USE OF ENHANCED NEHRP SOIL MAPS FOR HAZUS-MH ANALYSIS IN CHARLESTON, SC

A thesis submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

in

ENVIRONMENTAL STUDIES

by

JEFFREY JOSEPH WRIGHT BYERS MEDVES

MAY 2009

at

THE GRADUATE SCHOOL OF THE COLLEGE OF CHARLESTON

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ABSTRACT

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On August 31, 1886, Charleston, South Carolina experienced the most damaging earthquake recorded in the Eastern United States. The earthquake had an estimated magnitude of 6.9 to 7.3 and was felt over 2.5 million square miles. Earthquake events have been documented in South Carolina since 1698. Seventy percent of these are located in the Middleton Place - Summerville Seismic Zone (MPSSZ), 30 kilometers northwest of downtown Charleston. 137 earthquakes were recorded in the MPSSZ from 1996 through 2003. The amount of damage that could occur from a reoccurrence of an earthquake of magnitude 6.0 or higher within the region is greater now due to changes in land use and population growth. Major hazards are due to ground shaking and liquefaction.

HAZUS-MH is a natural hazard loss estimation methodology developed by FEMA in partnership with the National Institute of Building Sciences. HAZUS-MH provides state and local decision makers with a better understanding of the types and magnitude of damage caused by natural hazards. It is dependent on and sensitive to the quality of information that is used to determine the degree of hazard. The Earthquake module in HAZUS-MH requires information derived from the NEHRP (National Earthquake Hazards Reduction Program) soil maps in order to determine the extent of damage due to ground shaking and liquefaction. Small changes in the NEHRP soil maps can lead to major differences in the final HAZUS-MH determination. This research looks at the sensitivity of the HAZUS methodology related to the resolution and accuracy of the NEHRP Soil Maps, and how better soil maps can lead to better damage estimates for emergency managers and planners.

Supplemental information generated by this research is contained in an electronic format addendum. There are two file types. The first is a combined PDF of the HAZUS generated damage estimate reports for all scenarios mentioned in the body of the text. The second file type is that of the data tables used to develop the models. There are three data table files. There is one each of the USGS Geology, SSURGO Soils and STATSGO Soils data sets. Due to the extremely large size of the PDF and length of the tables, it was not feasible to include them as figures and tables in the text.

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Finally, I would like to thank my family. Without their continued support and motivation I would be lost. Mom (Joanne), you have been there to help push me to achieve my best, because you knew I could. Dad (Jeff), you have been there for any question great or small, with continued support, guidance, and always a bit of humor. Brother (S.F.), you have been there every time I called, and have been a friend as well.

I am truly a man blessed by God. I have had so many people contribute to my development and success, and I wish to thank those who have played such an important role in my life, yet go unmentioned in this acknowledgement.

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UNIT ABBREVIATIONS

m – meter

m/s – meters per second

LIST OF ACRONYMS

ACP – Atlantic Coastal Plain

CPT - Cone Penetration Test

DTWTBL – Depth to Water Table

FEMA – Federal Emergency Management Agency

GCS NAD 83 – Geographic Coordinates System North American Datum 1983

GIS – Geographic Information System

HAZUS-MH – Hazards United States Multi Hazard

MPSSZ - Middleton Place - Summerville Seismic Zone

Mw- Moment Magnitude

NEHRP – National Earthquake Hazards Reduction Program

NRCS – Natural Resources Conservation Service

Sa – Spectral Acceleration

SASW - Spectral-analysis-of-Surface-Waves

SCCP - South Carolina Coastal Plain

SCEMD – South Carolina Emergency Management Division

SCPT - Seismic Cone Penetrometer Test

SDV Tool – Soil Data Viewer Tool

SPT - Standard Penetration Test

SR – Site Response

SSURGO – Soil Survey Geographic

STATSGO - State Soil Geographic

USGS – United States Geological Survey

Vs – Shear Wave Velocity

VsMRL – Shear Wave Velocity to the Marl Interface

1.0 INTRODUCTION

1.1 Thesis Project Description

This project created a series of enhanced National Earthquake Hazards Reduction Program (NERHP) soil maps for the greater Charleston region for use in the HAZUS-MH earthquake analysis. HAZUS- MH was developed by the Federal Emergency Management Agency (FEMA). It is a software program designed to estimate the potential losses due to natural disasters. This study concentrates on an important step in improving the results from HAZUS-MH for the earthquake analysis portion of the program. The study was completed in four parts. The first part was the development of a methodology for incorporating seismic velocity data into current surface geology and soils layers for the study region. The second part was using this methodology for the development of models to be incorporated into the HAZUS-MH analysis environment. The third was the incorporation of the models into the HAZUS-MH environment. The fourth and final part of the project was to compare the developed model results to the baseline data to understand the effects different methodologies have in determining NEHRP soil classifications.

The models that were developed were based on fundamentally different datasets, a baseline model for comparison using South Carolina Emergency Management Division (SCEMD) data, a model based on the United States Geological Survey (USGS) surface geology for the study area, a model using the Natural Resources Conservation Service

Soil Survey Geographic (NRCS SSURGO) surface soils, and a model developed with the use of Natural Resources Conservation Service State Soil Geographic (NRCS STATSGO) surface soils. The models developed in this thesis illustrate that the current soil classifications used for disaster management are not representative of the study area, and that site specific data needs to be incorporated into future HAZUS-MH scenarios in order to improve the utility of disaster management analysis. This analysis also shows that the resolution of the NEHRP soil map is extremely important in developing useful scenarios.

1.2 Overview of Primary Study

The August 31, 1886 Charleston earthquake was the largest earthquake on the east coast of the United States in historic times. It is estimated to have had a moment magnitude of M_w of 7.3 and to have caused approximately 23 million dollars (1886 value) worth of property damage. The earthquake was felt as far as Chicago, Boston, Bermuda and Cuba (Juang and Li, 2007). The death toll from the earthquake was approximately 120 people in the Charleston area (Cote, 2006). Today, the aftermath of a similar earthquake would be devastating not only to the Charleston area but the entire low country coastal region.

Charleston, located in the southeastern coastal plain, is susceptible to seismically-induced liquefaction shaking hazards. The soil characteristics (soft, thick soils), coupled with the shallow water table, are known to amplify earthquake ground motion and increase liquefaction potential and seismic shaking. The potential for liquefaction and severe shaking during a strong (M 6.0-6.9), or possibly moderate (M 5.0-5.9), earthquake makes this region an important study area for the development of better National Earthquake Hazards Reduction Program (NEHRP) soil maps. The NEHRP soil maps can be used to enhance the current earthquake hazard analysis of the area. This study concentrates on developing a revised NEHRP soils classification for the region and assessing how the changes in the NEHRP soils affect the final HAZUS analysis.

The classification system used in this project is the 1997 NEHRP Provisions, where the soils are classified as “A-F” with “A” being the most stable and “F” being the least stable, as shown in Table 1 (HAZUS-MH MR III Technical Manual, 2007). This system is used to measure the soil amplification for a specific site in order to determine the potential behavior during a seismic event. Low-quality soils amplify (enhance) the ground motion effects during an earthquake, thereby contributing to a greater amount of damage. Figure 1 illustrates the NEHRP rating for the Charleston study area.

An important way of classifying these soils in the 1997 NEHRP Provisions is through shear wave velocity (Vs) measurements of the soils. “E” soils are classified as having a Vs below 180m/s (Table 1 (HAZUS MH MR-III Technical Manual, 2007). Three current research studies, Andrus and Fairbanks (2004), Andrus and Fairbanks (2005); and Chapman et al. (2003) have attempted to determine the shear wave velocities (Vs) in the upper 30 m of the surface soils and geologic units of the Greater Charleston area. Data from these studies were incorporated into the project as part of the mapping protocol.

Currently, the soil data set used for incorporation into hazard modeling is classified as a “D” (Stiff Soil) soil for the entire Greater Charleston area. Preliminary research showed that this appeared to be a generalization of the NEHRP soils present in the study area. “E” (Soft Soil) soils are more likely to be present in the study area. These soils in the study area are typically marsh, freshwater or estuarine deposits. These soil types greatly amplify the seismic waves that pass through them during any seismic activity, and are therefore a greater threat to the study area. As was seen in the December 16th, 2008, Charleston Earthquake, the soil type has a direct influence on the ground motion amplification. Figure 2 shows that with a M 3.6, there are different responses to the seismic waves. C1SC HNE is a “D” soil and has a lower amplification than the C2SC HNE “E” soil type. The difference in measured amplitude clearly illustrates that the NEHRP soil classification is an indicator of soil behavior, and that “E” class soils have a greater damage potential.

Central to this study was the creation of enhanced data models. There were two NEHRP classification types created for each of the enhanced models. The two classification types were the average Vs for the depth to marl (VsMRL), and the site response (SR). In the Charleston study region, the surface geology and soils overlay and semi-consolidated a restrictive layer know as the Cooper Marl (Juang and Li, 2007). Rarely does the depth of these surface types exceed 30 m. The depth to the Cooper Marls ranges from 5 to 21 m, (Juang and Li, 2007). The current method used for determining the NEHRP classification for a soil is by determining the Vs for the upper 30m of a study site (Chapman et al., 2003). By using a depth of 30m, there is considerable difference between the lower Vs of the surface features and the higher Vs of the marl. The result is an increase in the average Vs for 30m. This is problematic, because it leads to a less conservative measure of soil hazard potential. The VsMRL model addresses this issue by using only the average Vs to the interface of the surface features and the marl.

In addition to the Chapman et al. (2003) borehole Vs measurements, Jaumé et al. (2005) provided new Vs profiles, as well as corrected profiles for some Chapman et al. (2003) sites. This resulted in a more conservative measure of the soil hazard potential in the area. Conservative in this study refers to any method which results in the models creating a worst case scenario for damage, thus a less optimistic assessment of what will happen during seismic activity. By developing a model based on the VsMRL method, a more site specific classification was achieved. The second method used for model generation was that of the site response (SR) method. SR was developed to include other factors into the enhanced NEHRP classification of soils than a classification based strictly on Vs measurements. The factors included in this methodology were the average Vs, depth to water table, and age of the surface feature. The result of this method was an even more conservative rating of the NEHRP soil hazard potential.

1.3 Geology of the Area

The South Carolina Coastal Plain (SCCP), part of the Atlantic Coastal Plain, is composed of soft Quaternary soils that incorporate man-made fill as well as Holocene to Pleistocene sediments (Figure 3). Stiff Tertiary sediments are also included. Alluvial and marine deposits of soft clay, sandy clay, loose fine sands and silts varying from a few thousand to over 200,000 years old comprise the surficial geology layer (Figure 3). In this area the groundwater surface is close to the ground surface, which is important with relation to the earthquake-induced liquefaction potential of the region, as shallow groundwater in sandy and silty soil leads to higher liquefaction susceptibility. Sands ranging from loose to dense consistency, inorganic and organic clays, and silty clays compose the subsurface. The Cooper Group (locally referred to as the Cooper Marl), consists primarily of Tertiary sediments, as well as constituents of clayey soils in the deeper layer around 5 to 21 m, (Juang and Li, 2007).

Andrus and Fairbanks (2004) researched the use of shear wave seismic velocities (Vs) to measure the sediments in the Charleston quadrangle. Their study was completed to assess the liquefaction hazard in the Charleston region and to delineate seismic hazard zones for Charleston based on soil type and location as determined by surficial geology. Data was retrieved either by Seismic Core Penetration (SCPT), or by Spectral-analysis-of-Surface-Waves (SASW). The study indicated that the Charleston quadrangle surface geology, located in the upper 10-20 m, is soft and highly susceptible to ground motion amplification (Andrus and Fairbanks, 2004). In HAZUS terminology, soil of this type would receive an "E" rating.

1.4 Seismic Velocities

Charleston, South Carolina is shown to have the second highest earthquake hazard rating east of the Rocky Mountains due to the constant low-level seismicity (Petersen, 2008). Paleoseismic research shows that in the past 6000 years no less than four large prehistoric earthquakes have occurred in this region (Talwani and Shaeffer, 2001). While the geological processes causing Charleston coastal seismicity are not fully understood, it is evident that the area has potential for future ground motion related damage due to the liquefiable sandy soils, and the deep, soft soils of the area significantly increase damage potential (Chapman et al., 2003). This low-level seismicity combined with paleoliquefaction evidence suggests an earthquake similar to the M=6.9-7.3 earthquake of 1886 will reoccur within 500 to 600 years (Talwani and Schaeffer, 2001).

Field et al. (2001) discusses the variability of shaking intensity and damage to life and property in adjacent locations although they are equidistance from the ruptured fault. Researchers studied differences in ground softness (softer sedimentary soil as in valleys versus hard, crystalline rock in mountains) and correlated ground hardness to the amount of shaking during an earthquake. They noted that stronger shaking occurs in softer soils because seismic waves move slower through softer soils. The researchers reported that the softness of surface rocks and surrounding soil, as well as the thickness of the layer of sediments over bedrock, directly affected the amount and amplification of shaking during an earthquake (Field et al., 2001). In the Charleston area, shallow geological structures are impacted by incoming seismic motion, which thereby affects earthquake ground motion (Jaumé et al., 2005).

Data sampling of P and S-wave data was conducted as a transect of southeastern orientation through the Atlantic Coastal Plain by Odum et.al (2003). The geological strata became younger as transect moved to the southeast. Sedimentary deposits made the majority of the sample units. As reported by Odum et.al (2003) the data concluded that actual values ranged from NEHRP E to NEHRP C soils.

> Seismic refraction/reflection techniques produced S-wave data down to depths ranging from 30 to 80 m and identified in most cases two or three distinct velocity layers. ……At all sites

> (except the U.S. Highway 17 site where a substantial thickness of artificial fill is sampled), the upper most V_1 layer is interpreted to represent weathered (developed soil horizons) and transitional strength lithologies. Collectively V_1 layer thickness ranged from approximately 6.5 to 22 m and showed a velocity range of 125 m/s (artificial fill) to 367 m/s (upper Cretaceous Tuscaloosa Fm.). Excluding the Carolina Slate Group site (Lake Murray spillway), the overall average S-wave V_1 layer velocity is 225 m/s. For sites where the V_1 layer thickness was greater than 12 m, the V_1 layer played a dominant role in determining the NEHRP soil profile type classification regardless of the underlying V_2 layer velocity. This was especially evident at the Deep Creek site (Peedee Formation-Upper Cretaceous) where a NEHRP classification of “D” was determined even though the interpreted V2 layer velocity was 710 m/s.
>
> Odum et.al, 2003

1.5 Liquefaction

Liquefaction causes damage during an earthquake and is a phenomenon resulting from the relationship between ground shaking and the solid and liquid states of a specific porous soil. Although liquefaction is a form of ground failure it is related to the ground shaking responses that the NEHRP soils classification provides. It can occur in both saturated and partially saturated soils. Liquefaction is the loss of strength and stiffness that occurs when the effective stress between the grains of the soil is reduced (Liyanathirana and Poulos, 2002). Important in the role of liquefaction is the saturation of the soil. It has been shown that as saturation decreases, the liquefaction potential decreases. Conversely, as saturation increases, so does the liquefaction potential. This is due to the difference in the pore water pressures in saturated versus unsaturated soil (Bian, 2008). Liquefaction susceptibility of the soil is influenced by the size, permeability, and consistency of soil particles; by the duration of and amplification of shaking caused by an earthquake; and is directly affected by the height of the water table (Table 2) (HAZUS-MH Technical Manual, 2007). Liquefaction begins with deformation and consolidation of the soil leading to decreased pore space. This in turn increases pore pressure within the soil, which decreases the shear stress that the grains of soil can withstand due to a loss of effective stress. This leads to the changes in the elastic moduli of the soil, which converts to increased deformation of the soil (Snieder and van de Beukel, 2004).

Based on a simulation of the 1886 Charleston earthquake with an estimated magnitude of M_w 7.3, Juang and Li (2007) determined that the calculated liquefaction potential for the Charleston area could be as high 98% probability. This area could suffer severe to moderate effects of liquefaction. However this estimate does not agree with Dutton, who in 1889 reported only six craterlets of liquefaction. Three theories may explain the discrepancy. They are that the M_w may be elevated, a potential deficiency may exist in the cone penetration tests (CPT), or that soil age may influence liquefaction resistance above that of penetration resistance. However Juang and Li (2007) concluded that if a parameter of $M_w = 6.9$ was used for the 1886 earthquake, the liquefaction events would be consistent with that reported by Dutton. Another factor to consider is the likelihood of unstudied manifestations of the liquefaction events, which could have occurred as a result of the 1886 Charleston earthquake.

In 1996, Obermeier stated that liquefaction occurs only when sediment is thoroughly saturated. A part of the liquefaction problem in Charleston involves the groundwater surface (also referred to in literature as water table) elevation. Andrus and Fairbanks (2005) estimated the groundwater table in Charleston as only 1.5 m below the surface. The variability of groundwater surface estimates range from about 1 m to 3 m (Obermeier, 1996). Liquefaction is directly related to the local groundwater level. When the water table is higher, there is a greater chance of liquefaction. Accordingly, the lower the groundwater surface, the less chance of liquefaction. A small decrease in the groundwater level of several meters can decrease liquefaction susceptibility from high to low. Even seasonal changes in groundwater levels can effect liquefaction. Obermeier (1996) determined that in some cases (e.g. San Fernando Valley) a higher groundwater surface could increase liquefaction susceptibility. He stated that an earthquake with a magnitude of about 6.5 would produce the same amount of damage as an earthquake with a magnitude of 8 in a moderately susceptible environment having a lower groundwater surface (Obermeier, 1996).

Shear stress, due to the proliferation of cyclic shear waves during an earthquake, causes an increase of pore water pressure which in turn causes liquefaction of saturated, cohesionless sediments. These loosely packed sediments such as sand are compacted by cyclic shearing that triggers the pore-water pressure to suddenly intensify and leads to large strains and flows of both water and sediment (Obermeier, 1996). The soils are generally made up of random mixtures of minerals that form a porous media. When the sediments are saturated, the pores are full of fluid. A change in orientation can lead to a decrease in porosity of the sediment and inversely cause a rise in the fluid pressure in the pores. The result is that the sediment, which was once solid, now behaves as a heavily viscous liquid leading to structure damage (Figure 4) (Zeghal and Shamy, 2008). This shows that the surficial geology and soil conditions of an area are important in ascertaining the potential for liquefaction, which in this study is used as a proxy for developing an enhanced NEHRP soil classification. Drainage of the material may mitigate the extent of liquefaction by decreasing pore pressure (Snieder and van de Beukel, 2004). A well drained soil will have a lower liquefaction potential, because there is less moisture present in the pore spaces. When flowing water applies enough force to lift or separate grains of sand, fluidization, or liquefaction, happens (Obermeier, 1996). The development of hot springs, stream flows, and liquefaction has occurred in previously dry river beds; indicating that earthquakes may affect the water content and may lead to an increased permeability of the soils, which leads to surface expression of liquefaction (Wang, 2007).

Sitharam and Anbazhagan (2007) reported that liquefaction susceptibility, as established by soil's intrinsic resistance to deformation, is determined by how much seismic energy is necessary to trigger liquefaction. They believe that two main factors influence this process, thereby increasing susceptibility of soil to liquefaction. These two factors are sand layers of less than 20 m thick, and a groundwater surface (water table) of less than 10 m beneath the ground surface. Preliminary research shows that the study area for this thesis meets these qualifiers, and that these factors could affect the liquefaction potential in the Charleston area.

Another important factor for the development of a liquefaction proxy model is that of the age of the study unit. As suggested in Arango et al. (2000), the age of a unit may be more of a deciding factor than even the depth of the groundwater surface. Obermeier (1996) proposed that a soil sample in the Eastern United States with an age greater than 250,000 years is at a significantly lower risk of liquefaction potential. Soils younger than this are less likely to have experienced bonding between the sediment grains, therefore increasing the susceptibility of destabilization due to liquefaction. At the lower end of the age spectrum are surface units that are 80,000 years old or younger. These features are at a significantly greater risk of liquefaction, due to the relatively high groundwater surface (ground water table). For sediments that fall within the endpoint age ranges the water table depth is of much greater significance. The age ranges for the geology units study ranges from the Holocene 0-12 ka (thousand) to the Oligocene (30 ma). The surface soils of the study area primarily fall within the lower ranges of the spectrum (less than 250ka) (Juang and Li (2007). For this study, the interaction of age and groundwater surface depth is of significant consideration when the NEHRP classifications were being created.

1.6 National Earthquake Hazards Reduction Program (NEHRP)

NEHRP's purpose is to mitigate losses due to earthquakes by using research from the fields of earthquake science and engineering. The program has integrated seismological, geophysical, and geological research into maps that show national seismic hazards, as well as quantifying possible ground motion events. NEHRP has been successful in the development and implementation of guidelines directed to improve current and new construction, as well as updating building codes (NEHRP Strategic Plan, 2003). The program has four main goals:

A. Develop effective practices and policies for earthquake loss-reduction and accelerate their implementation.
B. Improve techniques to reduce seismic vulnerability of facilities and systems.
C. Improve seismic hazards identification and risk-assessment methods and their use.
D. Improve the understanding of earthquakes and their effects. (NEHRP Strategic Plan, 2003, p1).

Understanding the potential hazards due to an earthquake in the region of study requires a familiarity with what happens when an earthquake occurs. A primary factor in this study is on the effects of shear wave propagation through surface soils and geology. Shear wave seismic velocity (Vs), located in the first 30 to 60 m of the earth's surface, can have a significant impact on the amplification and duration of ground motion during earthquakes. NEHRP relies on near-surface seismic velocities as an important component in assigning soil classification values as related to significant shallow Vs values.

The accuracy of current HAZUS-MH maps may be scrutinized as related to the current NEHRP data. This standardized data is based on soil amplification factors of average shear wave velocity measured in the first 30 m of soil (HAZUS MH MR-III Technical Manual, 2007). Although shear wave velocity is an accepted criterion for classifying soil, problems exist in Charleston with using this data in predicting liquefaction in earthquakes. The problem is twofold. The currently available data do not represent the unique soil and surface geology characteristics of the Charleston Peninsula, because they are too generalized. Also, they do not consider the hydrologic influence of the shallow water table in Charleston. The models developed in this study clarify these issues and begin the corrective process by integrating more accurate data into the HAZUS-MH program to aid with better land use planning, community planning, and hazards mitigation.

2.0 Methodology

2.1 Study Area

The study area for this project is Charleston County, South Carolina. The county is located on the South Carolina Coastal Plain (SCCP), which is part of the Atlantic Coastal Plain (ACP). The study was done at the county scale, due to the belief that the highest resolution information will yield the best results (Figure 5). Also, the study region (especially the City of Charleston) was heavily damaged by a magnitude 7.3 earthquake on August 31, 1886. Earthquake events have been documented in South Carolina since 1698. Seventy percent of these are located in the Middleton Place - Summerville Seismic Zone (MPSSZ), which is located 30 kilometers northwest of the City of Charleston. This area is important, because 137 earthquakes were recorded in the MPSSZ from 1996 through 2003.

2.2 The Modeling Environment

2.2.1 Software

The majority of data analysis and modification was completed electronically. Three software programs were primarily used. They are ESRI's ArcGIS, FEMA's HAZUS-MH MR-III, and the MINITAB V.15 statistical software program. ArcGIS is a Geographic Information System (GIS) program used to layer spatial information and develop data from the layers. ArcGIS was be used to create data tables and to visually represent aspects of the data. HAZUS-MH MR-III is a program used by FEMA and other disaster management agencies to help assess the impact of a potential disaster scenario on an area. The program is a run as an additional layer in ESRI's ArcGIS software.

2.2.2 HAZUS

To initialize a HAZUS scenario, multiple factors must be chosen in order to run a model. When using HAZUS, the user inputs specific data parameters into the program in the forms of a GIS layers to develop a model of a potential disaster situation and scenario reports. A user guide automatically opens to help the user create a scenario when running the software. Also, detailed step by step instructions for creating a scenario can be found in the HAZUS-MH MR-III User Manual (2007).   The reports can be generated as a complete global report or in quick summary reports. For this project, surface geology and soils information for the Charleston area were used. Three magnitudes were run for all data model types. They were M_w 5.3, M_w 6.3 and M_w 7.3. These magnitudes were established by the South Carolina Emergency Management Division (SCEMD, 2001) study for seismic hazards. They represent possible reoccurrence events for scenarios similar to the 1886 Charleston earthquake.

2.2.3 ArcGIS

Integral to this study was the assessment of potential damage that could occur in the Charleston area as related to NEHRP soil classification. Current surface maps appear to be inadequate in their representation of the damage potential. Maps highlighting the actual soil characteristics were created in ESRI's Arc Map using literature information and the information from the HAZUS scenario. Maps of the surface features were generated using shear wave velocity, surface type, age of the unit, and the depth to water table. Also, after the HAZUS scenarios were completed, maps showing the differences between the soil data sets were constructed.

2.2.4 MINITAB

Version 15 of the software was used to determine the descriptive statistics for the Geology, SSURGO, and STATSGO data sets to aid in classification. The values desired from the descriptive statistics were the first order standard deviations for all data types. The standard deviations were used to establish a range in the data for classification.

2.3 Data Acquired

2.3.1 South Carolina Emergency Management Division (SCEMD)

The SCEMD (2001) data set contained the information necessary to complete the baseline data run. These data were comprised of the current statewide NEHRP classification for South Carolina (Figure 1). This NEHRP classification was used as the base comparison for all enhanced models.

2.3.2 USGS Geology

A United States Geological Survey (USGS) 1:24,000 detailed Digital Geologic Map of the Greater Charleston region was used as the geologic base data. This map and data were provided as provisional data to the College of Charleston by the USGS. The 1:24,000 scale geologic maps have formation and age information that make them suitable for this analysis (Figure 6).

2.3.3 NRCS SSURGO

This data set is used for detailed surface soils for the Charleston area. The Soil Survey Geographic (SSURGO) database is the Natural Resources Conservation Service (NRCS) data set used for local (farm, city, county) level soil information. Mapping scales for this data type range from 1:12,000 to 1:63,000. The file used for this project is at a 1:20,000 scale (Figure 5).

