command, and control to coordinate rescue efforts will be immediately critical. Transporting the injured to hospitals will require priority action. Directing firefighting efforts to the most essential facilities and to control the spread of fires will require prompt action to minimize casualties and property loss. The emergency inspection and repair of minimum critical water pipeline segments must be well focused in coordination with the fire department. Directing debris removal may require priority for passage of emergency vehicles.

By characterizing the nature and scope of potential impacts, the study performed for South Carolina represents a starting point for renewed and hopefully more effective efforts in earthquake hazard and loss mitigation. From this study, many in the state now well understand that a very significant earthquake hazard exists in South Carolina. During the past three years, earthquake emergency response plans have improved dramatically. Unfortunately and regardless of the study, funding at the local, state, and federal levels to mitigate the earthquake risk in South Carolina is unavailable.

What can or should the state do to mitigate the risk against earthquakes is a difficult question. Questions linger when considering the recurrence of hurricanes against that of large earthquakes within the state. Should the state adopt stronger earthquake codes, stronger hurricane (wind and flood) codes, or both? What economic impacts will the citizens incur as a result of these mitigative measures? The lack of funding and higher priority tasks, such as dealing with the losses from hurricanes, creates a situation where funding for earthquake hazard mitigation is a low priority despite the rather shocking, disastrous losses that our HAZUS assessment predicts.

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