2.3.4 NRCS STATSGO

State Soil Geographic (STATSGO) is the data set that is the regional database for the NRCS. This contains soil information on a larger (county, state, regional) scale (1:250,000) and is not as detailed as the SSURGO data (Figure 5). This information will be used to investigate the effect of scale on the data set. This will help to determine if the STATSGO level information is suitable or if SSURGO level information is necessary at a state-wide scale for use in the HAZUS scenario.

2.3.5 Borehole Data

The Chapman et al. (2003) data is the primary data source for shear wave velocity from borehole sites. This data contains information pertaining geographic location and shear wave velocity. The data set comes in three measurement methods, and contains a total of 281 borehole sites. The methods are the seismic cone penetrometer test (SCPT), the cone penetration test (CPT) and the standard penetration test (SPT). The data was collected by engineering firms performing site evaluations for construction. The shear wave velocities for the data were derived from the 52 SCPT boreholes. Some of the geographic coordinates for data points from the Chapman et al. (2003) do not match the physical location of the engineering sites. Jaumé et al. (2005) has rectified the points used in this study. There are a total of 26 sites that were either reclassified or added. The rectified sites were used instead of the Chapman et al. (2003) sites for those locations. In order to complete the project, the data was clipped in ArcGIS to fit Charleston County, thereby eliminating a total of 40 borehole points (Figure 6) that were outside of the county.

2.4 Data Storage Preparation

To facilitate proper data management, a series of directories and Personal Geodatabases were created to aid in file management. A main file directory was created for the entire project, which contained sub-directories for each model type (SSURGO, USGS Geology, STATSGO). The specific model type directory contained the data directories of the original data, as well as geodatabases used for storage of the enhanced data.

2.5 Coordinate System and Geodatabase Feature Class Creation

In order for the models to be completed and incorporated into the HAZUS simulations, preprocessing was required for all of the enhanced data sets (USGS Geology, SSURGO and STATSGO). The first step was reprojecting the data into the proper coordinate system, as well as conversion into a Geodatabase Feature Classes from the original Shapefile format. For data to be incorporated into HAZUS, the coordinate system must be that of GCS North American 1983 (GCS NAD 83), as well as being in Geodatabase Feature Classes. The base data layers were loaded into ESRI's ArcMap. The data layers were individually exported. The desired format was achieved by exporting the coordinate system of the data frame (GCS NAD 83) and by using the dropdown menu when specifying the storage location and data type. This process was used to export the layers as a "file and personal geodatabase feature class", and store them in the proper model type of personal geodatabase. Another preprocessing step was to clip all data feature classes to the HAZUS study area boundary of Charleston County. This was accomplished using the "Clip" tool in ArcToolbox. The final processing step was to alter the data attribute table to match the format necessary for a successful scenario run. The final table format and column properties are shown in (Figure 7). Once the layers had been modified to conform to HAZUS protocols, it was possible to proceed to enhancement of the data.

2.6 Incorporation of Shear Wave Values (Vs) Data

2.6.1 Shear Wave Velocity Borehole Creation

The first step in assigning the Vs data was through the creation of a unified set of borehole points, which was used to assign Vs values to the data surface types. There were two series of borehole data sets. The data sets used were created by Chapman et al. (2003) and Jaumé et al. (2005). There were a total of four point feature classes for the two data sets. It was necessary to first merge the three (SCPT, CPT & SPT) Chapman et al. (2003) data sets into one point feature class. This was accomplished by using the "Merge" tool found in ArcToolbox. The final step was to add the data table into the current map and to reproject the data as "xy" data in the proper coordinate system. This resulted in a completed, map-selectable version of the Chapman et al. (2003) data. The next step was to incorporate the corrected latitude and longitude for specific boreholes collected by Jaumé et al. (2005). There were a total of 267 borehole points contained in the study area, which were used for the development of Vs values for the surface feature types.

2.6.2 Joining the Borehole Vs Data with the Surface Feature Types

The method used to incorporate the borehole derived Vs data was to spatially join them to the individual surface layers. This method was chosen because it would assign Vs values to the surface feature polygons by using the geospatial location of borehole site point features. Of specific concern for this process was the incorporation of point feature class data (Borehole) into polygon feature class data (USGS, SSURGO, and STATSGO). Spatial join was used to connect the borehole data to the soil and geographic map data. This type of join uses the spatial (x, y, z) location of the different data types. This study consisted of two data geometry types. They were the polygon map unit data, and the point borehole data. The original Vs values were only present in the borehole point data. Spatial join assigned the Vs values from the borehole point data set to the polygons of the soil and geologic data sets. In order to assign a Vs value to the polygon data, the information contained in the individual boreholes would have to be assigned to polygons. When completing the initial pre-processing, it was found that not every polygon of the map unit contained a borehole inside of the map unit (Figure 8). Polygons that did not have borehole data assigned to them were populated by one of two methods. If data existed for that particular polygon class, the Vs values were averaged and missing values received the average Vs values (Figure 9). If a polygon did not have a corresponding Vs value attached at any point or at any other corresponding polygon, it was left as null. The result of this process was that all of the map unit types contained Vs values. In order to create an enhanced model, the yearly average depth to water table was also incorporated into the surface data layers. It is important to note that this process results in an averaged value for the Vs data. The result is that for each map unit type, there will be a different averaged Vs value.

2.7 Incorporation of Depth to Water Table Information

2.7.1 NRCS Soil Data Viewer Tool

The yearly mean depth to water table was created using the Soil Data Viewer Tool (SDV Tool) developed by the NRCS. This tool was developed to be used in conjunction with ESRI’s ArcMap GIS platform. The SDV Tool allows the user to develop maps and reports of the soil features using the components and attributes of the soil database provided by the NRCS. More detailed information about this tool can be found at the NRCS soil database site (http://soildataviewer.nrcs.usda.gov/). In this study, the soil data sets were SSURGO and STATSGO. A map layer is created by opening the SDV Tool inside of ArcMap, and specifying the database from where the soil data originates. This allows for the tool to open a list of features to map based upon the databases attribute tables. For this study, the yearly mean depth to water table

(DTWTBL) was chosen as the feature to be mapped. The tool generated a map layer for each surface soil type.

It is important to note that a DTWTBL data layer was not available for the USGS Surface Geology data set, because it did not contain the required database attribute tables. The DTWTBL layer used for the surface geology was that of the SSURGO layer. This was chosen as a proxy due to the similar scale ratios of the two data sets (USGS Geology is 1:24000 and the NRCS SSURGO is 1:20000). The reason the same DTWTBL data layer was not used for all surface feature types is because of the large disparity of mapping scales between the more detailed data sets; mainly the USGS (1:24000) & SSURGO (1:20000) and the less detailed STATSGO (1:250000) data set.

The proper DTWTBL data layer was joined to the proper surface feature layer through the same method used to join the borehole Vs data. The exception is that this was a join of polygon to polygon feature classes. Instead of a point assigning a value, a polygon was assigning a value to another polygon. The join could have been accomplished by using the “Spatial Join” tool in the “Overlay” toolset of the “Analysis Tools” in ArcToolbox, but a singular method for the joining data was preferred over multiple separate methodologies.

2.8 Model Development

There were four models used in this study that were input into the HAZUS scenarios. Of the four, three were the enhanced data created in this study, and one was based on the SCEMD (2001) study.

2.8.1 SCEMD Baseline Model

This model was designed around the data used in the SCEMD (2001) *Comprehensive Seismic Risk and Vulnerability Study for the State of South Carolina*. This report lists three earthquake scenarios that were used to model potential damages of a Charleston area earthquake. The scenarios were created to model the behavior of events similar to the 1886 Charleston earthquake. The scenarios were for magnitude 7.3, 6.3 and 5.3 earthquakes (SCEMD, 2001). The data used by the SCEMD was a South Carolina statewide NEHRP soils rating layer. This original SCEMD layer was used as the baseline model to be compared to the enhanced models developed by this thesis research. The SCEMD data was clipped in ArcGIS to the HAZUS scenario boundary. It served as a control with which to compare the data generated through the enhancement of the surface features and incorporation into the HAZUS scenarios.

2.8.2 USGS Geology Model

The USGS Surface Geology model was created in order to facilitate a NEHRP classification based on the surface geology for the Charleston area. After the data had been set up by incorporating the borehole Vs and DTWTBL data, it was necessary to process it further in order develop a NEHRP soils classification. There were two models developed for the geology data set. They were the Vs to marl depth (VsMRL) and the site response (SR) models. Tables 3 & 4 are a listing of USGS Geology properties used in both the VsMRL and SR methodologies.

2.8.2.1 USGS Geology VsMRL Method

The VsMRL model type was created using only the average Vs to the interface between the surface geology and the marl. This interface depth varied from 4 m to 26 m as derived from the borehole data. Creation of the model was accomplished using the "Selection" and "Field Calculator" features in ArcMap. The first task was to assign a Vs value to each individual geologic map unit types. The attribute table column of interest was that of "Map_Unit." This was the listing of the 28 units listed in the study area. The VsMRL process was accomplished by first selecting the desired "Map_Unit". The next step was to use the "Statistics" function to determine the average VsMRL for the desired "Map_Unit" type. This average Vs was then entered into a spreadsheet. These processes were repeated for each "Map_Unit" type until all 28 were assigned an average VsMRL. In the spreadsheet, a column was created to assign the NEHRP rating for VsMRL. The NEHRP rating was assigned by whether the average Vs met the 1997 NEHRP revision Vs rating. The cut off for an "E" rating was at 180 m/s (HAZUS MH MR-III Technical Manual, 2007). Any Vs value less than 180 m/s was listed as "E", where any value greater retained a "D" rating. The result was that five of the "Map_Unit" types were re-classified as NEHRP "E" soils. The remaining 23 remained NEHRP "D" soils.

After the classification spreadsheet was created it was necessary to create a field in the USGS Geology attribute table, labeled "NEHRP_Type." The field properties were defined in order to replicate the attribute table in the baseline data. Once the field had been created, a "Map_Unit" type was selected and the "NEHRP_Type" was assigned the corresponding NEHRP value using the “Field Calculator” tool. A final processing step was necessary in order for the model type to be incorporated into a HAZUS scenario. Microsoft Access was used to modify the attribute table to correspond to the necessary HAZUS input. At this point the VsMRL model type was ready to be incorporated into the HAZUS scenario.

2.8.2.2 USGS Geology SR Method

The SR model type required the development of a logic model in order to develop the NEHRP classifications (Table 4). The factors included in this classification process were average Vs to marl interface, age, and the depth to water table for the geologic unit. The VsMRL process was used as the basis for this process, and all average Vs to marl values were used. There were six columns created in the geology SR spread sheet. They contained information concerning map unit name, average VsMRL, average DTWTBL, age of the unit, standard deviation of the average VsMRL, and the final SR NEHRP classification.

Research was conducted in order to develop the methodology for this process. No method was described in any research explicitly stating a method for NEHRP reclassification. However, there was research pertaining to the development of liquefaction potential models. This liquefaction research was used as a proxy to develop a NEHRP reclassification methodology. The primary factor for reclassification was determined to be that of the average Vs velocity for the unit (Andrus and Fairbanks, 2005; Chapman et al., 2003). Primarily used was the Vs to 30 m method. As stated previously, this method over generalizes the soils in a sample Vs profile. For this research, the VsMRL method was used for the Vs velocities. The secondary reclassification factor was that of the age of the geologic unit. As suggested in Obermeier (1996), Juang and Li (2007), and Arango et al (2000), the age of a unit may be more important in determining stability than the depth to water table. The age of the sample is important for two reasons. The first is that the older samples have undergone a greater level of compaction and settling, and therefore the amount of pore space has decreased. This reduces the susceptibility to liquefaction. The second aspect of age is in the possibility of grain cementation. The older samples are believed to have experienced a greater degree of inter-grain cementation, which reduces the susceptibility to liquefaction. The third factor for classification was that of the average depth to water table. For this method, the cut off depth was one meter beneath the ground surface. Different literature references use a depth from one to three meters below the ground surface as a factor of liquefaction. In the study area the average maximum water surface depth below ground surface is 1.5 meters. If a larger value for depth below ground surface were used (2-3 m), then all of the average mean depth to water table values would be included, and therefore would be able to be reclassified. This was established from the data from Obermeier (1996), and Gassman et al (2002).

It was necessary to develop an initial limiting standard to be met in order for reclassification to proceed. This initial standard was the first order standard deviation of the 28 unit VsMRLs velocities. This was calculated using MINITAB Version 15. The value was determined to be + or - 24m/s, with a Vs range of 156 m/s to 204 m/s. Only geologic units that fell within this range were available to be reclassified. There were 17 units that fell within the range (Table 3). Once the standard had been met, it was possible to proceed to reclassifying the geologic unit (Table 3). An immediate classification of "E" was assigned if the unit was less than 80,000 years old. An immediate classification of "D" was assigned if the unit was older than 250,000 years old. This range was established from the research of Obermeier (1996), Juang and Li (2007), and Arango et al (2000). If a unit fell between these ranges, it was necessary to proceed to the next step. The research of Obermeier (1996), and Gassman et al (2002), indicates that if the mean yearly depth to water table is between 1 and 3 m, then the sample would be prone to liquefaction. For the SR method, a 1 m cut off was used in order to be more conservative in the estimation of the hazard potential. If the unit's DTWTBL was greater than 1 m, then it retained a "D" NEHRP rating. If the DTWTBL was less than 1 m, then it was reclassified as an "E" soil. Once all geologic units had been assigned a NEHRP rating, it was necessary to edit the attribute table. The attribute table was created similarly to the VsMRL method where the "Selection" and "Field Calculator" functions were used to assign the NEHRP rating. Once the attribute table had been completed, the Geology SR model type was input into a HAZUS scenario.

2.8.3 NRCS Soil Models

The NRCS SSURGO and STATSGO models were created in order to facilitate a NEHRP classification based on the surface soil characteristics for the Charleston County study area. After the data had been set up by incorporating the borehole Vs and DTWTBL data, it was necessary to process it further to develop a NEHRP soils classification. A characteristic difference between the USGS Geology and NRCS Soil models was the way the models were developed. In the geology classification, the attribute table “MAP_Unit” was the column selected for comparison. The attribute column selected for the soil models was that of “taxclname”. This column contains the information about a soils specific taxonomic classification. A taxonomic classification is based on 6 basic categories, which are Order; Suborder; Great Group; Subgroup; Family and Series (Buol et al., 2003). The categories are arranged from less descriptive to more descriptive. The “taxclname” field is a combination of the “subgroup and family” properties of the individual soils. This resulted in a detailed description of soil properties, including particle size, moisture content, soil horizon and reaction potential. By using this as the NEHRP classification field for the NRCS soil datasets, a like comparison was possible even though the mapping scales were greatly different. This comparison was necessary to determine if the mapping scale impacted the scenario outcome.

Specifically of interest was whether the overgeneralization of the lager mapping scale would show significant differences in the resultant data generation. The reason for this difference between the soil method and the one used for the geology models was that the geology unit name is based solely on the description of the unit type for geology. The soil unit name describes not only use the soil composition, but includes locality variation. For the SSURGO and STATSGO soils, they may be of the same composition, but do not have the same common name. The taxonomic description speaks to the pedogenesis of the soil, while the common name also includes other properties that are due to local variations in specific compositions and textures. An example is that there are two SSURGO soils with different map unit names, Cg (CAPERS SILTY CLAY LOAM) & TF (TIDAL MARSH, FIRM). However, they are of the same taxonomic class name (Typic Sulfaquents, fine, mixed, nonacid, thermic). There is a similar example in the

STATSGO data set, S6703 (Capers-Bohicket) & S6702 (Pungo-Levy-Handsboro-Capers). These are both Typic Sulfaquents, fine, mixed, nonacid, thermic. There is no correlation within a specific soil data set, and there is no commonality across the soil data sets. The result was that for the soil classifications, it was necessary to use the Soil Taxonomic Class Name (Table 5 and Table 6). This allowed for a comparison between the soil data sets.

To accomplish this, additional processing steps were required of the soil data sets. The process was the same for both the SSURGO and STATSGO data sets. Two data tables were joined to each soil data set. These joins had to be carried out in a specific order to the "Fields" used for the join process. In ArcMap the soil layer was selected using the right click function. The menu option of "Join" was selected. This join process differs from the "Spatial Join" used previously, in that the join was not constructed on a georeferenced location, but by using the field properties of the data attribute table. The first join was made using the "mukey" field in soil data set and "component" tables. The result was a soil data table containing the original data fields as well as the new fields acquired from the "component" table. The next join was based on the "cokey" field shared by the "component" and "chorizon" data tables. This order was necessary due to the lack of "cokey' field in the original soil data set. By first joining with the "component" table the soil data set was able to acquire the data fields form the "chorizon" table. With these joins in place, the SSURGO and STATSGO soil data sets were exported into a geodatabase to permanently add the joined fields. It was through this process that the "taxclname" field was added. From this point on, the steps used for developing the VsMRL and SR models were the essentially the same except that the soil data sets used “taxclname” instead of “MAP_Unit”. Another additional difference was that due to the age of the soils falling below the 250,000 year cutoff, the age factor was discarded from the SR method (Table 7).

2.8.3.1 SSURGO Soils

2.8.3.1.1 SSURGO VsMRL Method

Once the new fields had been added to the soil data set, the process was similar to that of the geology VsMRL (see geology procedural steps listed previously). The similarities were that the NEHRP classification was made using only the average Vs value to the marl interface. This interface depth varied from 4 m to 26 m as derived from the borehole data. Once the NEHRP rating had been accomplished, the layer was modified to the necessary HAZUS format (Figure 7) and input into the scenario.

2.8.3.1.2 SSURGO SR Method

The difference between the soils and geology SR methods is due to the age of the soils falling below the 250,000 year cutoff, so the age factor was discarded from the SR method (Table 7). This means that only the VsMRL and DTWTBL were used as classification factors. The value for the first order standard deviation was determined to be + or – 19 m/s, with a Vs range of 161 to 199 m/s. Once the NEHRP rating had been accomplished, the layer was modified to the necessary HAZUS format (Figure 7) and input into the scenario.

2.8.3.2 STATSGO Soils

2.8.3.2.1 STATSGO VsMRL Method

Once the new fields had been added to the soil dataset, the process was similar to that of the geology VsMRL (See geology procedural steeps listed previously). The similarities were that the NEHRP classification was made using only the average Vs value to the marl interface. This interface depth varied from 4 to 26 m as derived from the borehole data. Once the NEHRP rating had been accomplished, the layer was modified to the necessary HAZUS format (Figure 7) and input into the scenario. Another difference is that a NEHRP classification was created for the entire statewide data set in order to examine if the methodology could be transferable to a larger data set. The statewide STATSGO NEHRP classification was created using the soil Taxonomic Order. This was used, because all map unit classification present in the clipped STATSGO data set were also present at the statewide level.

2.8.3.2.2 STATSGO SR Method

The difference between the soils and geology SR methods is that the age of the soils for all of the NRCS data types fall below the 250,000 year cutoff, so the age factor was discarded from the SR method (Table 7). This means that only the VsMRL and DTWTBL were used as classification factors. The value for the first order standard deviation of the clipped STATSGO data set was determined to be + or – 36 m/s, with a Vs range of 144 to 216 m/s. The value for the first order standard deviation of the statewide STATSGO data set was determined to be + or – 16 m/s, with a Vs range of 164 to 196 m/s. Once the NEHRP rating had been accomplished, the layer was modified to the necessary HAZUS format (Figure 7) and input into the scenario.

2.8.4 Incorporation of Data Models Into HAZUS

Before the HAZUS scenarios could be run, it was essential to check the format of the data. The first characteristic to check was that of projection. Only the projection of GCS North American 1983 can be used. Second, was to check the format of the data attribute tables. They must be in the correct order and named correctly for the run to work properly (Figure 7).

The completed data models were each run at three different magnitudes. They were at magnitudes 7.3, 6.3, and 5.3. These were based on the original SCEMD data runs. There were a total of 18 enhanced scenarios run, with 3 magnitude scenarios for each of the 6 model methods. The only factors that changed between the scenarios were the magnitudes and the NEHRP classification of the soil maps. The magnitudes variants are explained above. The soil maps defined were the model methods created previously. The process for setting up and running a scenario are listed in the HAZUS-MH MRIII User Manual (2007).

2.8.5 Representation and Comparison of HAZUS Outputs

Once HAZUS runs were completed, it was necessary to process the completed data. The first step was the representation of the hazard map and scenario map. This was accomplished by generating map layers. Another important feature of HAZUS is the automated report generation process. This is accomplished by using the report generation dialog window. There are multiple reports that can be generated. The reports chosen for this project were those of the "Global" reports. This report type contains all the other reports combined into one file. However it is important to note that in the M5.3 scenarios, there is an error in the software. For the "Debris" section of the "Global" report, all values are reported as zero. This is incorrect as there are values for the debris attribute column in the attribute table of the scenario. Reports for debris must be obtained individually by choosing the "Debris Generated" selection from the "Induced" tab of the reports dialog window.

In order to compare the enhanced scenarios to the baseline scenarios, factors for comparison had to be chosen. Factors chose in this research were the total debris generated, total building related direct economic impact, and total casualties, which was further subdivided into 2 am, 2 pm and 5 pm earthquake times. These factors were chosen as the comparison features due to both the immediately visible and long term impacts on the population of the study area.

Also chosen was the 0.3 second spectral acceleration (Sa). This is a significant analysis factor, because it represents the highly frequency shaking potential for the buildings located on the study surface. Two main types of spectral acceleration frequencies are commonly used. They are a Sa 0.3sec (High Frequency) and Sa 1.0sec (Low Frequency). The frequency is a relationship for the building types in an area. Low, stiff buildings have a greater chance of damage at a higher frequency, where as tall, flexible buildings have greater damage potential at lower frequencies. The majority of the buildings in the study area are lower buildings. Therefore the use of the Sa 0.3sec is a better estimation of locating potential building damage. A large rating signifies a greater potential for damage (Stewart et al., 2003).

3.0 Results

The results summary section will be presented for each of the models run in HAZUS. Appendix 1 contains the global report information for each of the HAZUS runs discussed in this section of the thesis. Additionally Appendix 2 will contain the entire series map unit data sets, which contain the spatially joined borehole information.

3.1 Baseline Data

The NEHRP Classification map used for the Baseline HAZUS scenarios is composed of only NEHRP “D” class units (Figure 10). The scenario results values can be seen in Table 8. The debris generated ranged from 0.279 million tons in the M 5.3 scenario to 7.00 million tons in the Mw 7.3 scenario (Figures 11c, 12c and 13c). Casualties for all time intervals ranged from 223 for the Mw 5.3 event to 16,593 for the Mw 7.3 event. The building-related economic cost was between 1.0 and 15.6 billion dollars (Figures 11b, 12b and 13b). As the magnitude of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.6086g (Figure 11a), a Mw 6.3 maximum value of 1.128g (Figure 12a), and a Mw 7.3 maximum value of 2.245g (Figure 13a).

3.2 USGS Geology

3.2.1 Geology VsMRL

The NEHRP Classification map created for use in the USGS Geology VsMRL HAZUS scenarios is composed primarily of NEHRP "D" soils (Figure 14). However, there are expressions of NEHRP "E" class soils primarily in the north central and northwestern sections of the study area (Figure 14). The resulting values for this scenario can be seen in Table 9. The debris generated ranged from 0.281million tons in the Mw 5.3 scenario to 7.00 million tons in the Mw 7.3 scenario (Figures 15c, 16c and 17c). Casualties for all time intervals ranged from 225 for the Mw 5.3 event to 16,608 for the Mw 7.3 event. The building-related economic cost was between 1.06 and 15.6 billion dollars (Figures 15b, 16b and 17b). As the magnitudes of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.768g (Figure 15a), a Mw 6.3 maximum value of 1.128g (Figure 16a), and a Mw 7.3 maximum value of 2.245g (Figure 17a). An increase in both debris generated and the building related economic visible in the maps as the magnitude increases from 5.3 to 7.3 (Figures 15 b and c, 16 b and c &17 b and c).

3.2.2 Geology Site Response

The NEHRP Classification map created using the USGS Geology SR HAZUS scenarios is primarily classified as NEHRP "E" soils (Figure 18). However, the NEHRP "D" class soils are located along the periphery the map. Clear NEHRP "D" expressions are found at the north-central, south-central and northeastern boundaries of the map (Figure 18). The resulting values from this scenario can be seen in Table 9. The debris generated ranged from 0.487 million tons in the Mw 5.3 scenario to 8.00 million tons in the Mw 7.3

scenario (Figures 19c, 20c and 21c). Casualties for all time intervals ranged from 422 for the Mw 5.3 event to 20,402 for the Mw 7.3 event. The building related economic cost was between 1.47 and 16.9 billion dollars (Figures 19b, 20b and 21b). As the magnitudes of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.818g (Figure 19a), a Mw 6.3 maximum value of 1.192g (Figure 20a), and a Mw 7.3 maximum value of 2.222g (Figure 21a). An increase in both debris generated and the building related economic cost is visible in the maps as the magnitude increases from 5.3 to 7.3 (Figures 19 b and c, 20 b and c, & 21 b and c).

3.3 NRCS SSURGO

3.3.1 SSURGO VsMRL

The NEHRP Classification map used in the NRCS SSURGO VsMRL HAZUS scenarios consist primarily of NEHRP "D" soils (Figure 22). However, there is a concentration of NEHRP "E" soils in the northwestern section of the study area (Figure 22). The scenario results values can be seen in Table 10. The debris generated ranged from 0.279 million tons in the Mw 5.3 scenario to 7.00 million tons in the Mw 7.3 scenario (Figures 23c, 24c and 25c). Casualties for all time intervals ranged from 223 for the Mw 5.3 event to 16,593 for the Mw 7.3 event. The building related economic cost was between 1.06 and 15.6 billion dollars (Figures 23b, 24b and 25b). As the magnitudes of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.720g (Figure 23a), a Mw 6.3 maximum value of 1.128g (Figure 24a), and a Mw 7.3 maximum value of 2.245g (Figure 25a). For earthquake magnitudes 5.3 to 7.3, there is an increase in the amount of both the debris generated and the building related economic cost (Figures 23 b and c, 24 b and c, & 25 b and c).

3.3.2 SSURGO Site Response

The NEHRP Classification map used for the NRCS SSURGO SR HAZUS scenarios is composed of an interlaced mix of NEHRP "D" and "E" soils throughout the study region (Figure 26). Also seen is the "D" classification for all soils within the Charleston peninsula (Figure 26). The scenario results values can be seen in Table 10. The debris generated ranged from 0.322 million tons in the Mw 5.3 scenario to 7.00 million tons in the Mw 7.3 scenario (Figures 27c, 28c and 29c). Casualties for all time intervals ranged from 267 for the Mw 5.3 event to 17,797 for the Mw 7.3 event. The building related economic cost was between 1.19 and 15.8 billion dollars Figures 27b, 28b and 29b). As the magnitudes of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.772g (Figure 27a), a Mw 6.3 maximum value of 1.128g (Figure 28a), and a Mw 7.3 maximum value of 2.245g (Figure 29a). Other trends visible in the maps are the increase of both debris generated and the building related economic cost as the magnitudes increase from 5.3 to 7.3 (Figures 27 b and c, 28 b and c & 29 b and c).

3.4 NRCS STATSGO

3.4.1 STATSGO VsMRL

The clipped NEHRP Classification map used in the NRCS STATGO VsMRL HAZUS scenarios is composed of both NEHRP "D" and "E" soils (Figure 30). The majority of the mapped soils are a NEHRP rating of "D". However, the NEHRP "E" soils are represented by discrete large regions occurring in the northern area of the map (Figure 30). The statewide NEHRP map for the NRCS SSURGO VsMRL map is entirely composed of “D” soils (Figure 31). The scenario results values can be seen in Table 11. The debris generated ranged from 0.280 million tons in the Mw 5.3 scenario to 7.00 million tons in the Mw 7.3 scenario (Figures 32c, 33c and 34c). Casualties for all time intervals ranged from 223 for the Mw 5.3 event to 16,638 for the Mw 7.3 event. The building related economic cost was between 1.06 and 15.6 billion dollars (Figures 32b, 33b and 34b). As the magnitudes of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.752g (Figure 32 a), a Mw 6.3 maximum value of 1.128g (Figure 33 a), and a Mw 7.3 maximum value of 2.245g (Figure 34 a). For earthquake magnitudes 5.3 to 7.3, there is an increase in the amount of both the debris generated and the building related economic cost (Figures 32 b and c, 33 b and c, & 34 b and c).

3.4.2 STATSGO Site Response

The clipped NEHRP Classification map used in the NRCS STATGO SR HAZUS scenarios is composed of both NEHRP “D” and “E” soils (Figure 35). The majority of the mapped soils are a NEHRP rating of “E”. However, the NEHRP “D” soils are represented by discrete large regions occurring in the northern area of the map (Figure 35). The statewide STATSGO SR data set map shows that a ”D” rating was assigned to the entire state of South Carolina (Figure 36). The debris generated ranged from 0.506 million tons in the Mw 5.3 scenario to 8.00 million tons in the Mw 7.3 scenario (Figures 37c, 38c and 39c). Casualties for all time intervals ranged from 440 for the Mw 5.3 event to 20862 for the Mw 7.3 event. The building related economic cost was between 1.52

and 17.0 billion dollars (Figures 37b, 38b and 39b). As the magnitudes of the earthquakes increase, the 0.3 second spectral acceleration intensity increases outward from the epicenter with a Mw 5.3 maximum value of 0.815g (Figure 37a), a Mw 6.3 maximum value of 1.048g (Figure 38a), and a Mw 7.3 maximum value of 2.053g (Figure 39a). Other trends visible in the maps are the increase of both debris generated and the building related economic cost as the magnitudes increase from 5.3 to 7.3 (Figures 37 b and c, 38 b and c, & 39 b and c). The scenario results values can be seen in Table 11.

4.0 Discussion

4.1 Baseline Data

The baseline data was used as the control for this study. Each of the enhanced scenarios was compared to the base line maps and tabular results to create a series of tables and figures to show relevant information. The baseline data was created using the NEHRP classification listed in the SCEMD (2001) study. This study rated the entire study region as a “D” rating. This was significant, because historical evidence and preliminary research showed that there were likely “E” soils present in the area. These baseline values resulted in a low range estimate for hazard potential in the area. This hazard potential estimate served as the baseline used for comparing the enhanced NEHRP analysis. An important difference between the SCEMD study and this research was the removal of liquefaction potential maps from the model methodology. Instead, the liquefaction potential parameters were included as a proxy values into the SR method.

4.2 USGS Geology

4.2.1 USGS VsMRL

When compared to the baseline data, there was little if any change between the baseline and USGS VsMRL data sets (Table 12). An explanation was that the USGS VsMRL map appears to overestimate the presence of NEHRP “D” soils. This overestimation resulted in HAZUS scenario output values that are similar to the baseline values. An exception was in the Mw 5.3 scenario, where there was a small increase for debris generation, 2 am casualties and 5 pm casualties. Notable is the decrease in 2 pm casualties. The fact that there are few “E” class NEHRP soils present in the map is contradictory to what would be expected logically. There should have been an increase, or at least no change in the casualties when compared to the baseline map, where all soils are NEHRP “D”. The presence of any “E” class soils, which by their nature enhance ground motion and therefore increase damage, should increase the amount of damage results. Another problem with the USGS VsMRL map is that the location of “E” soils shown on the map to not fit likely actual “E” soil locations. The location of “E” soils would likely be in areas of poor soil conditions, usually in low elevation, high groundwater surface locations like swamps and marshes, or on the margins of riverine systems. “E” soils usually present along the riverine systems vary from fluvial silt, tidal marsh deposits to beach/barrier island sand and clay facies. “D” soils tend to be composed of clean sands, barrier island sands and clayey sand facies. The majority of the “E” areas are in the upper portion of the map in higher elevation areas and away from the swamp and estuarine systems. This indicates that this map is not likely a true representation of the surface geology of the study area, as well as not being a plausible representative NEHRP map for the Charleston region.

4.2.2 USGS Site Response

The map comparison between the baseline and USGS Site Response shows that the SR map is primarily composed of “E” class NEHRP units. This map is a radical change from the USGS VsMRL enhanced map. An overestimation of “E” class soils appears to be present. This unlikely classification leads to a greater degree of damage than would likely occur. The “D” class locations are distributed around the outside regions of the map. The “D” soil locations are probably related to the presence of dune/beach ridge systems in the south-central study area. This is a likely location of “D” class soils, however there is only a limited distribution. The north central presence of “D” soils may be an impact of the underlying marl influencing the Vs profiles. When comparing the HAZUS output data a large increase in the HAZUS-MH output values is shown in these areas (Table 12). The degree of increase lessens as the earthquake magnitude increases. This may be the role of the increased amount of “E” class soils. As the 0.3 second spectral acceleration increases, the presence of a large quantity of “E” soils may have a dampening effect on the system. This could be due to the failure of soils due to the non-linear behavior of liquefiable soils. Another possible explanation may be that the rate of intensity increase is greater for the lower magnitude scenarios. This would result in a greater amount and increase of damage at the low magnitudes, but the total values between scenarios would remain similar due to the total degree of devastation present at the Mw 7.3 scenarios.

4.3 NRCS SSURGO

4.3.1 SSURGO VsMRL

“D” soils compose the majority of NEHRP soils for the SSURGO VsMRL map. There are expressions of “E” class soils, primarily localized in the western quadrant, as well as scattered “E” soils throughout the map. The similarities between the SSURGO VsMRL and baseline maps result in a negligible amount of change in the HAZUS data outputs (Table 13). The only change greater than one percent is that of the 2 am casualties for the Mw 7.3 scenario. The overestimation of NEHRP “D” soils is the cause of the similarities, and is likely a result of model error. This map is not a likely representation of the soils conditions in the study region.

4.3.2 SSURGO Site Response

The SSURGO Site Response map is composed of a well distributed amount of NEHRP “D” and “E” soils. The different soil types appear to be located in intuitively expected locations based on geologic patterns and historical data. The “E” soils tend to be located in areas of swamp/marsh as well as distributed along wetlands and backshore estuarine environments. The “D” class soils appear to be in patterns similar to beach ridge/dune systems, and in the more elevated areas. Visible in the map is the apparent system of beach ridges/dunes interlaced with estuarine depositions. This system trends from the southeast to northwest. Bisecting the dune/ridge systems are prominent riverine systems. These are located in the northwestern and southwestern half of the map. This surface soil map appears to approximate the expressions of what would be expected for the surface geology of the study area.

However, evident in the data is the likely incorrect assignment of a NEHRP “D” rating to the peninsula of Charleston. This is an error in the original dataset. There is insufficient soil data for the area due to the high density of development, which makes accurate mapping difficult. The result of the difficulty in mapping the soils is that the soils of the peninsula are classified as a null value. Historical evidence, however, shows that the area experienced liquefaction during the 1886 earthquake (Cote, 2006). There are also significant areas of man-made land or landfill throughout the peninsula (Andrus and Fairbanks, 2004 & 2005). The historical and geological information suggests that the modeling method is incorrect in the application of a categorical “D” rating to known liquefiable (“E”) soils.

When compared to the baseline HAZUS results, there is a general increase in data values (Table 13). The notable exception is that of the 2 am casualties for the Mw 7.3 earthquake, which has a seven percent decrease. This decrease may be caused by the extreme ground motion present at the 7.3 magnitude. The "E" soils present may play a role in dampening the response to the ground motion as a result of a failure of the potentially liquefiable soils. The high 0.3 second spectral accelerations (up to 2.245g) may cause the soils to fail, leading to an actual decrease of felt intensity.

4.4 NRCS STATSGO

4.4.1 STATSGO VsMRL

Both "D" and "E" class NEHRP soils are present in the STATSGO VsMRL map. The "E" soils are distributed into large, distinct groups primarily in the northern portions of the study area. There are more "E" class soils present on this map than on the NRCS SSURGO VsMRL map. A possible explanation of the greater presence of "E" class soils may be an expression of the data format of the STATSGO VsMRL map. The STATSGO data is mapped at a scale ten times greater than that of the SSURGO data. This influences the distribution of the soil groups. The greater mapping scale over generalizes the soils in the study area, which may have contributed to the greater volume of "E" soils. When comparing the SSURGO and STATSGO VsMRL maps, the location of the "E" soils of both maps are in the northern portion of the study area. The difference may be that the less detailed mapping scale of the STATSGO data magnified the presence of the NEHRP "E" soils. However, the "E" soils present do not appear to be located in the anticipated areas as described previously. The HAZUS output data shows little if any change in the amount of casualties or damage for the three magnitude scenarios (Table

14). As mentioned previously, with the incorporation of "E" class NEHRP soils into the enhanced map, it was expected to see an increase in the amount of damage or casualties resulting from the scenarios. As seen in the Statewide STATSGO VsMRL map, the entire state is classified as a "D" soil. This is erroneous, because the SCEMD (2001) report specifically says that there are "E" class soils in the upstate. A likely cause for the total "D" class is due to the limited number of borehole sites available.

4.4.2 STATSGO Site Response

When comparing the STATSGO SR enhanced map to the STATSGO VsMRL map, there appears to be a flip between "D" and "E" soils. The regions that were "D" soils in the VsMRL map are "E" class soils in the SR map. This reversal signifies a likely error in the NEHRP enhancement method used, because it is assumed that if a soil is classified as "E" based solely on Vs values, it would not be reclassified as a "D" rating using the SR method. The results of this methodology indicate that areas with an average VsMRL lower than 180m/s become more stable when incorporating the site response parameter of depth to water table. This is an unlikely possibility, since a shallow water table is known to increase the susceptibility to increased ground motion and therefore contribute to greater damage potential (Juang and Li, 2007 & Obermeier, 1996). While some of the areas classified as "E" soils in the SR map are "E" class soils, the result of the NEHRP inversion suggests a major error in the STATSGO SR method. The HAZUS output data shows a significant increase in damage and casualties for both the Mw 5.3 and Mw 6.3 scenarios (Table 14). As seen in other Mw 7.3 scenarios, there is not a large increase in values for the outputs. This is likely due to the destabilization and failure of the soils caused by the extremely high 0.3 second spectral acceleration values achieved. The Statewide STATSGO SR map, also shows that the entire state is classified as a "D" soil. This is erroneous, because the SCEMD (2001) report specifically says that there are "E" class soils in the upstate. A likely cause for the total "D" class is due to the limited number of borehole sites available.

4.5 Overall Data Trends

The HAZUS output values for the enhanced scenarios and were compared to the baseline outputs. The amount of increase, decrease or no change was plotted on charts for the comparison parameters (Debris Generation: Figure 40, 2 am Casualties: Figure 41, 2pm Casualties: Figure 42, 5 pm Casualties: Figure 43, and Total Building Related Loss: Figure 44). This data was visualized as the percent of change within the data sets. The only charts representing a negative change were of the 2 am casualties (Figure 41) and the 2 pm casualties (Figure 42). The possible causes were mentioned previously. The only scenarios exhibiting a noticeable increase were the SR scenarios, while the majority of the VsMRL scenarios exhibited little change. The lack of change among the VsMRL scenarios is interesting, because NEHRP "E" class soils are expressed in all of the enhanced maps. It was expected that even the limited presence would affect an increase in disaster modeling outcomes.

Few scenarios even exhibited a greater than one percent increase. This suggests that only using the VsMRL method does not have a significant effect on disaster modeling and does not appear to be a significant improvement over the Vs to 30m method currently in use. When viewing the SR scenarios a different trend can be seen.

The majority of the SR scenarios (with the exception of SSURGO Mw 7.3 scenarios) experience a consistent increase. Also of importance was the degree of percent increase experienced by the scenarios. The lower magnitude scenarios express a greater intensity of increase throughout the data parameters. This trend was not expected. An increase was expected to grow from the lower magnitude to the higher magnitude scenarios. A possible reason for the inverse effect could be that as the magnitude, and therefore ground shaking intensity increased, a dampening effect was happing in the soils (Stewart, 2003). This dampening effect could actually decrease the perceived damage to the induced failure of the "E" class soils. As the soils failed, the transfer of non-linear energy waves would decrease, thereby lessening the percent increase effect of the larger magnitude events. This is most visible in the SSURGO SR scenarios. Due to the more even distribution and balance of "D" and "E" class soils, this model has the least degree of damage potential increase.

A factor also important to consider is the role of maximum damage potential. Essentially, there is only a specific amount of destruction that could occur in the study region (the difference between minimal, moderate, and complete). As the magnitude of the scenario events increased, they began to approach the maximum threshold for damage potential (complete devastation). This could explain why the intensity of the percent change was a decreasing percent change downward trend, instead of an increasing percent change upward trend.

4.6 Model Limitations

While conducting the research, limitations and errors became evident in several general areas. There were limitations and errors in the data sets used, the methods developed, as well as the software/programs used. There two primary types of data used were borehole and map unit data. The borehole data contained information about the shear wave velocities and depths to the marl. The map unit data consisted of the USGS and SSURGO data sets. A significant limitation in the borehole data was that the majority of the Vs values were derive from only a few actual Vs value determinations. This extrapolation of Vs values is inherently prone to error due to not actually having the Vs profile for all boreholes. This became evident in the methodology used to join the borehole data to the map unit data, which will be discussed later. The map unit data was limited by the different scales used to map the units as well as the different types of units mapped. When comparing the geology data to the surface soil data, a type to type comparison could not be made, because the geology and soils data was developed using different mapping properties (Geology map units versus the Soils taxonomic class name). The relationship had to be established using the geospatial location of the units available. The different mapping scales led to an error in the relationship of the geospatial data. The detailed SSURGO (1:20000) and USGS (1:24000) date did not compare well to the coarse STATSGO (1:250000) data. This is evident in the data used to create the NEHRP maps. The STATSGO data over generalized the soils in the study area.

Another problem present in the soil data sets was that of the urbanized Charleston peninsula. There was little information developed for the Charleston peninsula, because of the building and population density. The soil surveys listed null values, which contributed to a categorical rating for the peninsula. Historical evidence, however, shows that this area was heavily damaged during the 1886 earthquake (Cote, 2006). Also known on the peninsula are areas of potentially liquefiable soils. When comparing the enhanced data to the historical data, the enhanced data does not match the known regions of liquefaction potential, which is used as an indicator of strong ground motion (Andrus and Fairbanks, 2004 & 2005). These data set limitations contributed to errors in the methodology used to classify the NEHRP soils.

The methodology was developed to apply a uniform series of steps to the data involved to produce a repeatable series of steps that are then used to develop the enhanced NEHRP maps. Due to the differences in data sets used, the use of a single method contributed to the skewing of final data product. A primary limitation was on the combination of the borehole Vs data and the map unit data. When performing the initial join between the borehole data and the USGS Geology map data, it was found that the geologic unit types do not spatially correlate. The result was that the geologic information contained in the original borehole data did not correlate with the USGS geologic information at the same site. This map layer discrepancy may have contributed to the assignment of an incorrect Vs value for the USGS map units.

Issues were also present in both the USGS and NRCS joins necessary in the GIS program. In order to join the borehole data and the map data, the average Vs value was assigned to map unit polygons that did not originally contain borehole Vs data. The series of polygons for a specific unit type (USGS=Qal) were averaged to determine the Vs value for that type. During the original creation of the enhanced maps, the standard deviation of the averaged values was used to determine NEHRP SR soil type. This resulted in an error in part of the implementation of the methodology. The Standard Deviation of the VsMRL that was used was based on the average of an averaged table. To correct this error, the standard deviations were re-run for the entire dataset, and then the half standard deviation of the total record set was used and compared to that of the previous method. The result was a series of corrected NEHRP maps created using the standard deviation of the total record series USGS Geology shows a 3% change with the corrected model (Figure 45), NRCS SSURGO shows a 25% change (Figure 46), NRCS STATSGO Clipped shows a 6% change (Figure 47), and STATSGO Statewide shows a 24% change (Figure 48). The changes between the original method and corrected method can be seen in the map figures for each NEHRP SR type. Tables showing the map units affected were also created. Four geologic units are affected (Table 15) in the USGS data. There are seventeen changes in the SSURGO data set (Table 16). Four changes occur in the STATSGO data set (Table 17). In the STATSGO Statewide data set, there are five changes (Table 18).

Final limitations for this project are those present in the tools used to accomplish the research. This research relied heavily on the use of computer software programs to assist in model creation and analysis. During the course of using these products, specific issues were discovered. The program used for the disaster modeling (HAZUS-MH MR III) contributed a few important limitations. A major limitation was that the minimum magnitude that can be used for scenarios is a Mw 5.0 event. This eliminated the possibility of using any recent events in the study region. A second limitation was that only a point source could be used for the origin/epicenter of the scenario event, while most large Charleston earthquakes have a linear source. Other issues arose from how the final data results were generated. Some of the hazard output data numbers were rounded by the software (debris generation for Mw 6.3 and 7.3 scenarios). Also, the global report function always describes the debris generation for the Mw 5.3 events as zero tons. The individual report must be generated for each scenario to determine the actual estimates of debris generation.

4.7 Future Considerations

Future application of this research would be focused on applying the knowledge learned to develop a more precise method for combining the different data sets. An important step would be in collecting a larger number of actual Vs measurements instead of extrapolating values from a limited number of known sites. In addition to developing a large borehole database, a site rectification study would be beneficial to determine what surface geology and surface soils are actually present in the study region. A comparison of enhanced data to known effects of the 1886 Charleston earthquake would be beneficial in better determining the accuracy of the enhancement methodologies and the initial data sets used. An important aspect of any comparison would be the incorporation of liquefaction probability data into the future methodology. This research study used liquefaction potential parameters as a proxy in order to determine the SR method. While it was important to the study, liquefaction potential maps were not actually generated.

5.0 Conclusions

The goal of this research project was to investigate NEHRP soil rating re-classification using presently available data to better understand the possible future impacts of earthquake events in the Charleston area. There were four primary data sets used in this project. They were Borehole Shear Wave Velocity Values, USGS Surface Geology map units, NRCS SSURGO surface soil map units and NRCS STATSGO surface soil units. The study was completed in four sections. The first was to develop a methodology for incorporating seismic shear wave velocity data into current surface geology and soils layers for the study region. The second part was using this methodology for the development of models to be incorporated into the HAZUS analysis environment. These models were the development of a base model for comparison (Baseline) based on previous SCEMD research; a model based on USGS surface geology for the study area; a model using NRCS SSURGO surface soils; and a model developed with the use of NRCS STATSGO surface soils. Third was the incorporation of the models into the HAZUS modeling environment. The fourth and final portion of the project was to analyze the developed model results and make a comparison to the baseline data in order to understand the effects of the different methodologies on determining enhanced NEHRP soil classifications.

The past seismic history of the area illustrates the relevancy of the study area. Previous research has shown that the Charleston region has been susceptible to and will likely be affected by future seismic events (Jaumé et al. 2005). Important to the assessment of possible damage potential areas was the NEHRP soil classification ratings. These provisions are used to approximate the potential of soil amplification for a specific site during a seismic event. Low-quality ("E") soils amplify (enhance) the ground motion effects during an earthquake, thereby contributing to a greater amount of damage. This project developed a series of maps that showed the possible locations of "E" soils in the Charleston area, which were then used in hazard estimation modeling.

The project incorporated many different aspects for creating the enhanced maps and in generation hazard analysis. Surface geology and soils units were combined with borehole derived Vs data to produce data sets that resulted in two types of enhanced NEHRP data. They were the Average Vs to Marl Interface (VsMRL) and the Site Response Method (SR). The VsMRL method was created using only the average Vs to the surface unit/marl boundary. The majority of current research is focused only on the Vs to 30 m boundary. In the study region setting, this is impractical. An impedance contrast is present between the soft overlying surface features and the harder underlying Cooper Marl. It was believed that this harder unit influenced the Vs by increasing the average 30 m velocity. The average depth to marl for the study area ranges from 4 to 26 meters as derived from the borehole data. The higher Vs values of the marl would overcompensate for the lower surface units. This is why the VsMRL was developed. Also, research shows that Vs alone may not be the best method for assessing hazard potential (Obermeier, 1996). Important factors include the age of the unit studied as well as the groundwater surface depth of the study region (Arango et al., 2000). These factors were included into the SR method for the three map unit data sets, as well as the STATSGO statewide data set. The completed enhanced NEHRP SR classification maps for USGS Geology (Figure 45 a, b and c), NRCS SSURGO (Figure 46 a, b and c), NRCS STATSGO Clipped (Figure 47 a, b and c) and NRCS STATSGO Statewide (Figure 48 a, b and c) show the original SR classification, new SR classification as well as the areas that experienced change. After the enhanced maps were created, they were incorporated in to HAZUS for disaster modeling.

The VsMRL and SR methods were applied to the three map unit types resulting in eighteen enhanced maps. Also used were three baseline maps created using information from the SCEMD study. This study suggested that three magnitudes be used. A magnitude 5.3, 6.3 and 7.3 earthquake scenario was used for each enhanced map and the three baseline scenarios. This resulted in twenty-one hazard potential scenarios. The scenario output information was compared between the enhanced scenarios and the baseline scenarios to determine hazard potential and trends resulting from the incorporation of the enhanced NEHRP maps. The output parameters chosen were the total debris generated, total building-related direct economic impact, total casualties (further subdivided by 2 am, 2 pm and 5pm), and 0.3 second spectral acceleration (Sa 0.3). The factors were chosen due to their importance to hazards estimation and planning, as well as to illustrate the effects of the seismic events on the human environment.

The output results illustrated several important trends. The first was that the VsMRL scenarios resulted in very similar values when compared to the baseline data. There was usually less than a one percent change. This is important for two reasons. First, it shows that the VsMRL NEHRP assignment does not achieve a significantly better approximation of the soil conditions of the area. Second, was that the minor addition of “E” class values did not induce a sizeable increase in damage potential. The second trend was noticed in the SR method. When looking at the change between the baseline and SR data, several things become apparent. First is that that there is a significant increase in damage values for the majority of the SR scenarios. Second is that as the magnitude of the earthquake increases, the percent increase of the damage output data decreases. This suggests two things. First is that there may be a maximum damage potential for the area, and that the rate of approach of this potential is more pronounced in the lower magnitude scenarios. This is likely that the degree of damage that can be generated is limited to the amount of materials present in the study area. The greatest magnitude events (Mw 7.3) approach this value regardless of the NEHRP rating. This is important, because lower level seismic events are more likely to occur, and the damage increase seen in the SR method allows planners to better prepare for the hazard. The study concludes that the SR method may better approximate the conditions present in the Charleston study area. Historical evidence and previous research support the presence of increased damage potential soils in the area. Past evidence of liquefaction shows that there are likely “E” class NEHRP soils present in the study area (Andrus and Fairbanks, 2004 & 2005).

There are multiple future applications of this project. First would be of a comparison of the enhanced NEHRP maps to the damages experienced during the 1886 Charleston earthquake. A second application would be in the incorporation of liquefaction potential maps for hazard analysis. This research used liquefaction potential as a proxy component in the SR methodology. A final application would be in the development of models using recent seismic events in the Charleston region. Currently HAZUS only allows for a minimum event magnitude of 5.0. This project was used to develop an understanding of a NEHRP soil rating re-classification using presently available data.

Enhancing NEHRP classifications for the study region enhanced the results of the HAZUS analysis of the region. The SSURGO soils data was the most useful data set for creating enhanced NEHRP soils classifications in this region. This same technique should also be applicable to other regions on the Atlantic Coastal Plain and most likely will yield superior results across South Carolina. The SSURGO VsMRL method yielded only a slight increase in HAZUS damage results for the region, where as the SR method produced a significant increase in these same results. Since the historic information about damage and liquefaction is best represented by the SSURGO Site Response Map, the changes in the damage calculations are reflective of a better model for NERHP soil response. These data are important, because they shows the impact of site specific versus regional application of the NEHRP provisions and suggests SSURGO level information and associated methodologies should be implemented in HAZUS earthquake analysis. This will make the HAZUS earthquake analysis more useful to emergency planners in the event of an actual earthquake.

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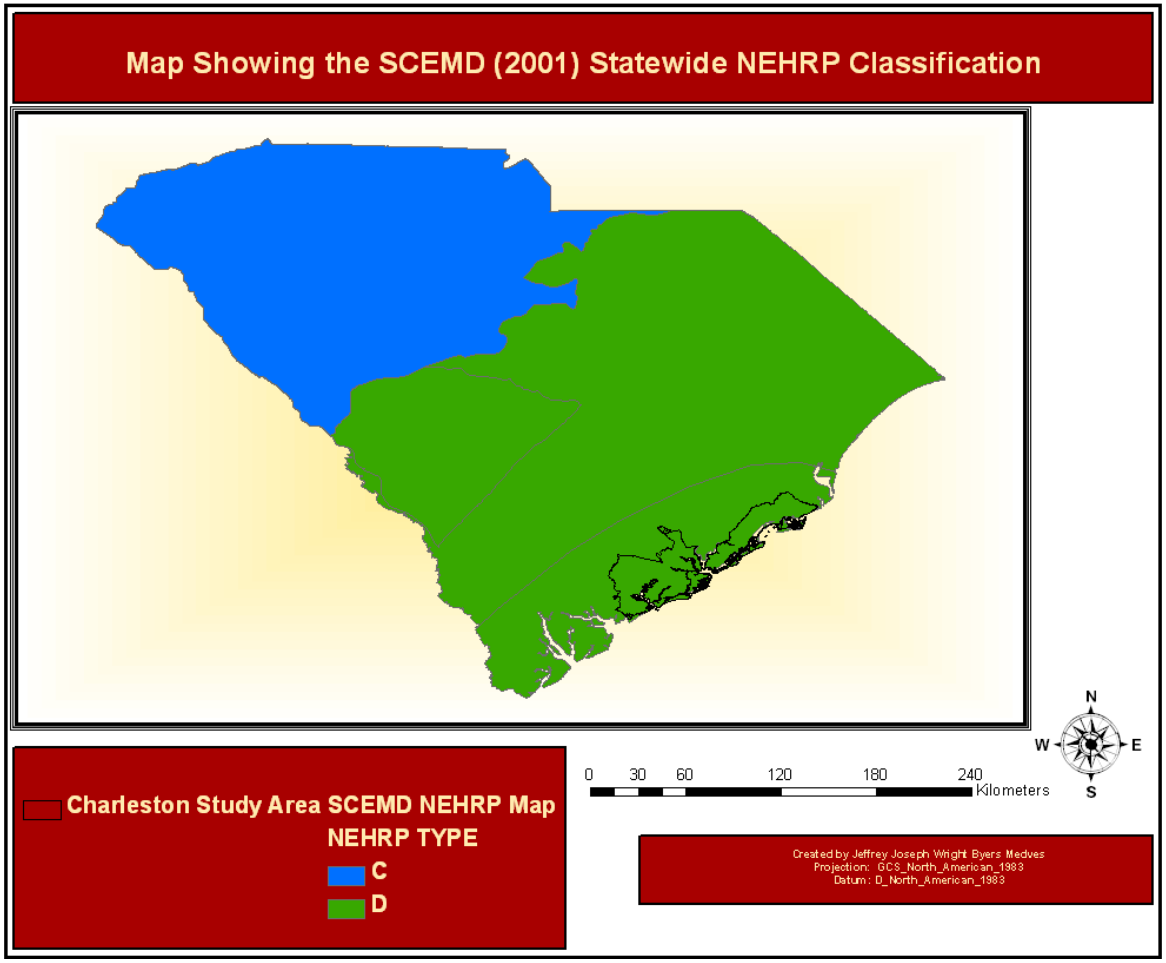


Figure 1 Map showing the statewide NEHRP classifications, as derived from the SCEMD (2001) study. The study region is signified by the black outline in the southeast area of the map.

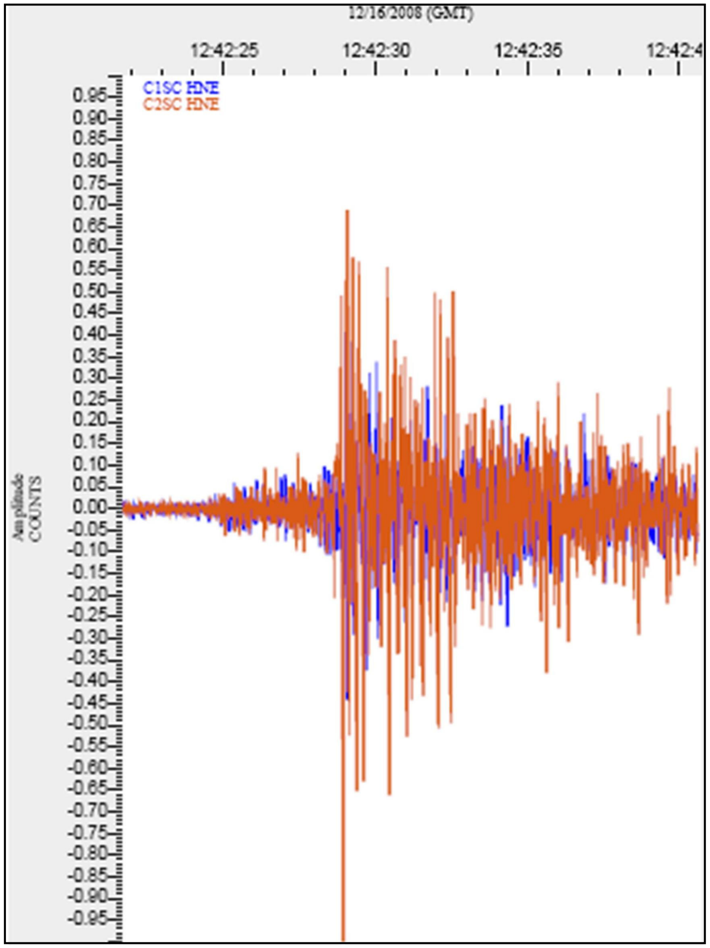


Figure 2 Graph showing the amplitude of ground motion waves from the M 3.6 Charleston Earthquake of 16/16/2008.   This figure indicates that the amplitude is magnified in C2SC HNE (orange) which are “E” Class NEHRP soils, where as C1SC HNE (blue) are “D” class soils.

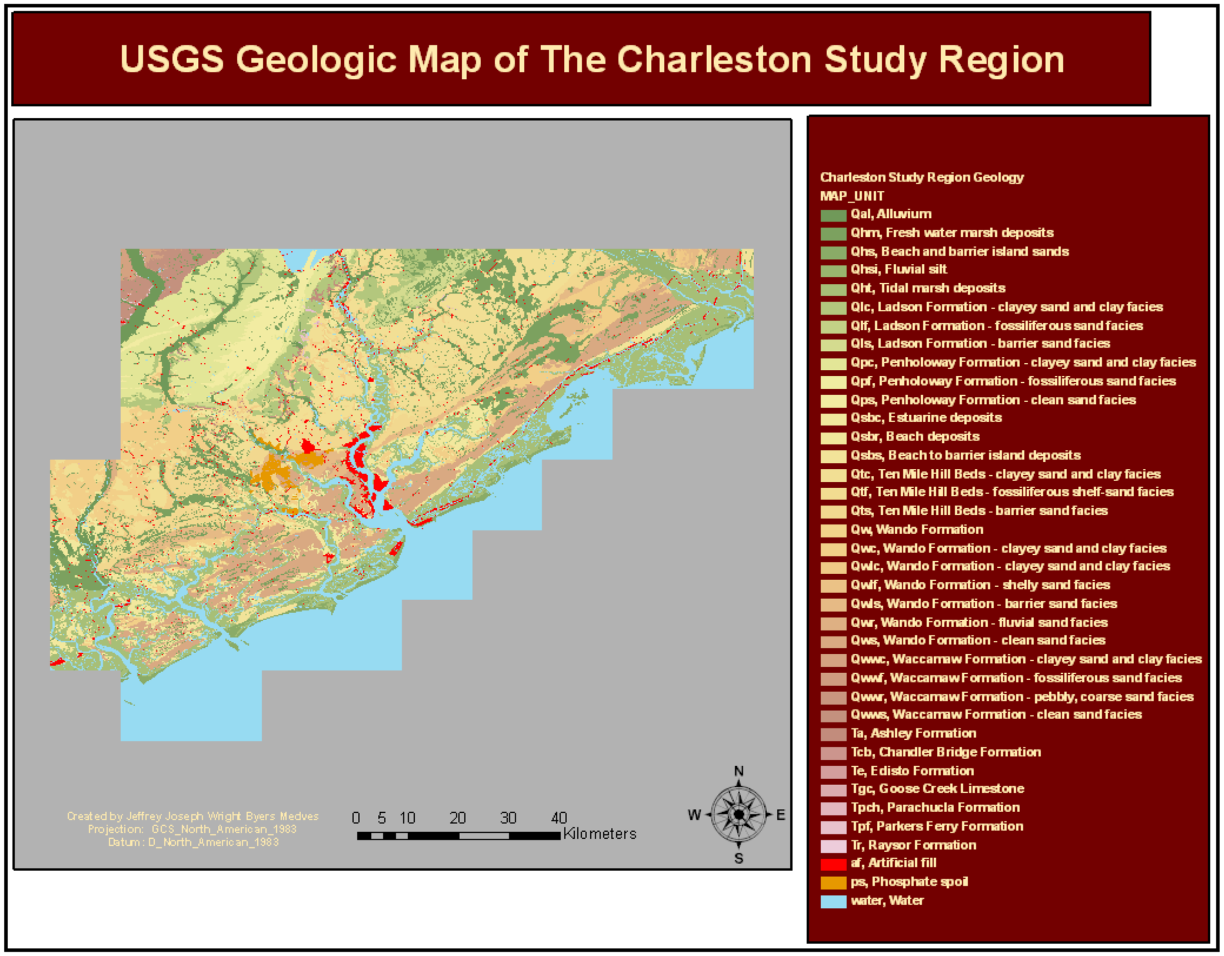


Figure 3 Shows the USGS Geologic units for the study area.

The particular units of interest are the “af” (In Red) and “ps” (In Orange).

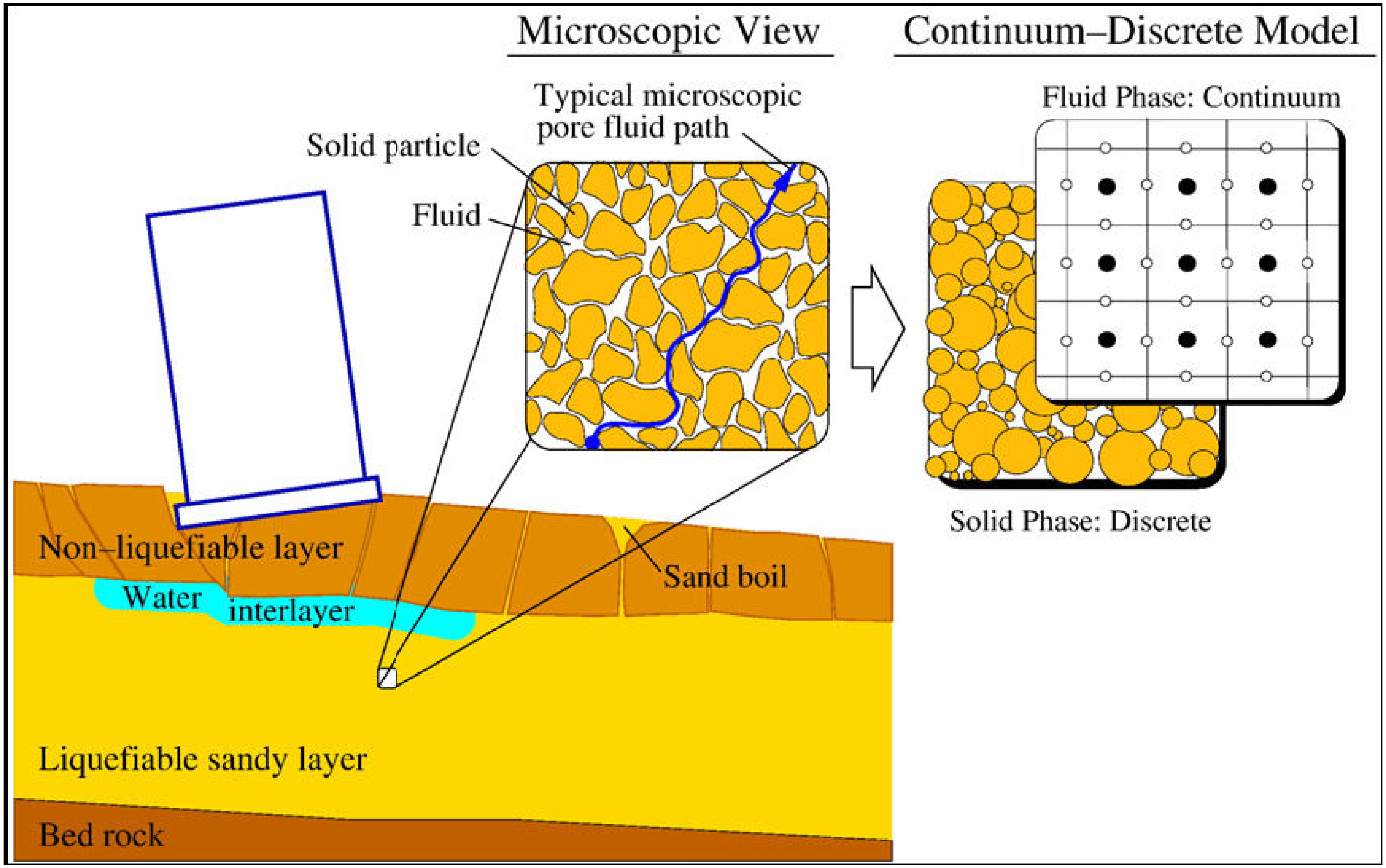


Figure 4 Illustration of the effects of liquefaction on the movement of fluid between soil grains; from Zeghal and Shamy, 2008

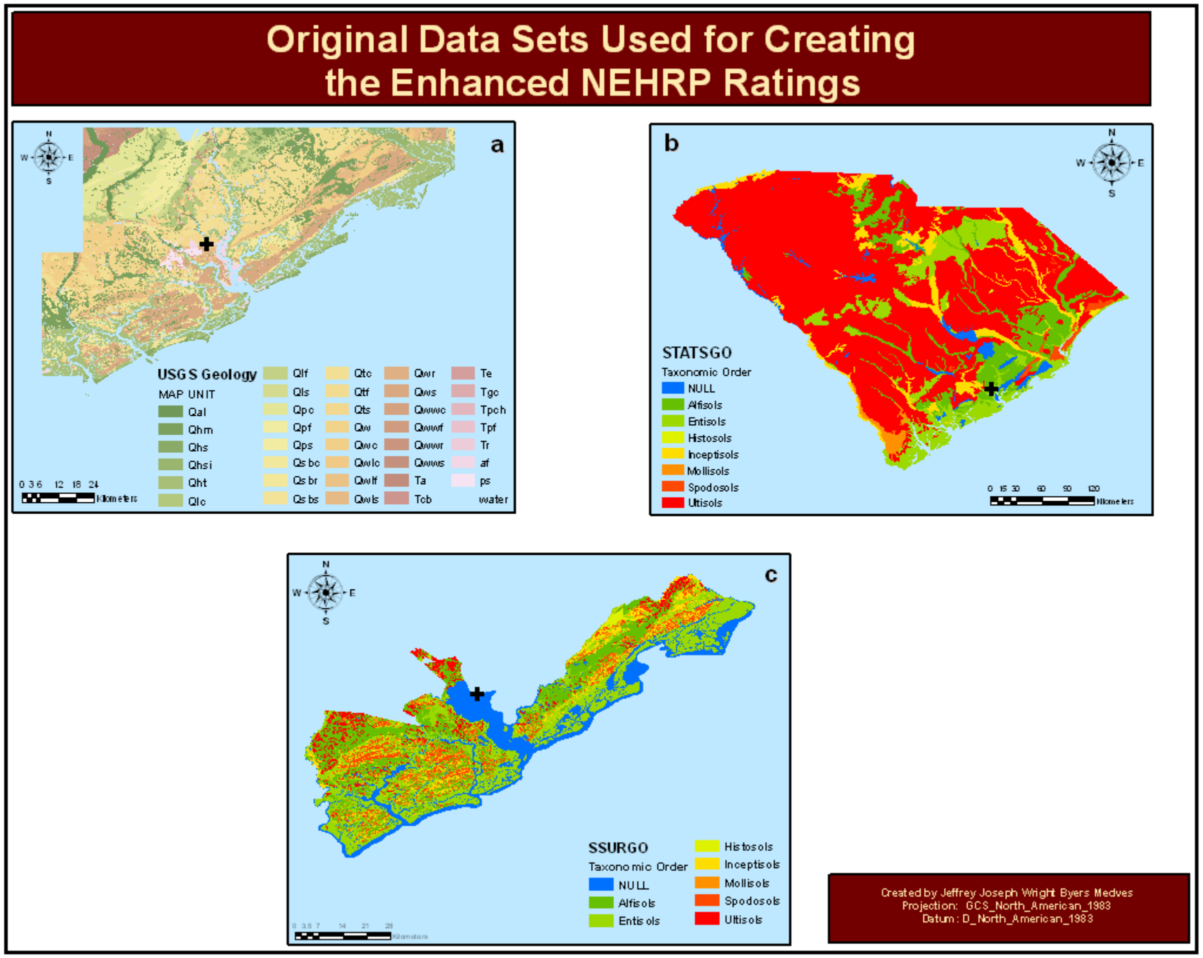
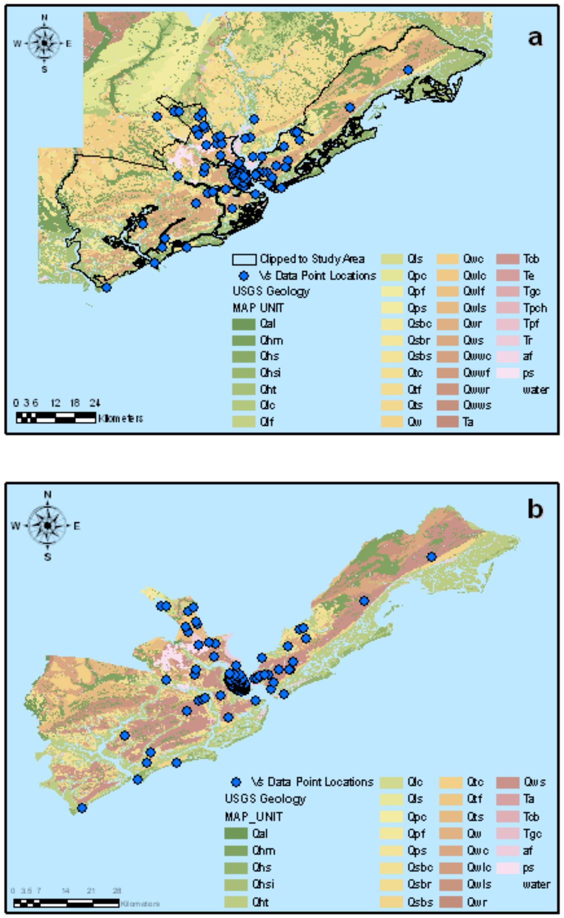


Figure 5 Illustration of the original data sets used for the project.

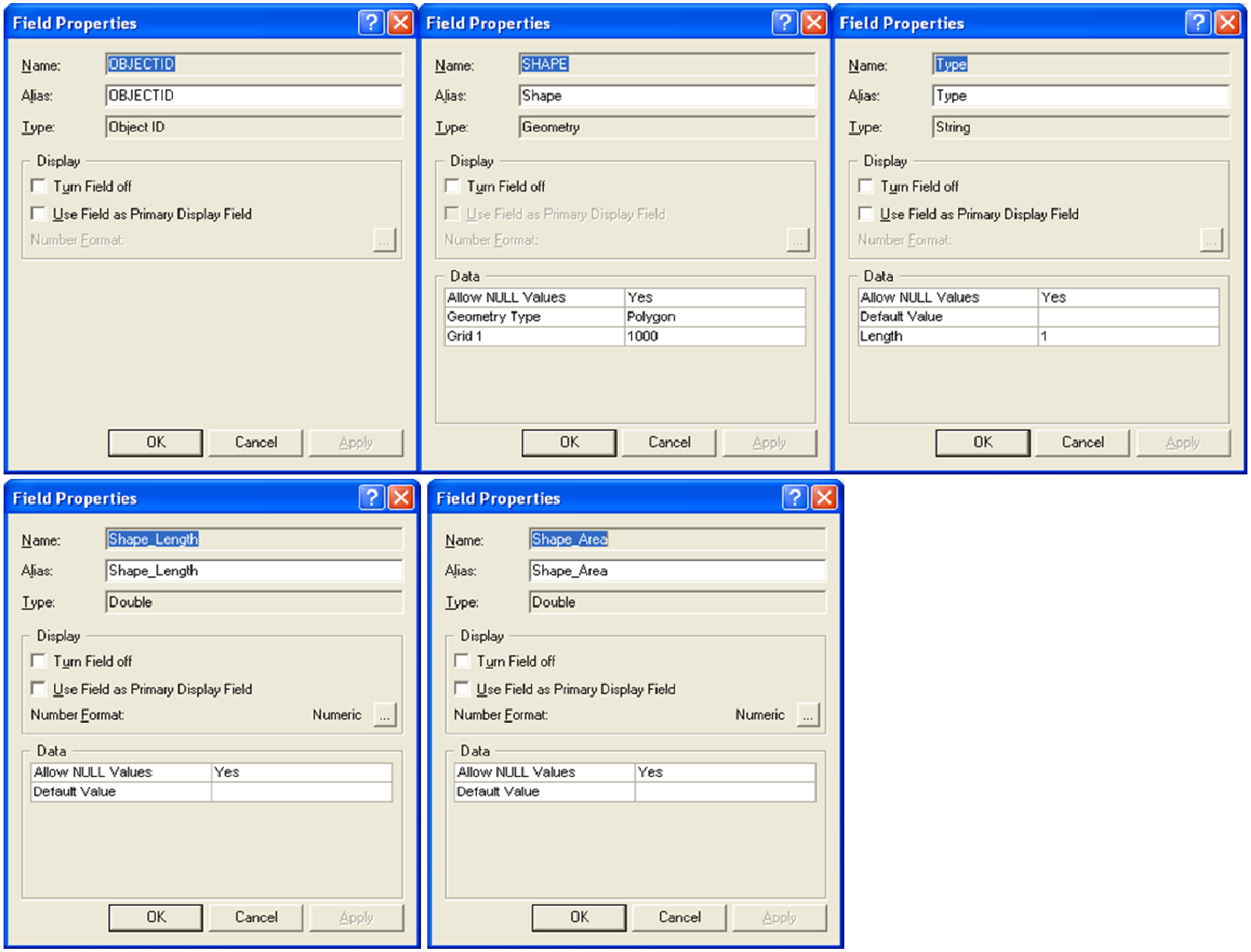
The USGS Geologic data is shown in (a), NRCS STATSGO shown in (b), and NRCS SSURGO shown in (c).

Vs Data Points shown in the Original and Clipped USGS Geologic Maps



Created by Jeffrey Joseph Wright Byers Medves
Projection: GCS_North_American_1983
Datum: D_North_American_1983

Figure 6 Representation of the location of the original borehole sites relative to the USGS Geologic data.



Name: OBJECTID
Alias: OBJECTID
Type: Object ID
Display
☐ Turn Field off
☐ Use Field as Primary Display Field
Number Format:

Name: SHAPE
Alias: Shape
Type: Geometry
Display
☐ Turn Field off
☐ Use Field as Primary Display Field
Number Format:
Data

Allow NULL Values	Yes
Geometry Type	Polygon
Grid 1	1000

Name: Type
Alias: Type
Type: String
Display
☐ Turn Field off
☐ Use Field as Primary Display Field
Number Format:
Data

Allow NULL Values	Yes
Default Value	
Length	1

Name: Shape_Length
Alias: Shape_Length
Type: Double
Display
☐ Turn Field off
☐ Use Field as Primary Display Field
Number Format: Numeric
Data

Allow NULL Values	Yes
Default Value	

Name: Shape_Area
Alias: Shape_Area
Type: Double
Display
☐ Turn Field off
☐ Use Field as Primary Display Field
Number Format: Numeric
Data

Allow NULL Values	Yes
Default Value	

Figure 7 Field property formats necessary for the data sets to e incorporated into the HAZUS-MH modeling environment.

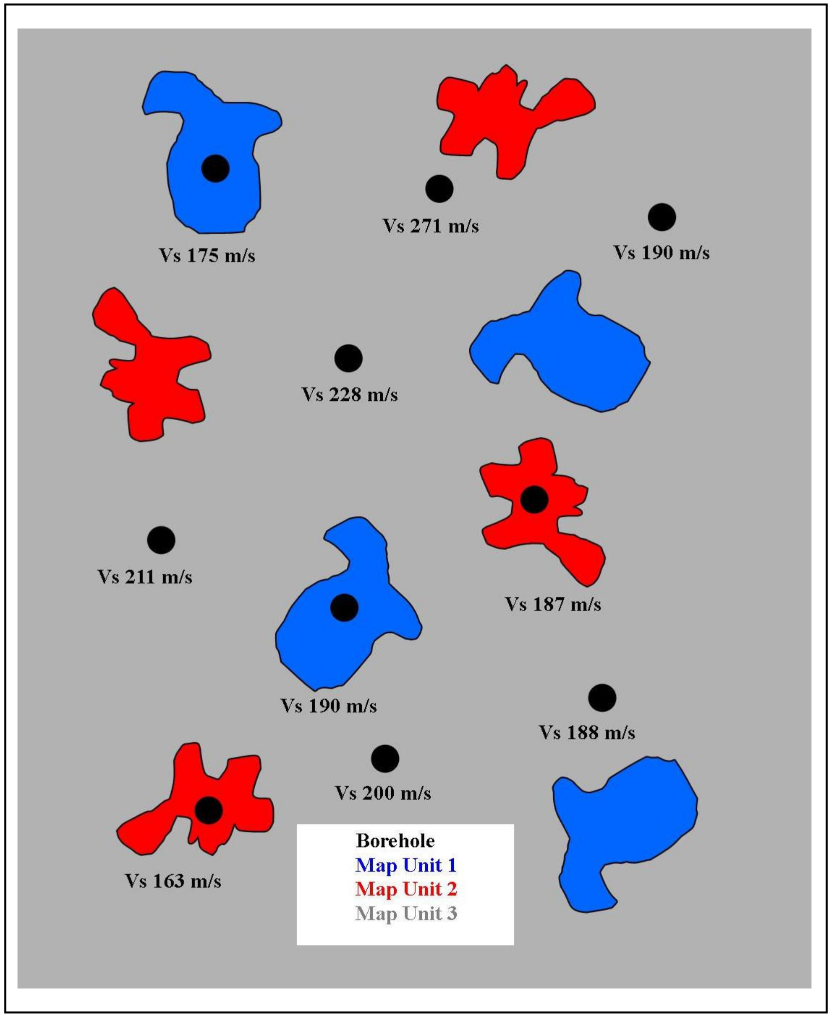


Figure 8 This figure illustrates the original data conditions present after the initial spatial join. Some of the map unit data type contain borehole information, and therefore are assigned a Vs value. However, some map units do not have borehole data and therefore do not have a Vs value assigned. Also present are the borehole that are outside of the individual polygons.

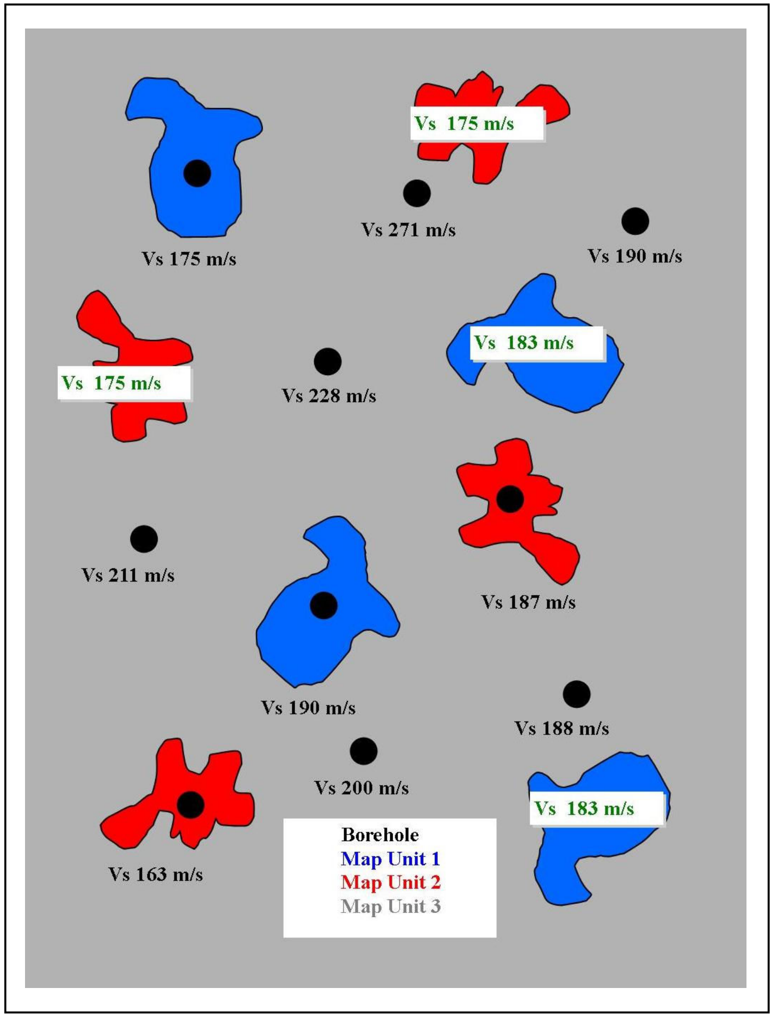


Figure 9 This figure illustrates the result of the spatial join, where all of the map unit polygons have been assigned Vs values. The Vs value assigned to each polygon is an average of all of the Vs values for boreholes that fall within that map unit type, except where the map unit had an original Vs value.

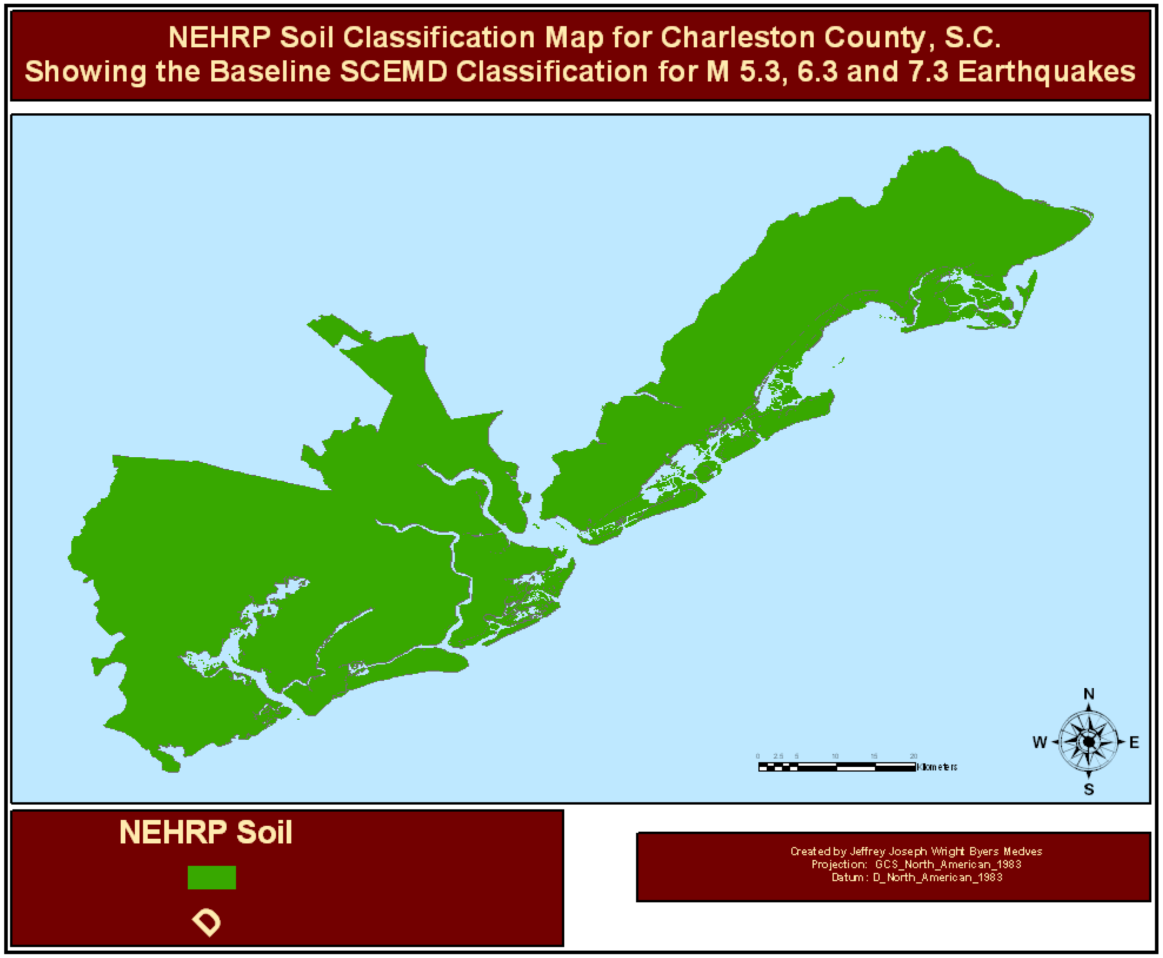


Figure 10 Baseline NEHRP classification for the Charleston study region, where the whole region is a “D” soil.

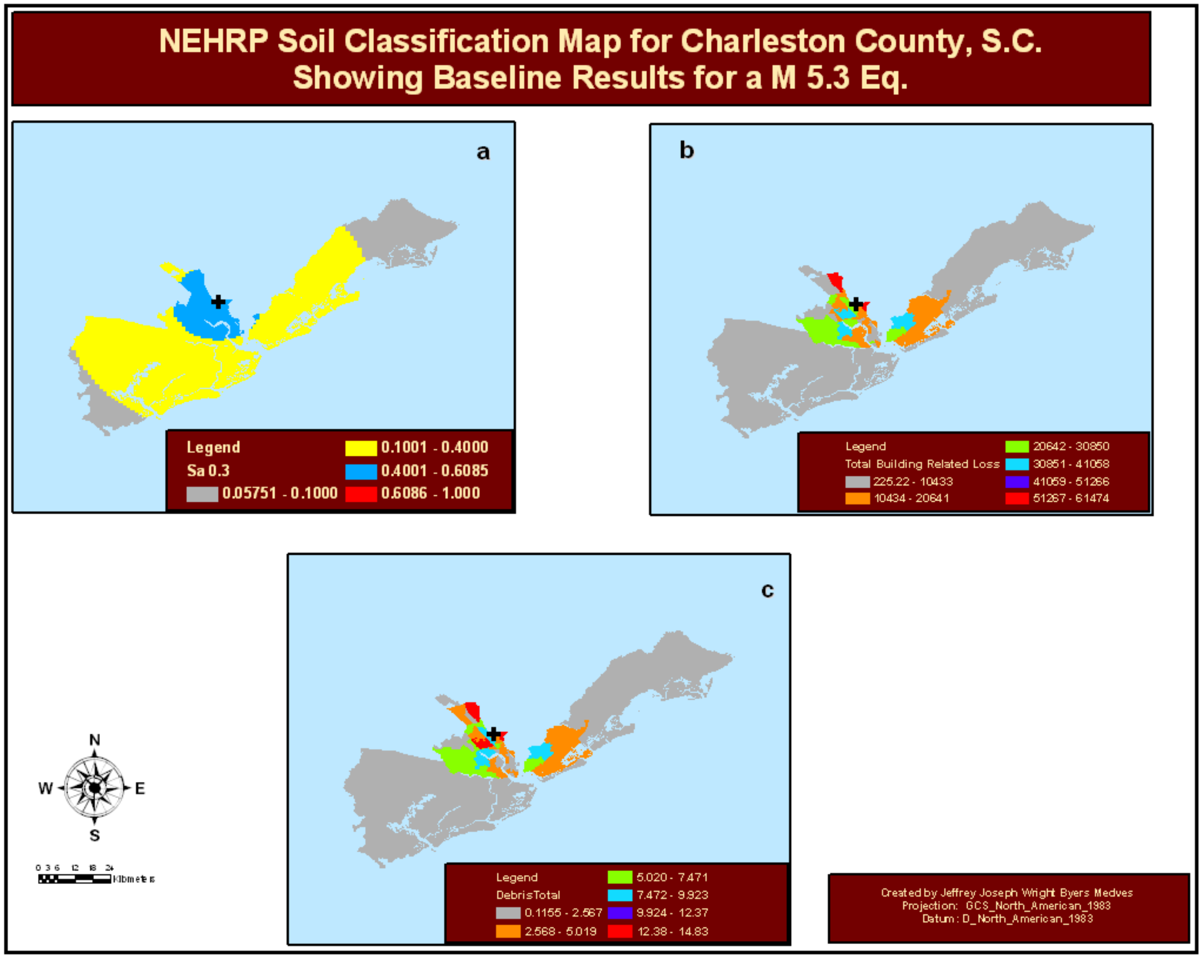


Figure 11 Figure showing the results of HAZUS-MH modeling for the Baseline M 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

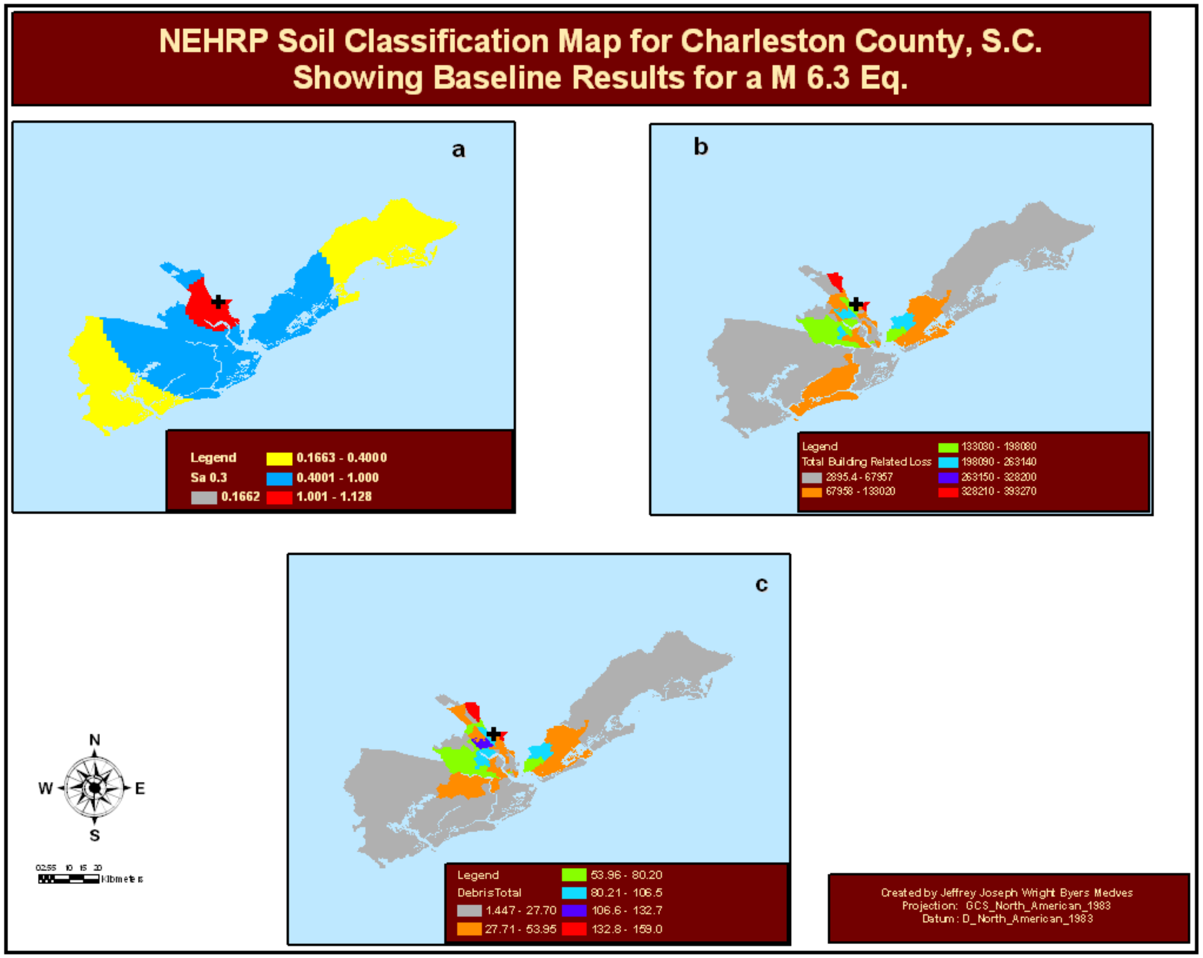


Figure 12 Figure showing the results of HAZUS-MH modeling for the Baseline M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

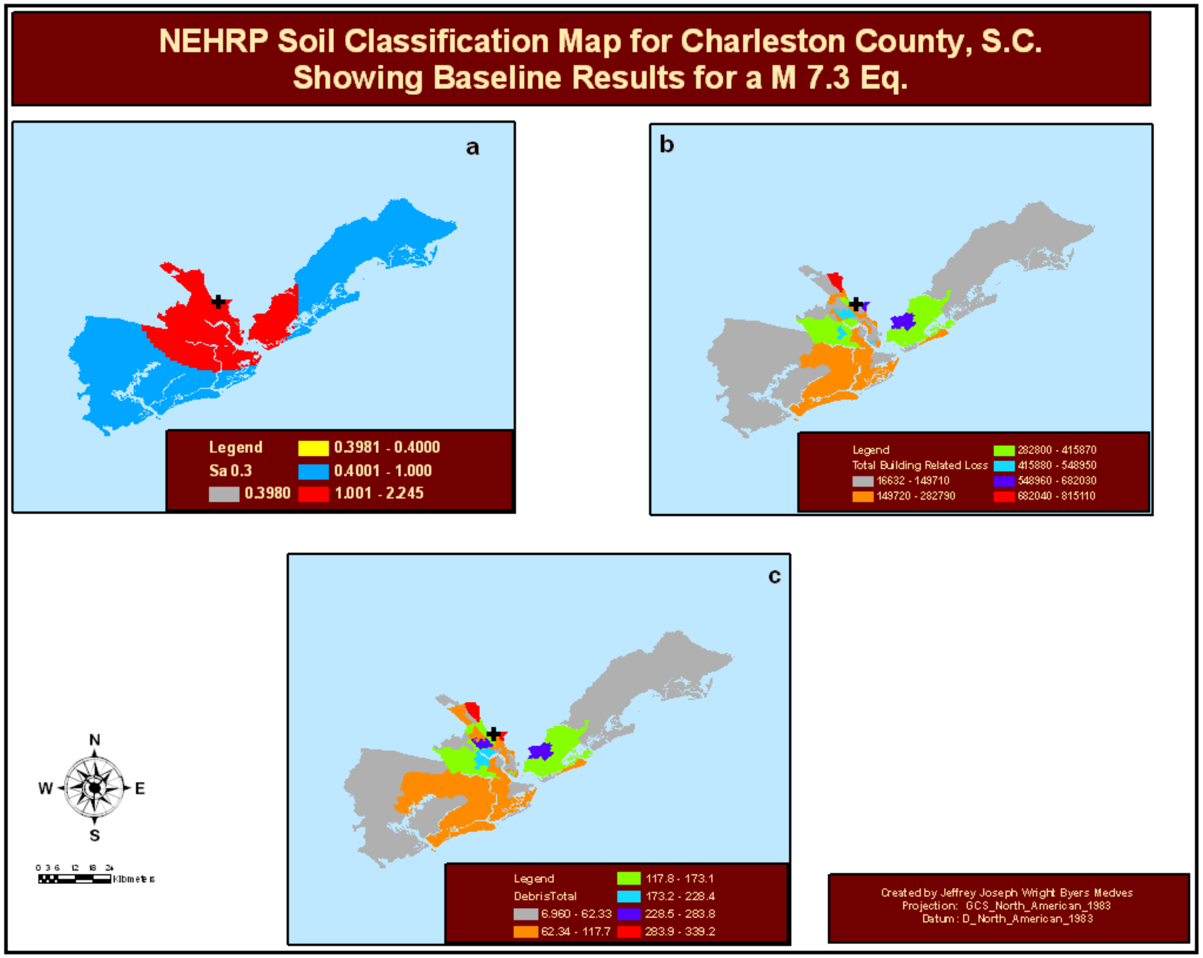


Figure 13 The mapped results of HAZUS-MH modeling for the Baseline M 7.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

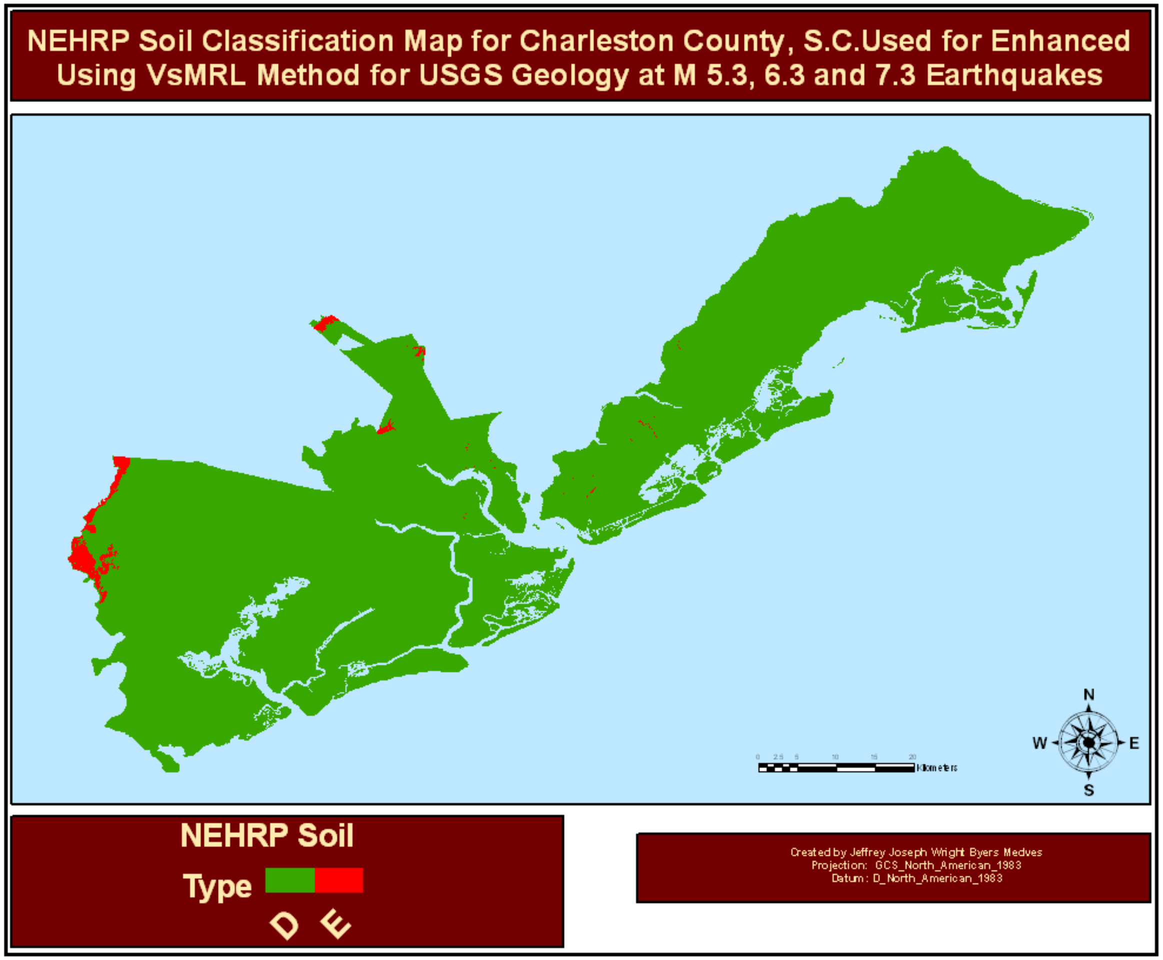


Figure 14 Map of the USGS Geology VsMRL method, illustrating that the majority of the NEHRP soils are ranked as “D”. However, there are expressions of “E” class soils present in the north central and northwestern regions of the map.

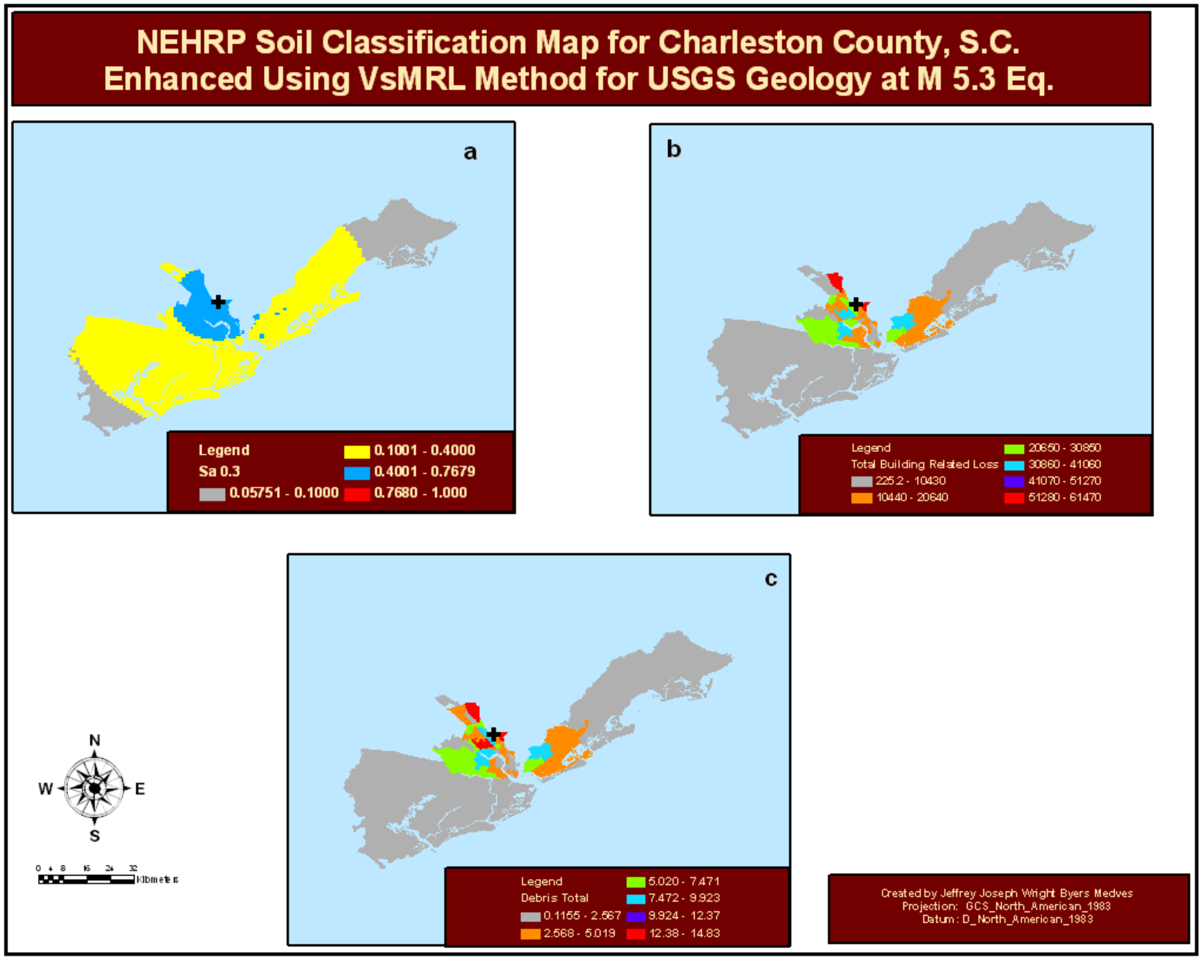


Figure 15 Figure showing the results of HAZUS-MH modeling for the USGS VsMRL M 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

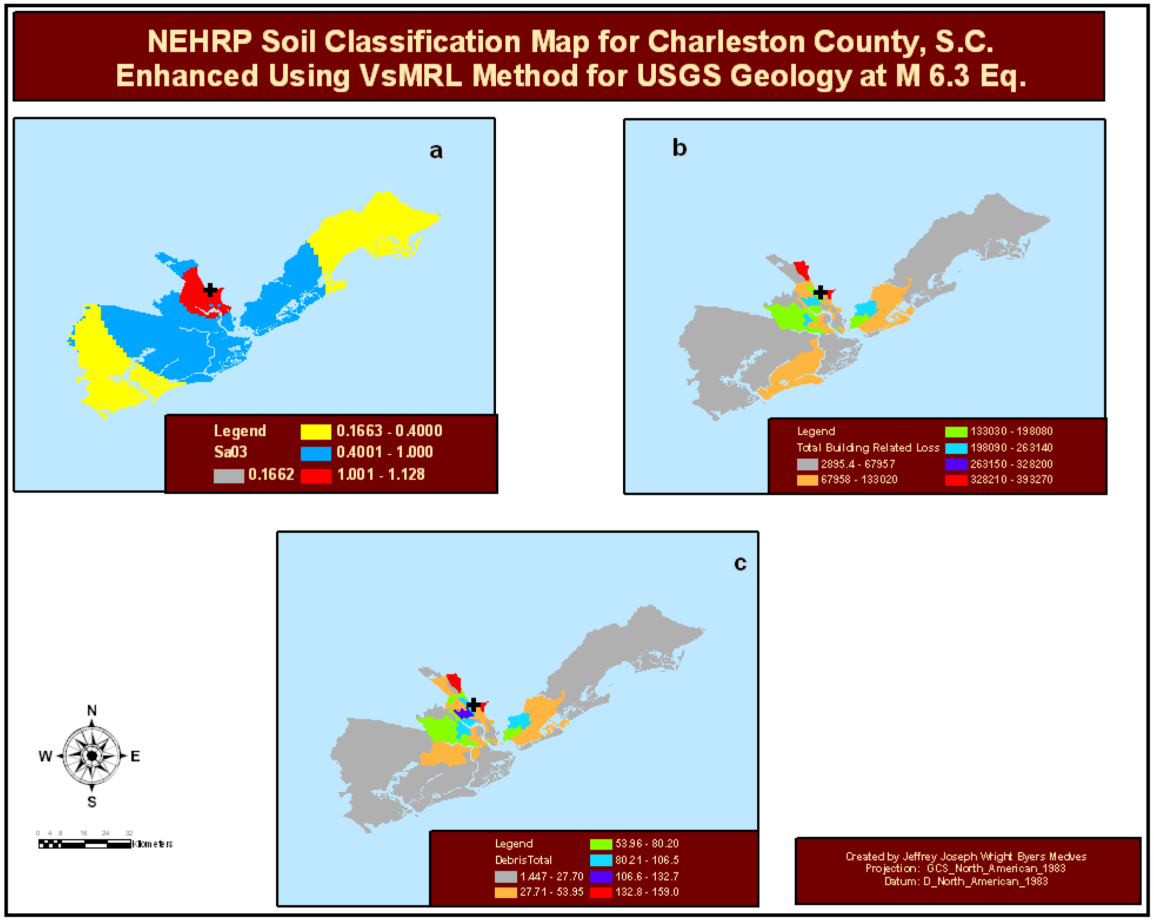


Figure 16 Illustration showing the results of HAZUS-MH modeling for the USGS VsMRL M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

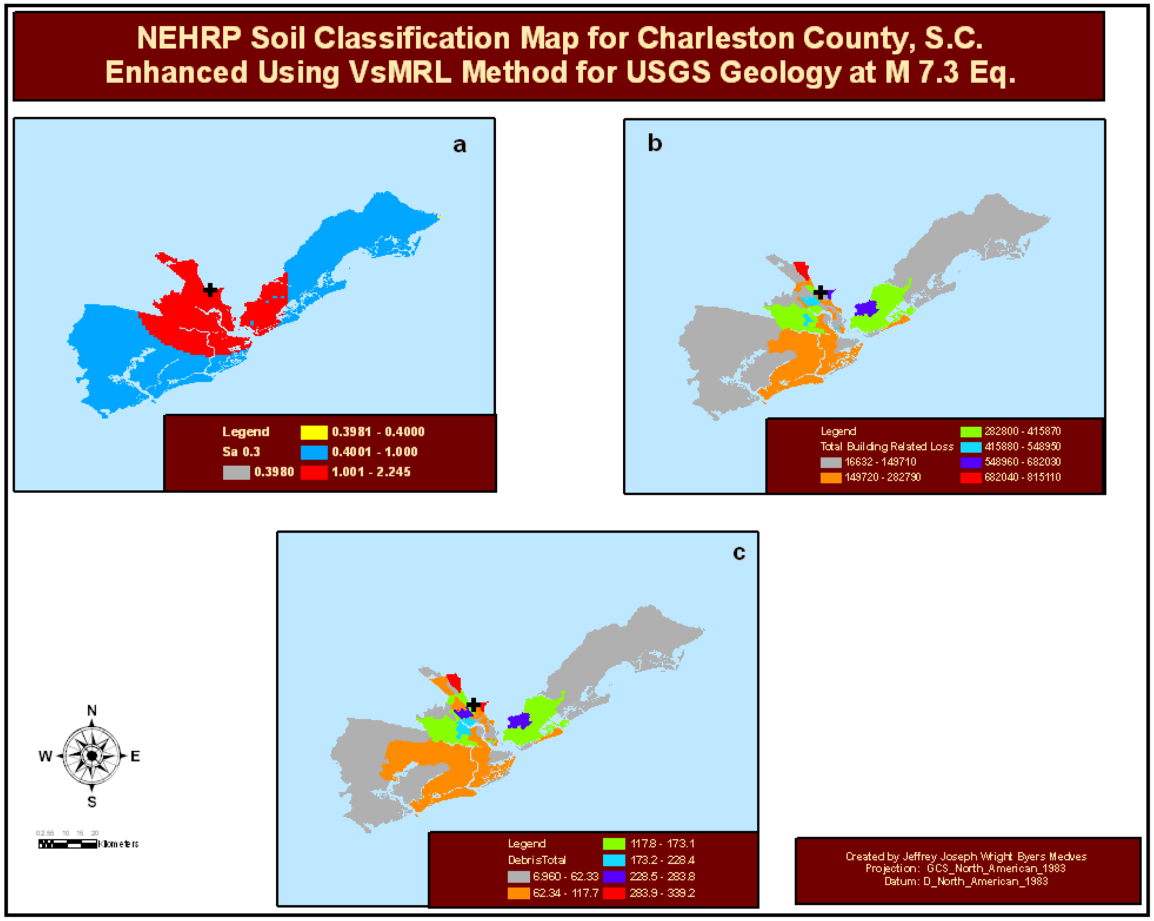


Figure 17 Map representing the results of HAZUS-MH modeling for the USGS VsMRL M 7.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

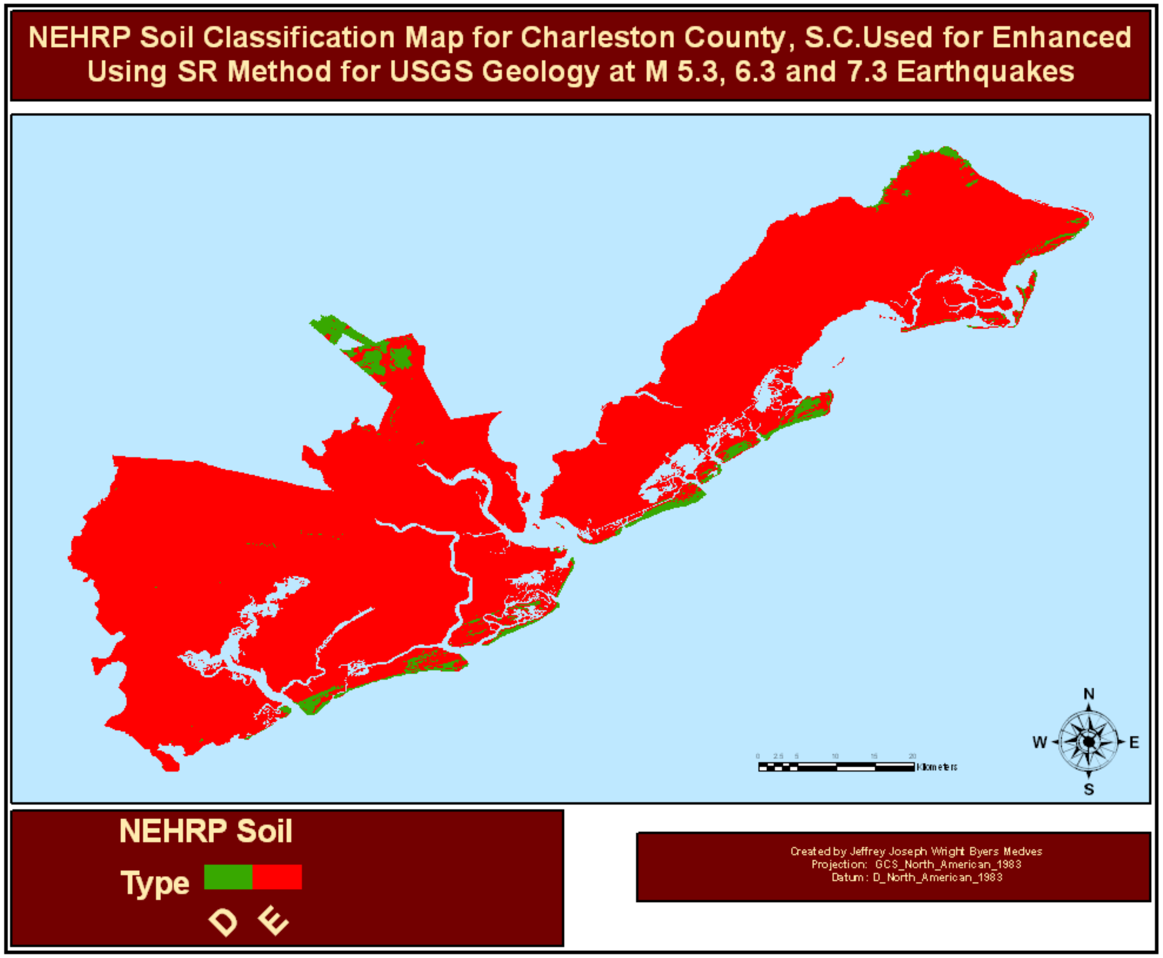


Figure 18 Illustration of the USGS SR mapping method. The majority of units in the region are classified as “E” NEHRP soils. “D” soils are also present on the northern and southern boundaries of the study area.

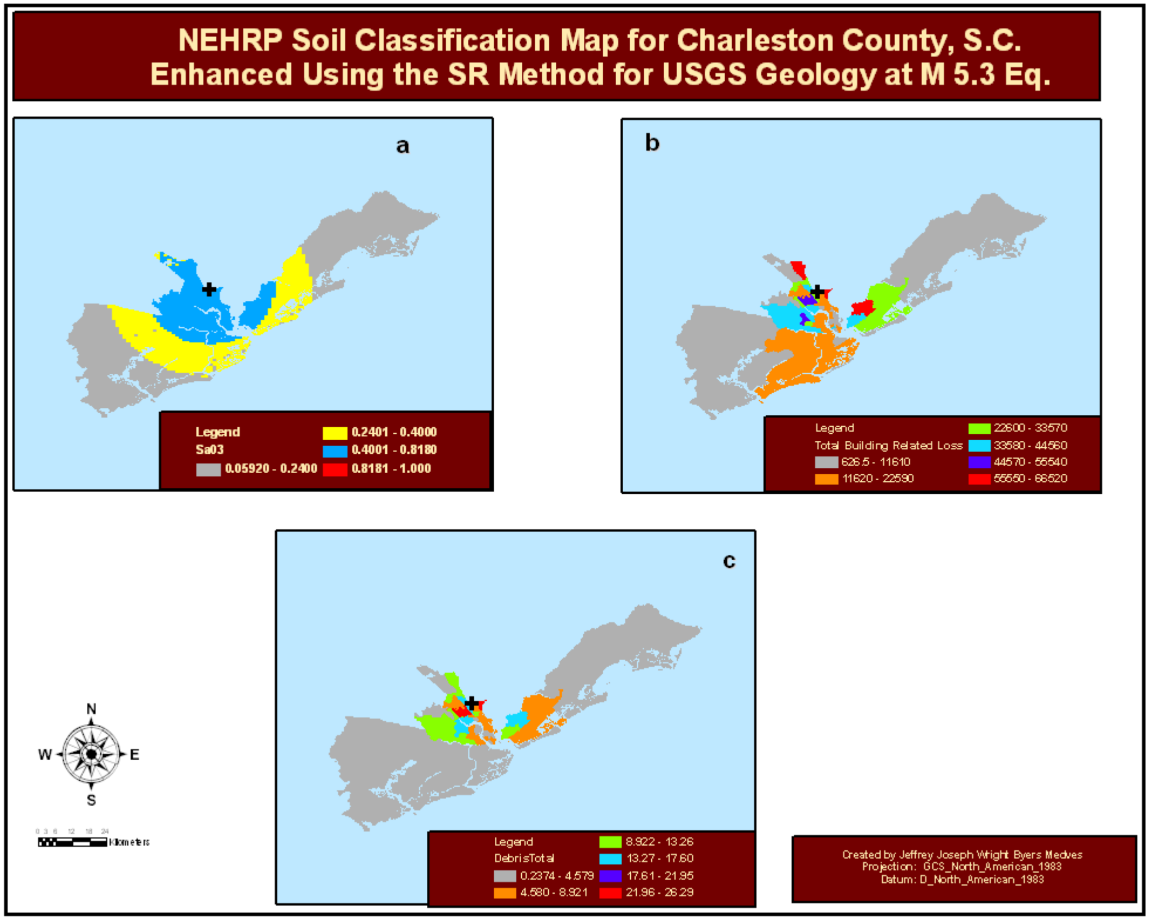


Figure 19 Figure showing the results of HAZUS-MH modeling for the USGS M SR 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

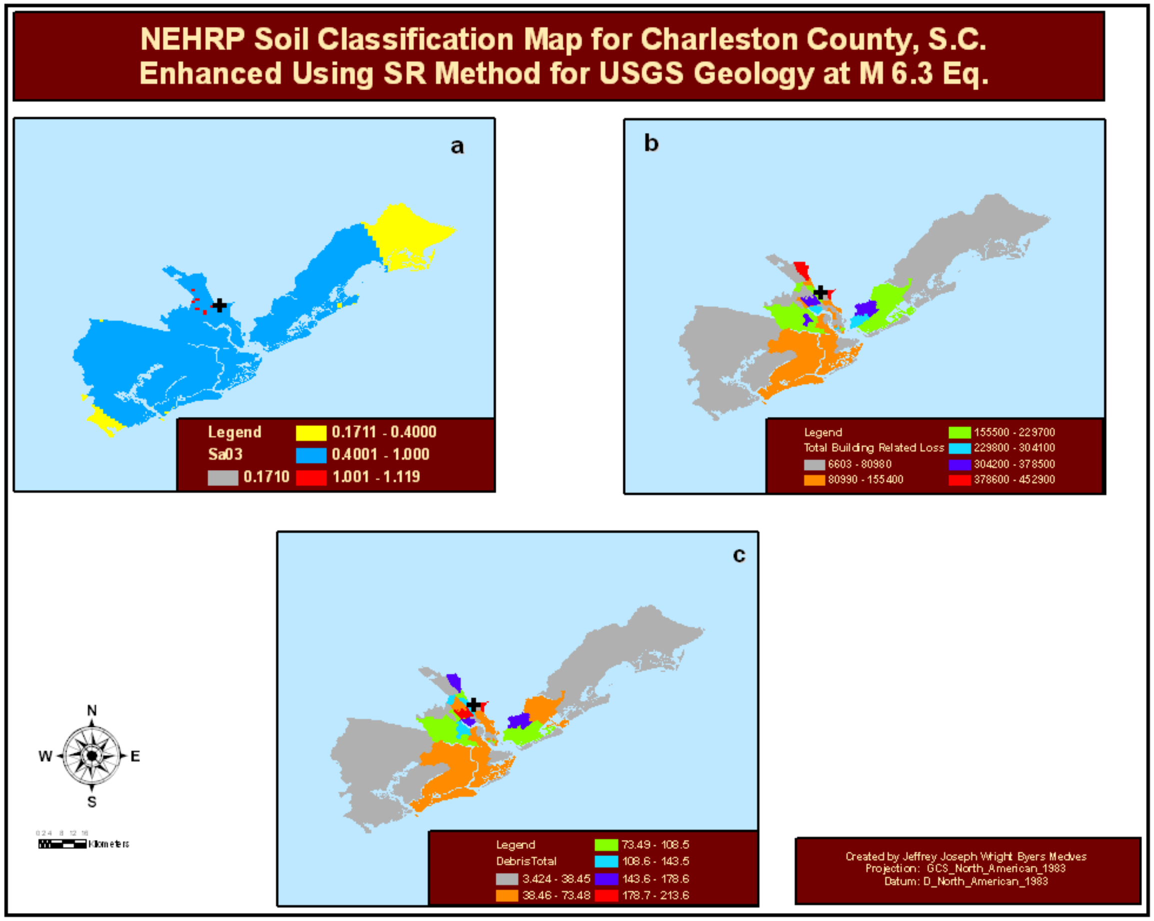


Figure 20 Illustration showing the results of HAZUS-MH modeling for the USGS SR M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

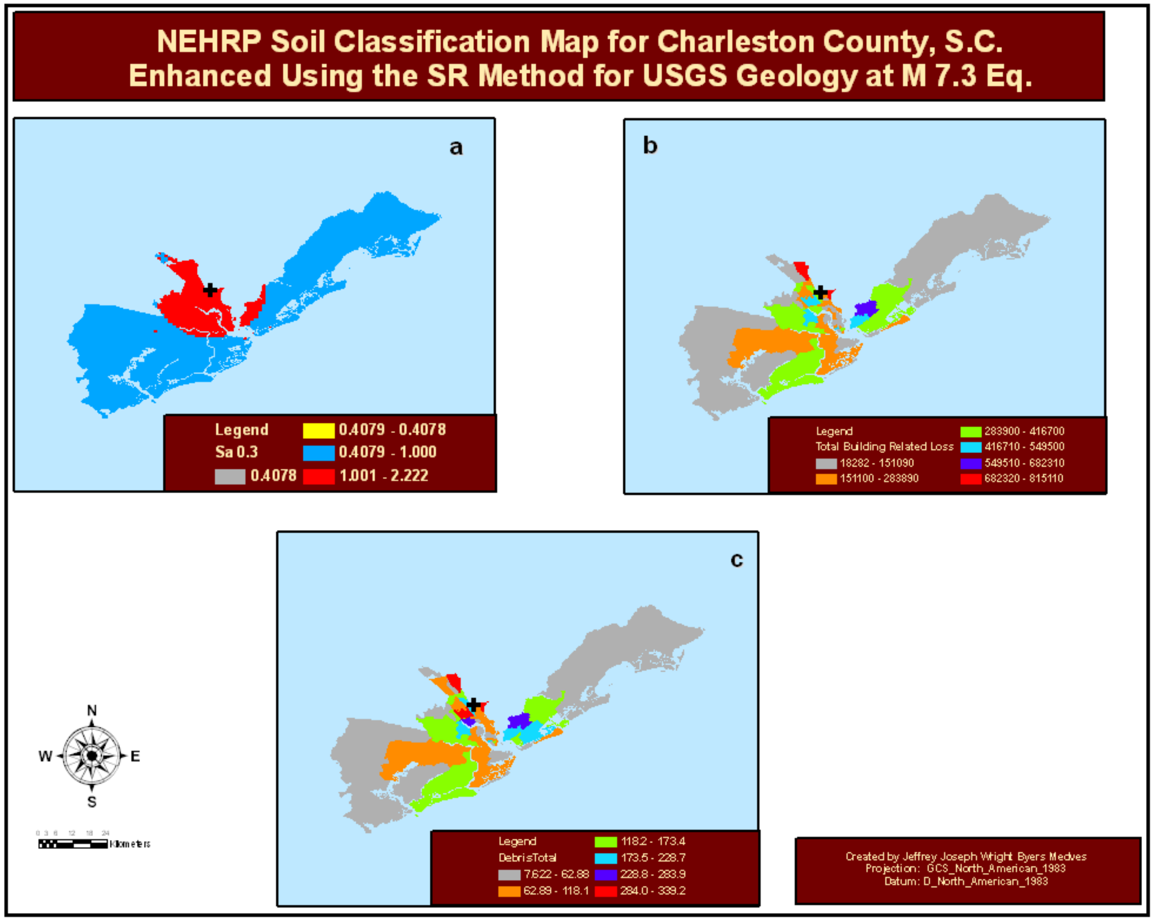


Figure 21 Map showing the results of HAZUS-MH modeling for the USGS M 7.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

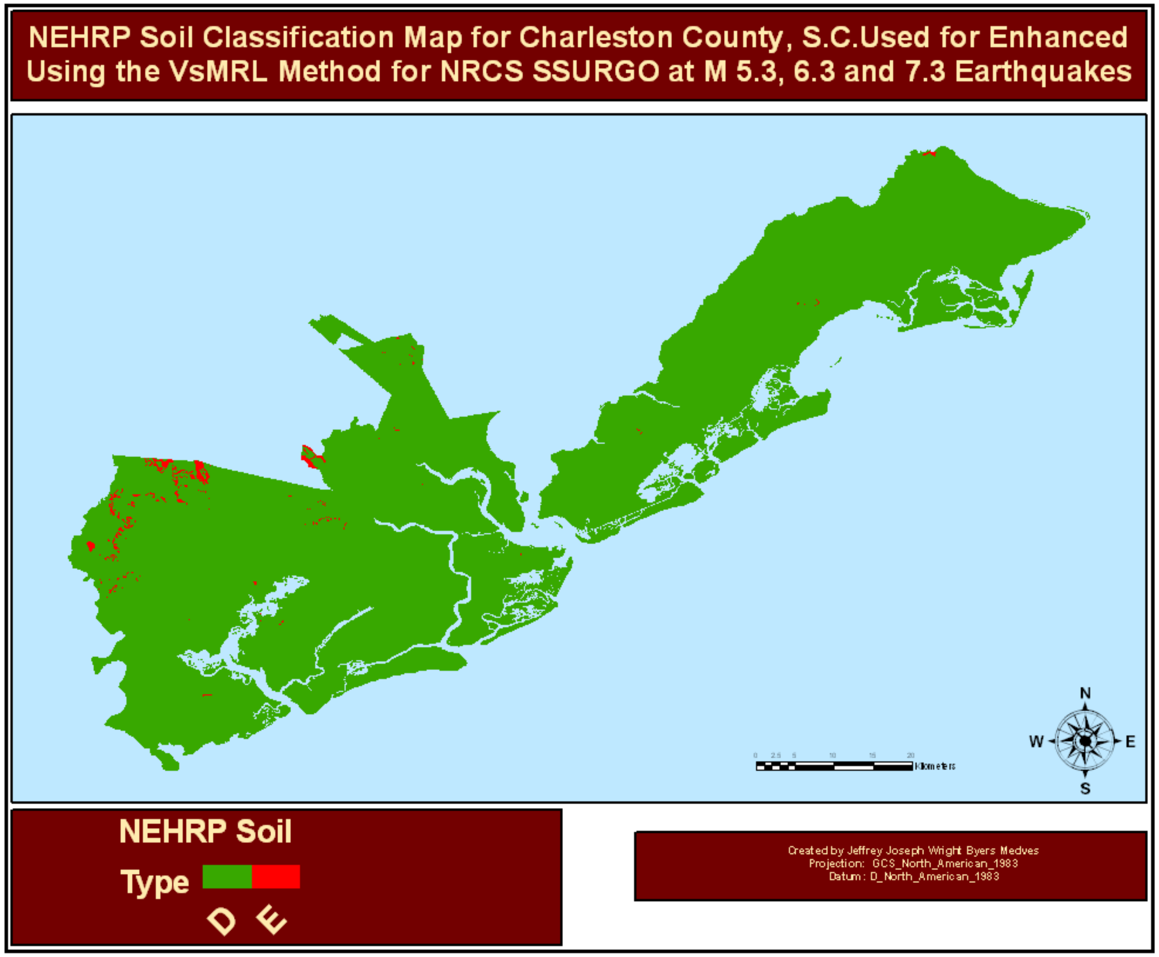


Figure 22 Map of the SSURGO VsMRL NEHRP Classification. The majority of the region is composed of “D” soils, with a few scattered expressions of “E” in the northwestern area.

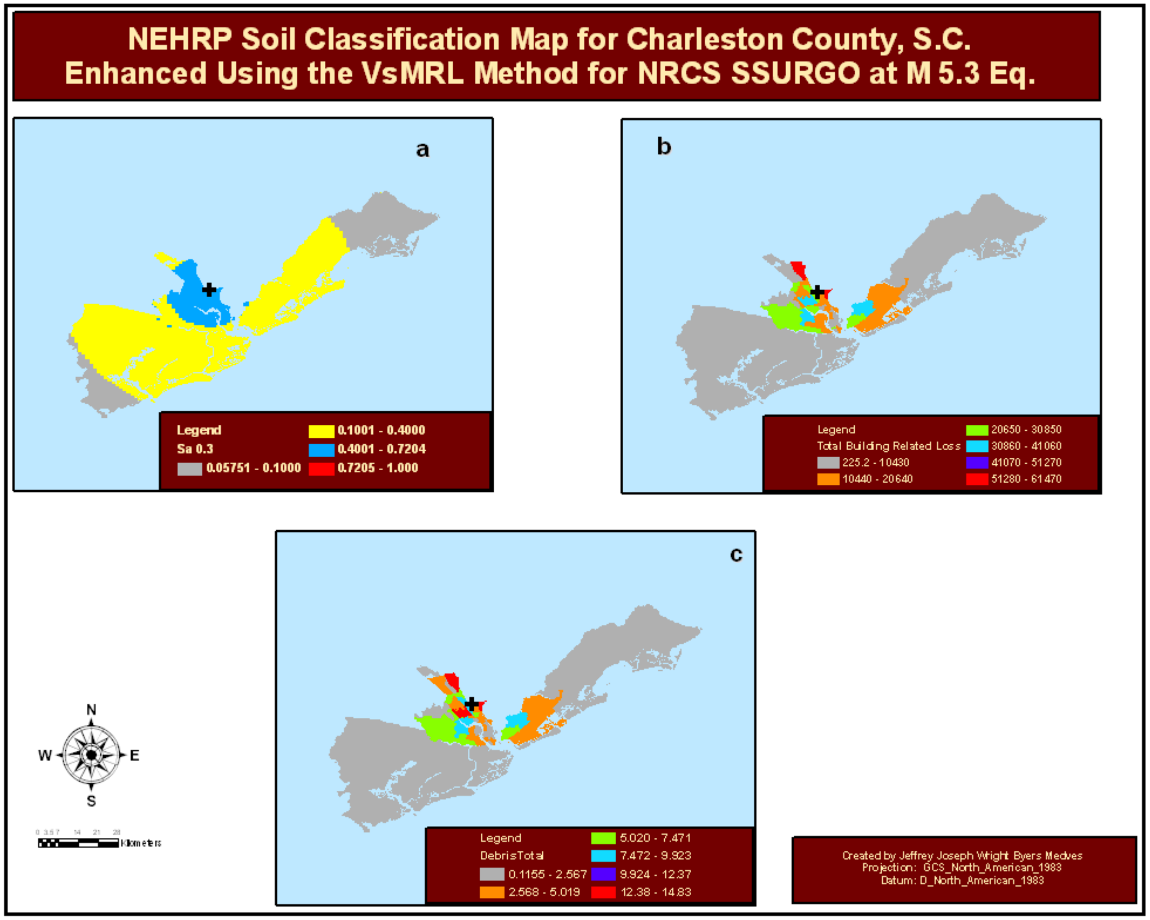


Figure 23 Representation of the HAZUS-MH modeling results for the SSURGO VsMRL M 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

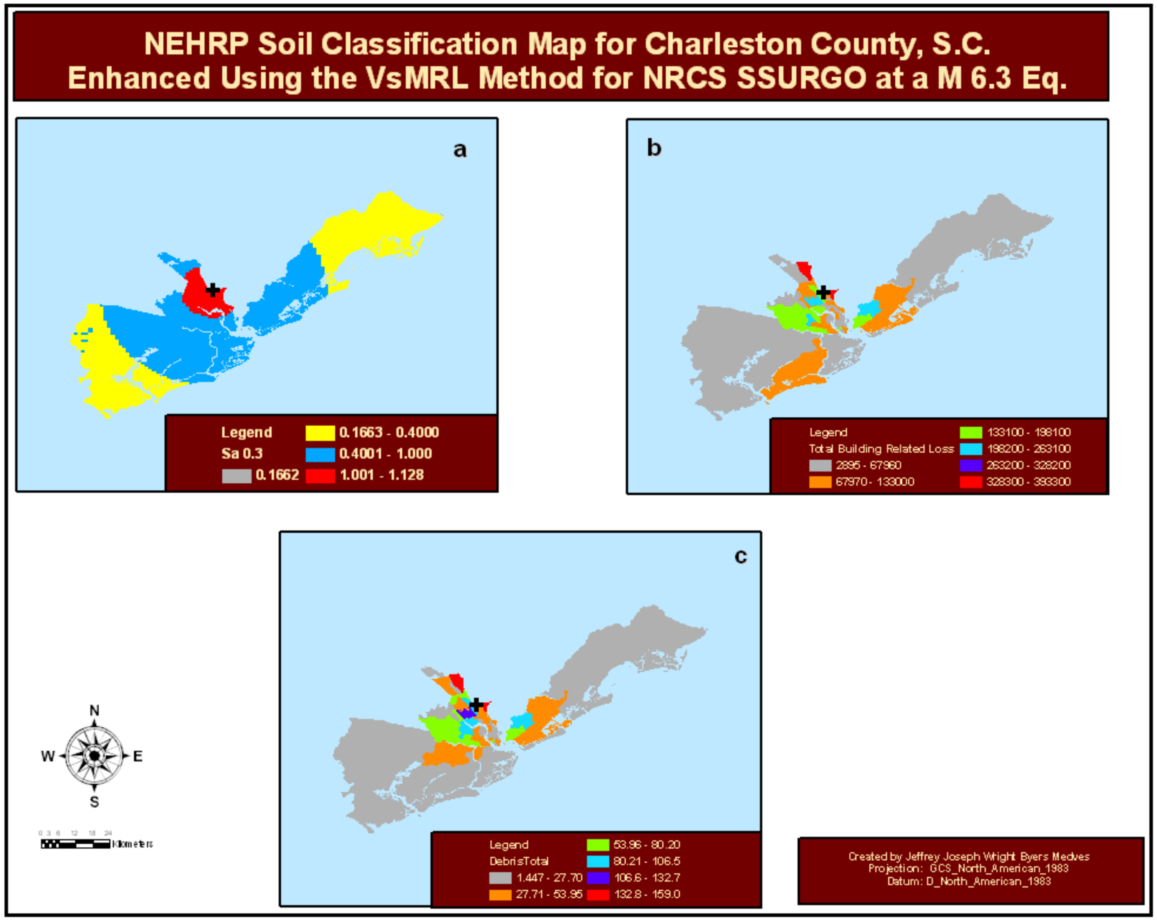


Figure 24 Map of the HAZUS-MH modeling results for the SSURGO VsMRL M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

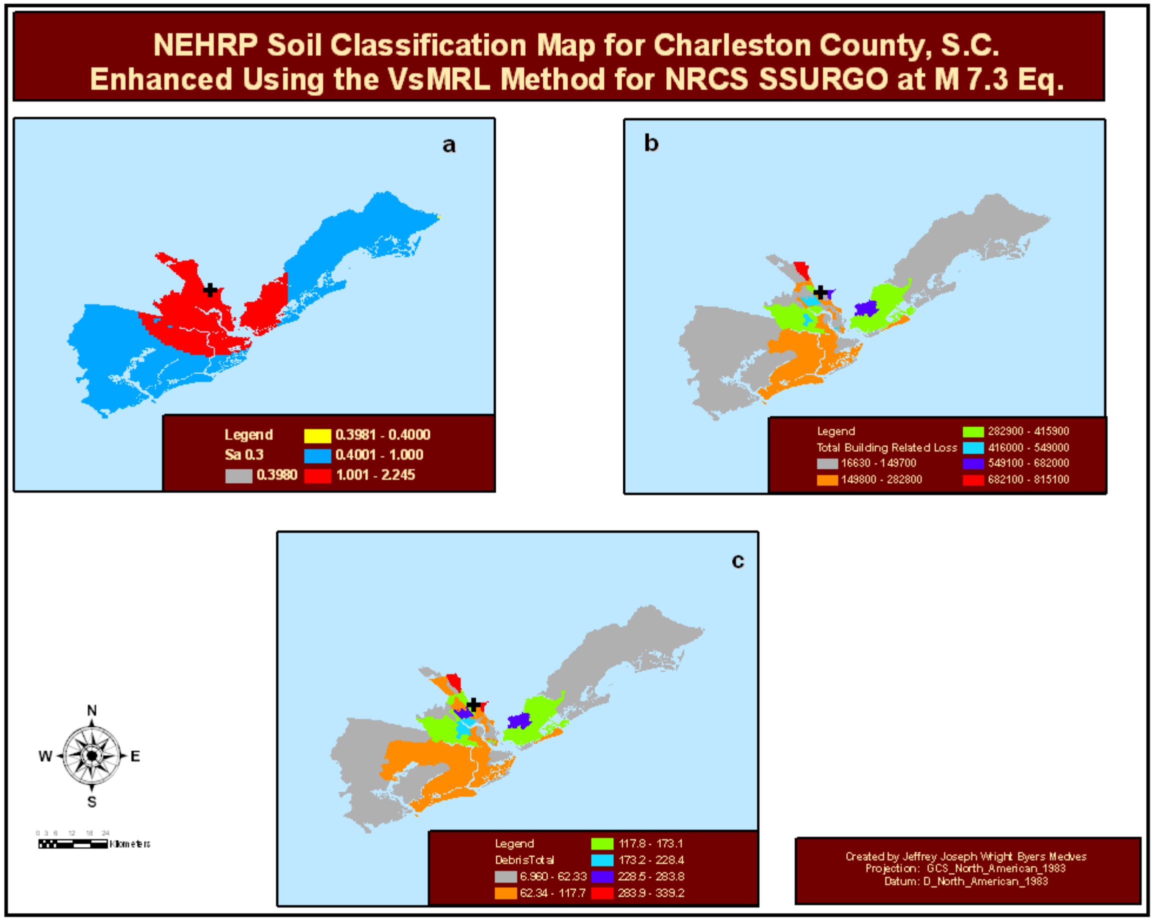


Figure 25 Map of the HAZUS-MH modeling results for the SSURGO VsMRL M 7.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

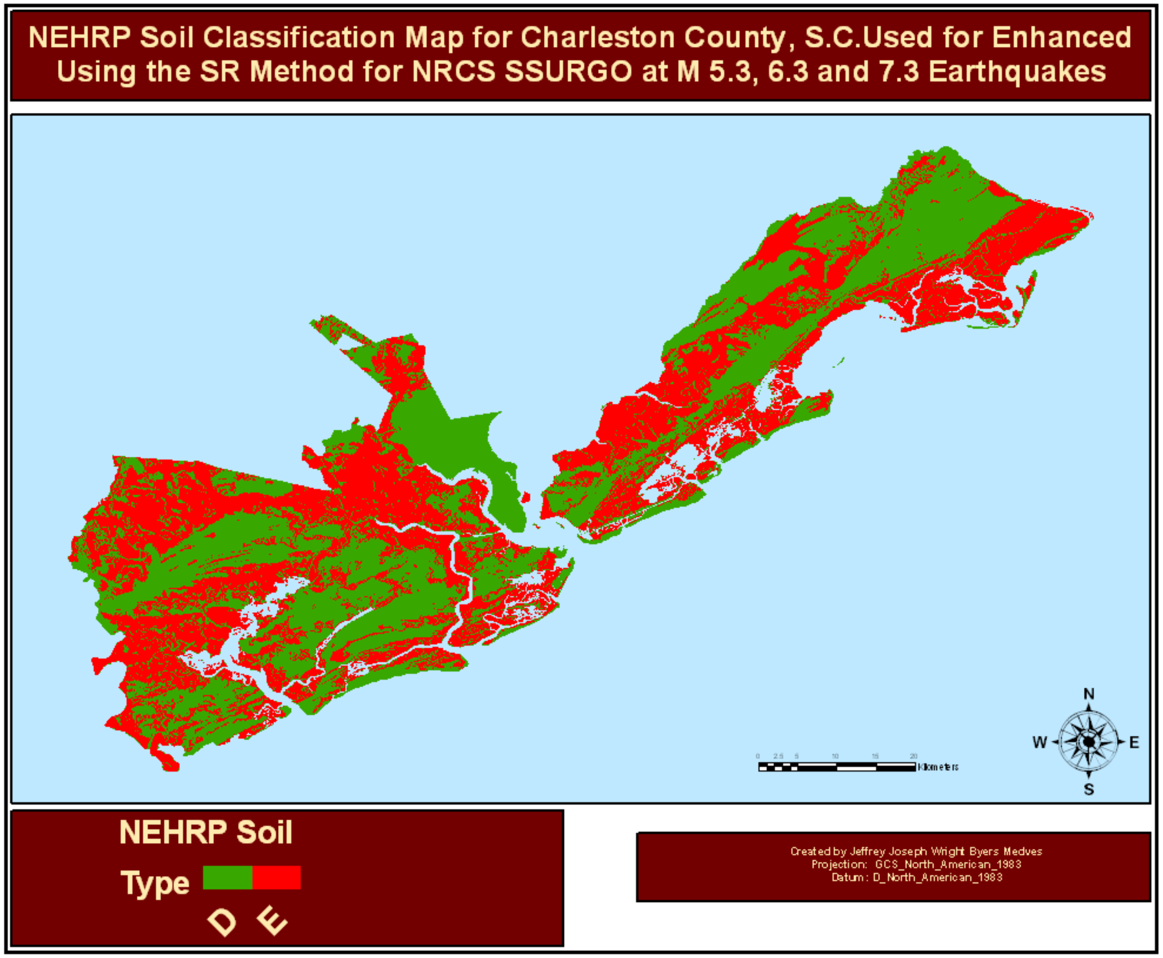


Figure 26 Map of the SSURGO SR method NEHRP classification.

Visible are the dispersion of “D” and “E” soils throughout the map

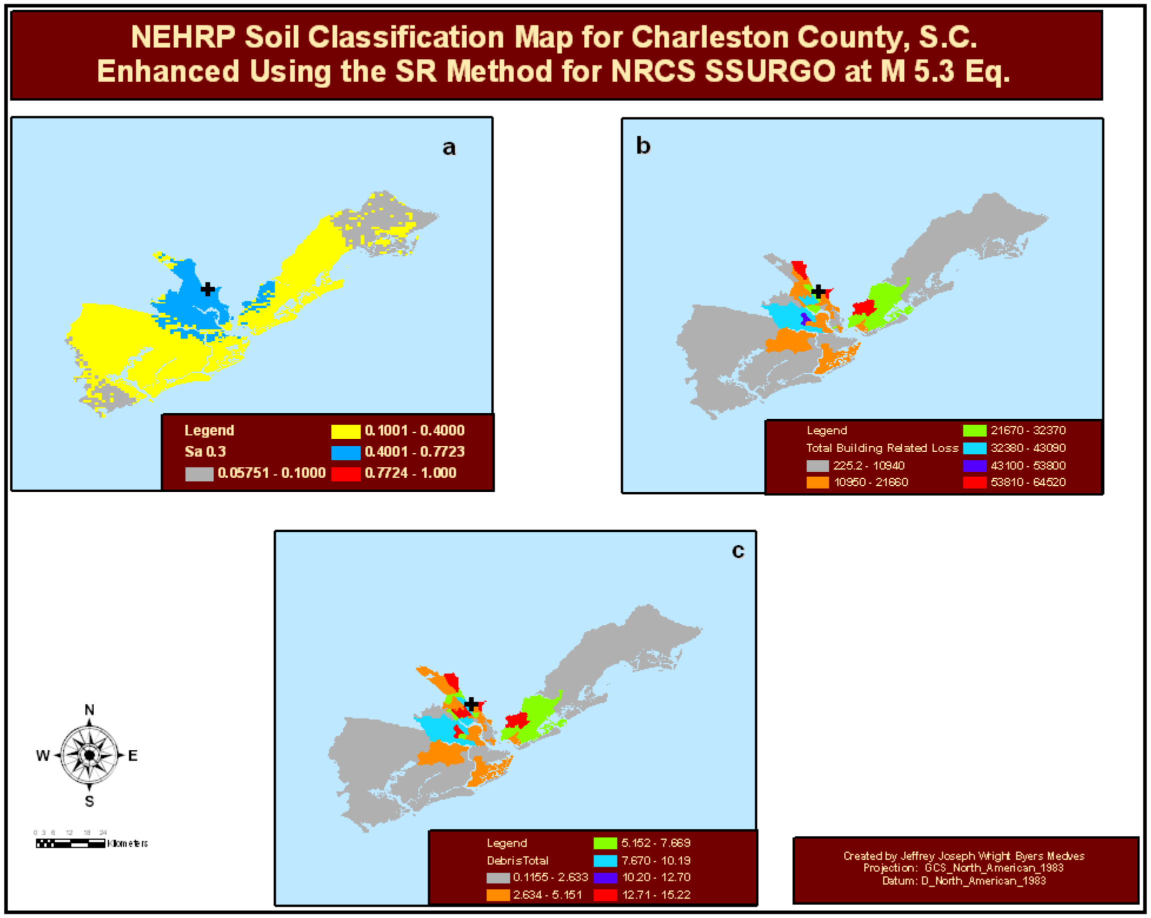


Figure 27 Representation of the HAZUS-MH modeling results for the SSURGO SR M 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

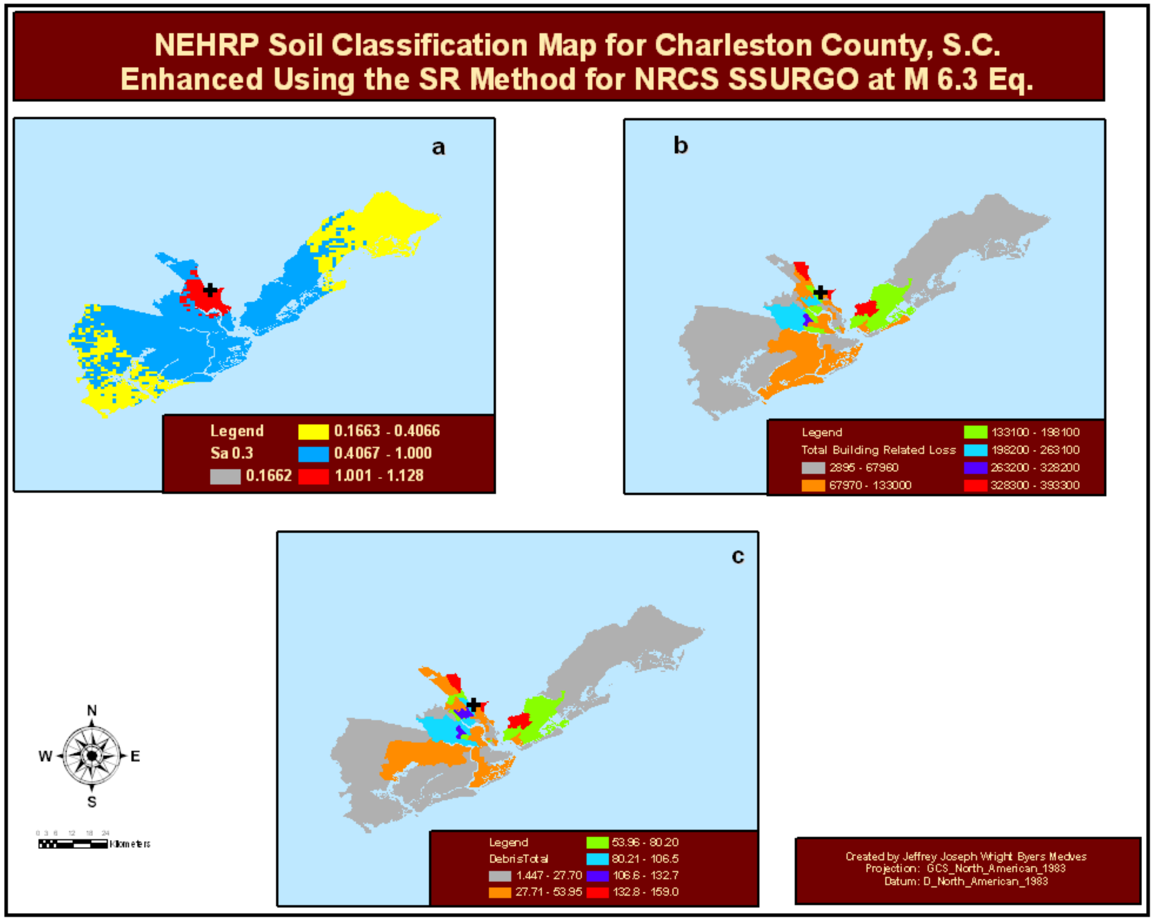


Figure 28 Map of the HAZUS-MH modeling results for the SSURGO SR M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

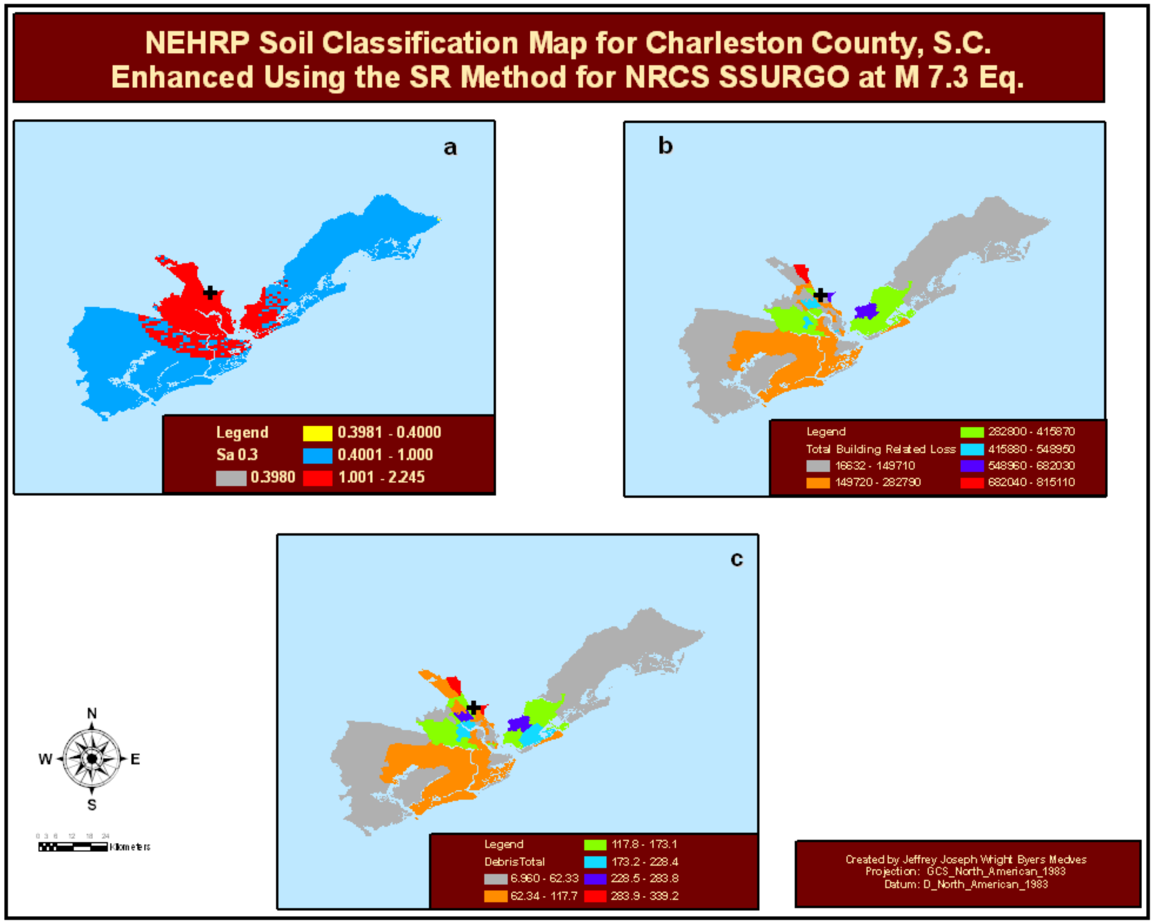


Figure 29 Representation of the HAZUS-MH modeling results for the SSURGO SR M 7.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

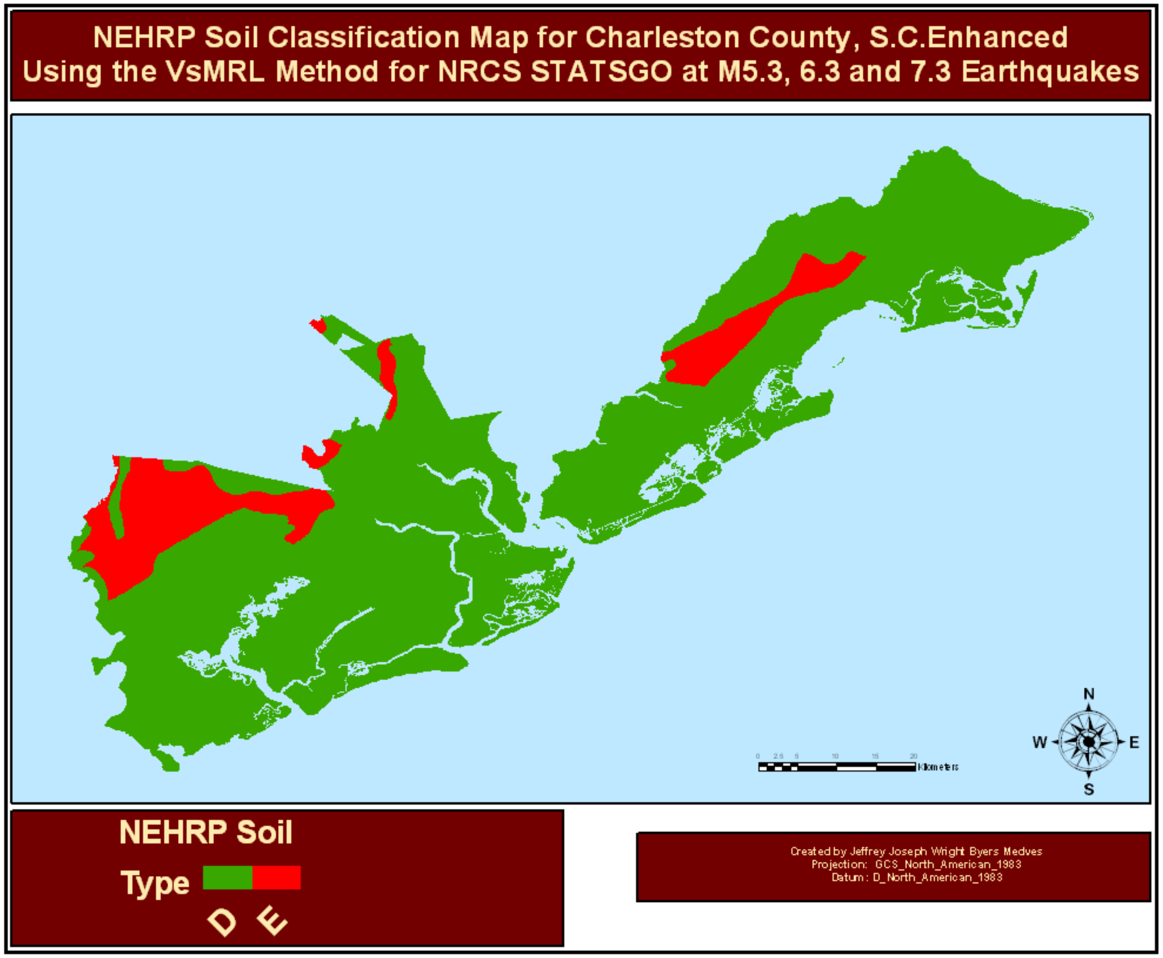


Figure 30 Map of the STATSGO VsMRL NEHRP classification for the Charleston study area.

"E" soils are located in distinct regions located in the northern part of the study area.

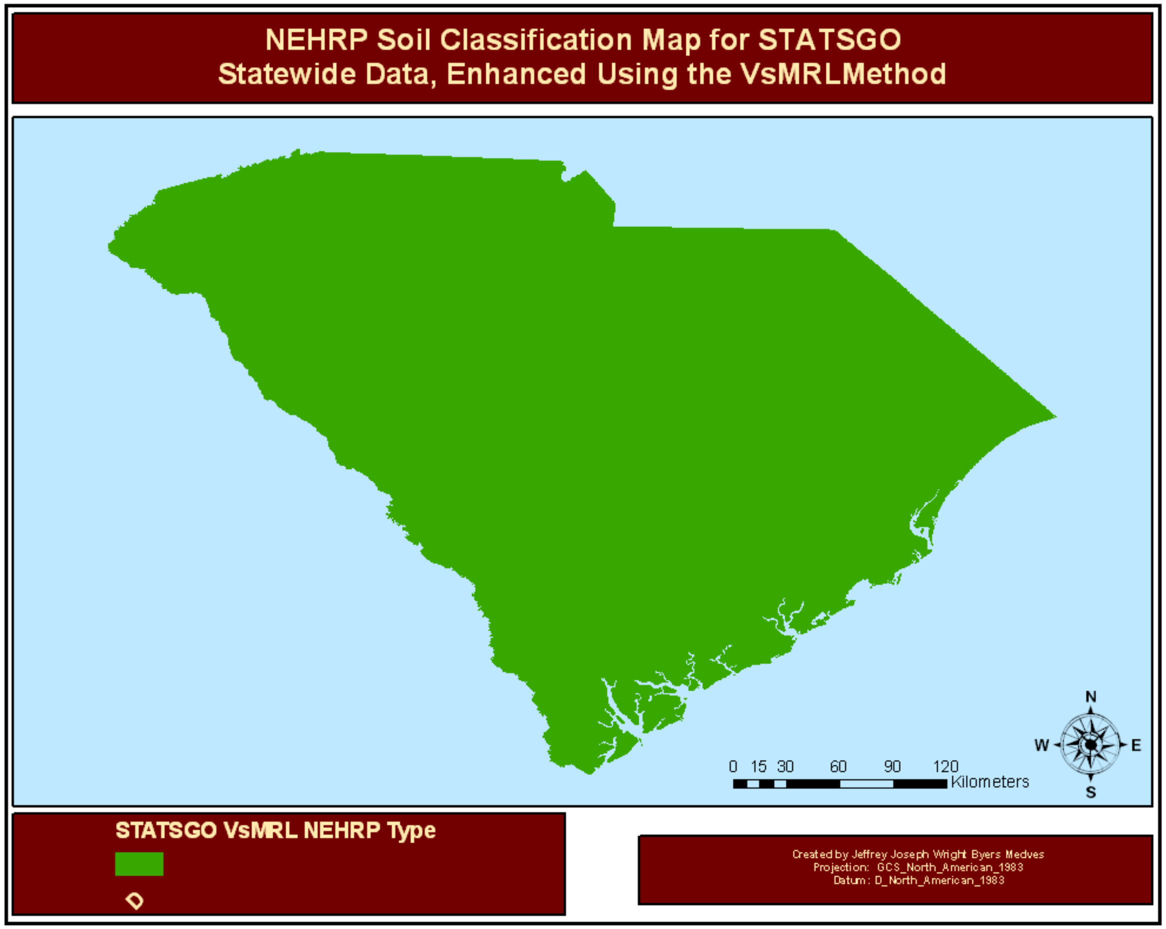


Figure 31 STATSGO Statewide VsMRL NEHRP classification map.

This method resulted in a “D” classification for the entire state of South Carolina.

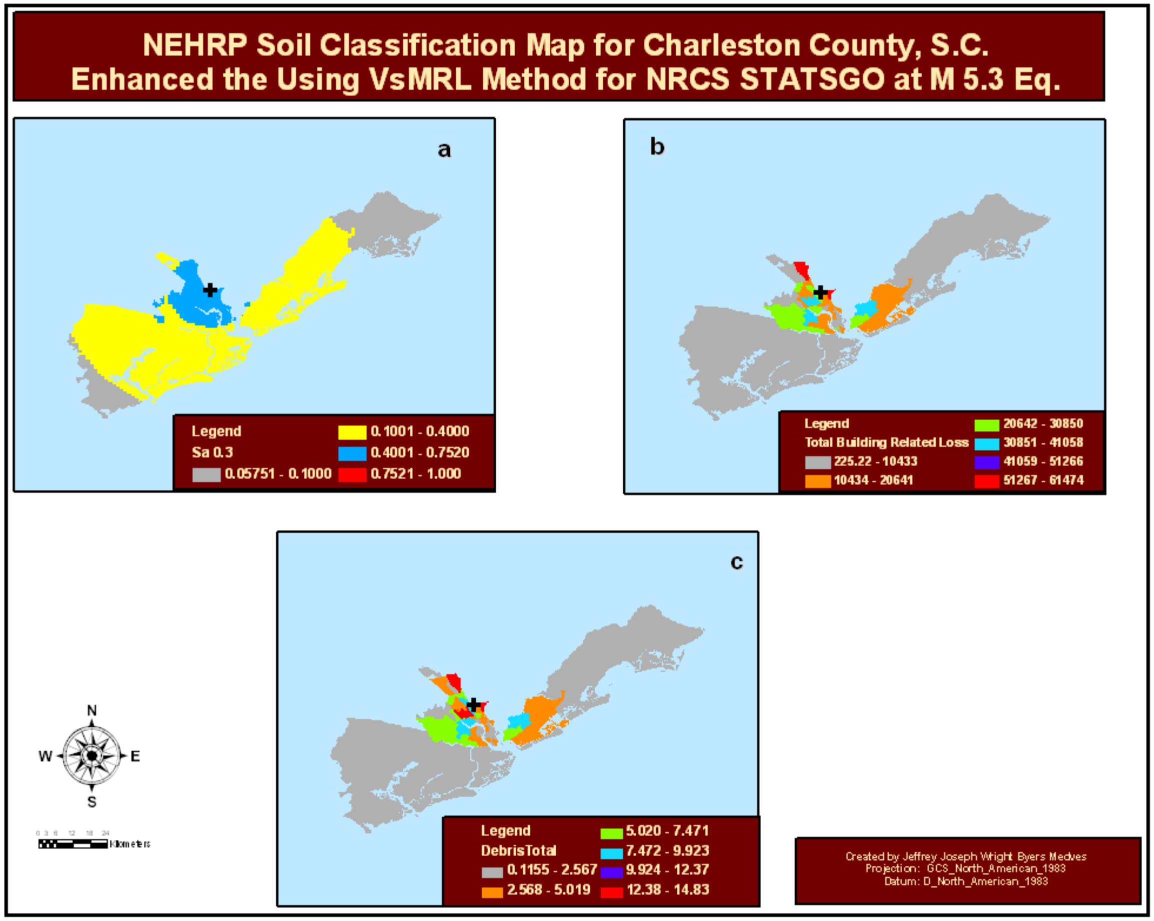


Figure 32 Representation of the HAZUS-MH modeling results for the STATSGO VsMRL M 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

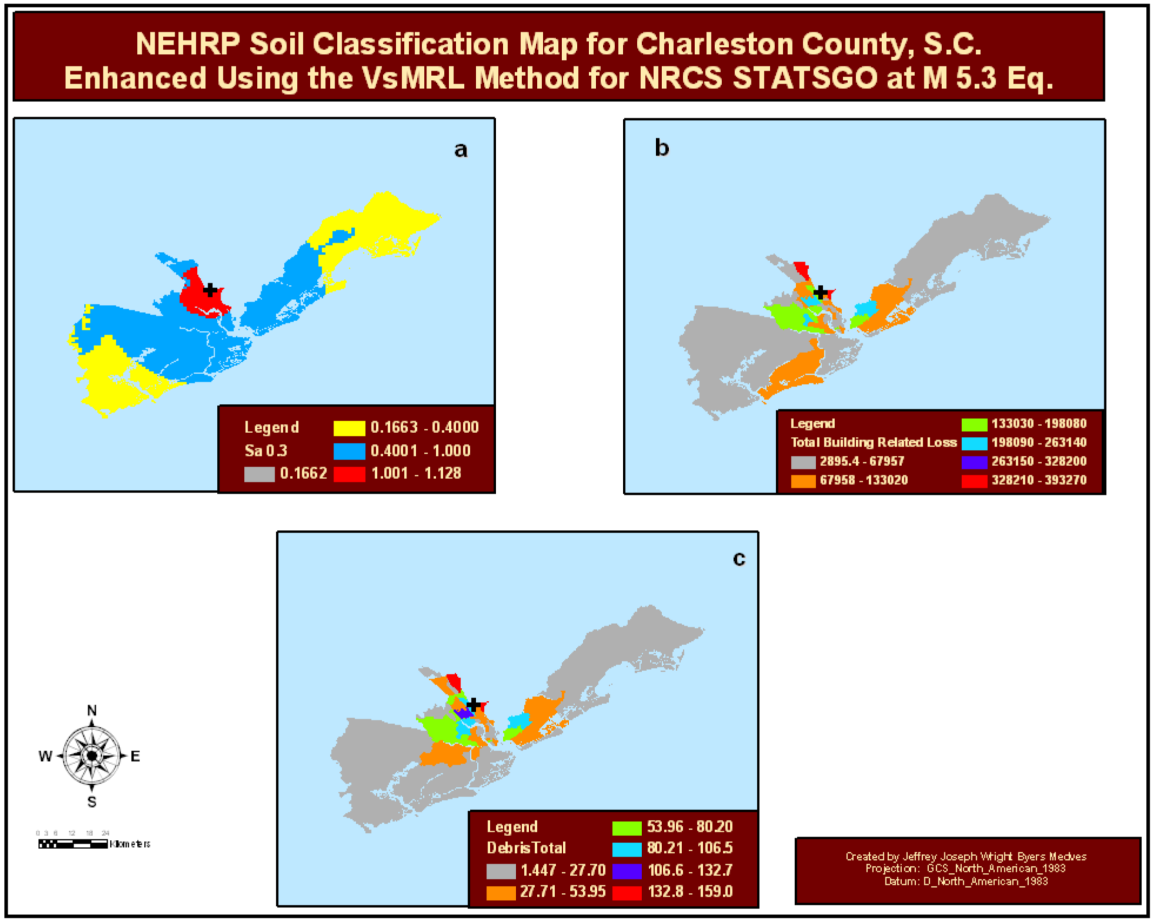


Figure 33 HAZUS-MH modeling results for the STATSGO VsMRL M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

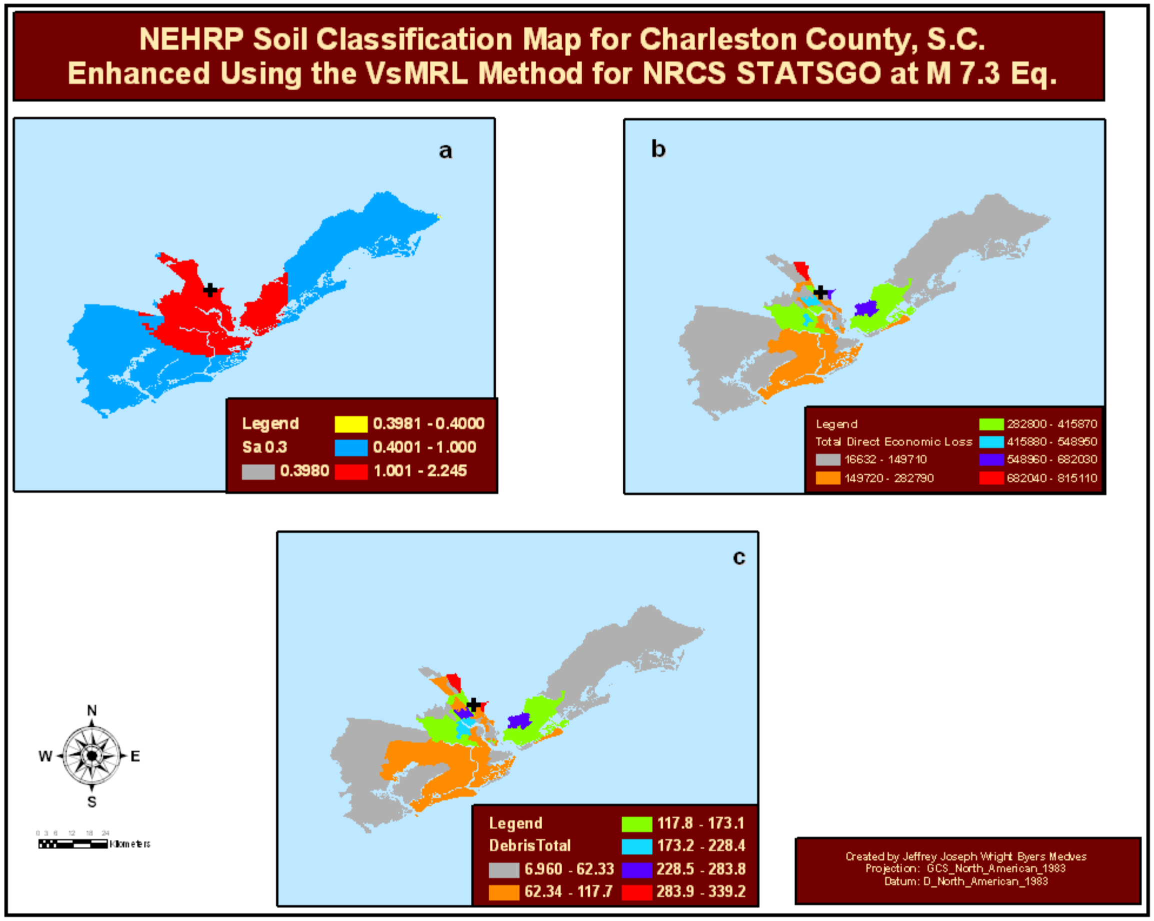


Figure 34 Representation of the HAZUS-MH modeling results for the STATSGO VsMRL M 7.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

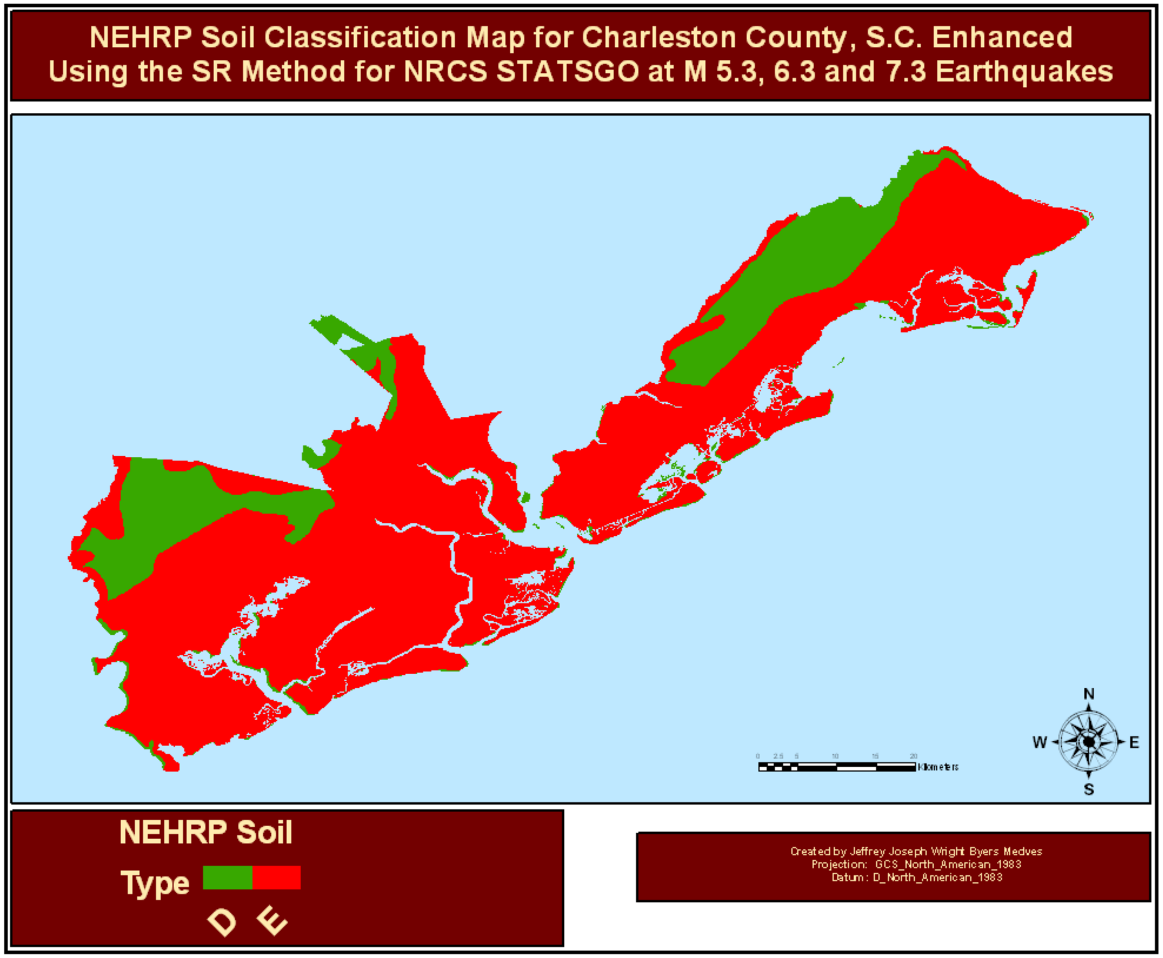


Figure 35 Map of the STATSGO SR NEHRP classification for the Charleston study area.

“D” soils are located in distinct regions located in the northern part of the study area.

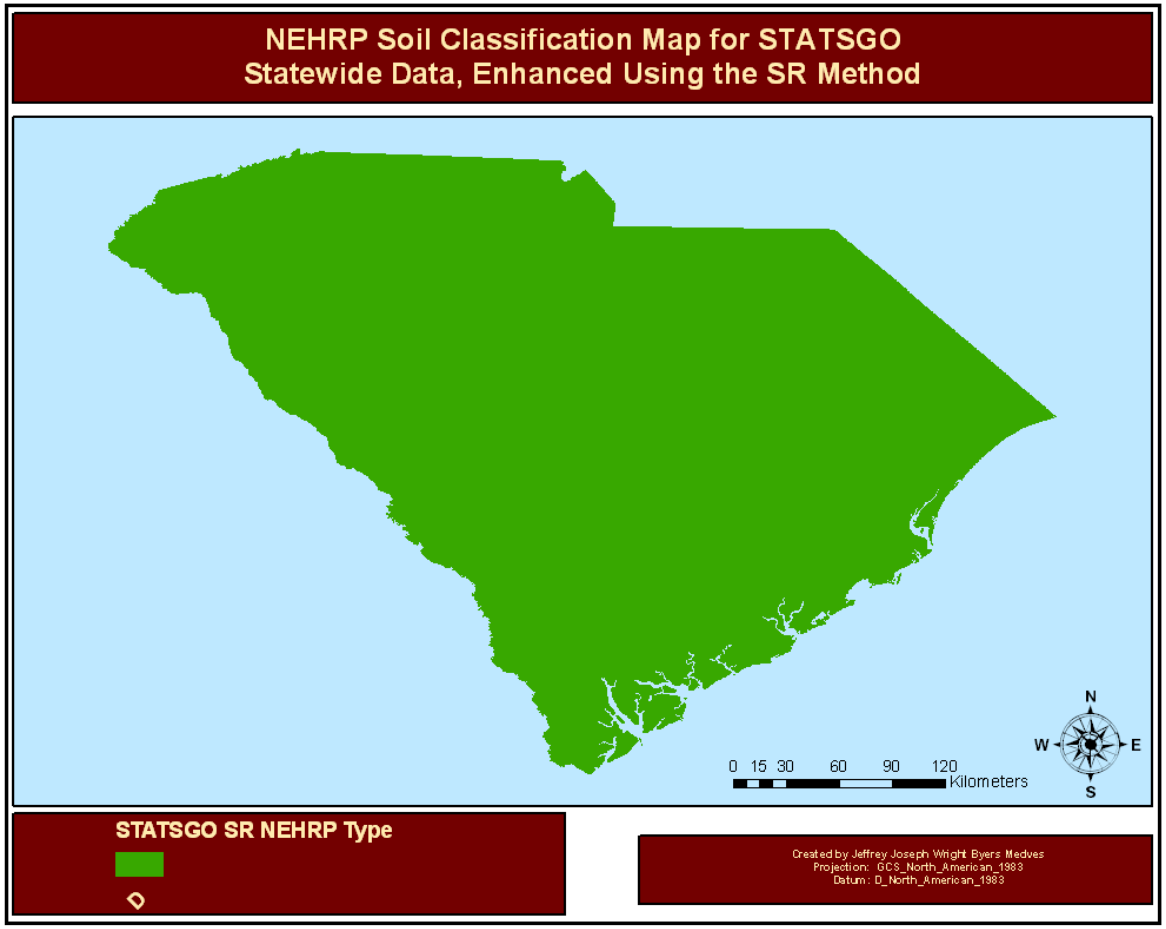


Figure 36 Map of the Statewide STATSGO SR Method. The entire state is classified as an “D” soil.

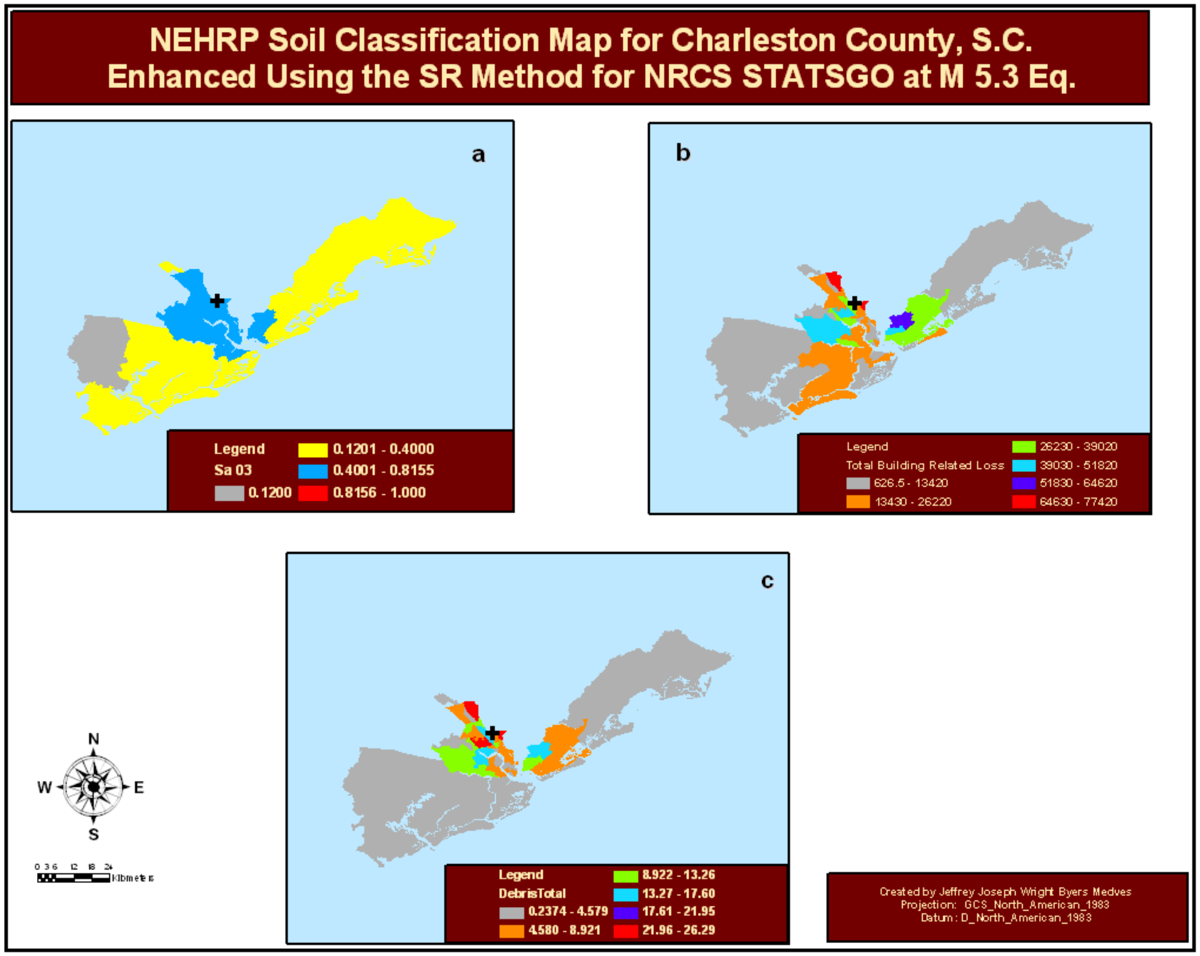


Figure 37 Representation of the HAZUS-MH modeling results for the STATSGO SR M 5.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

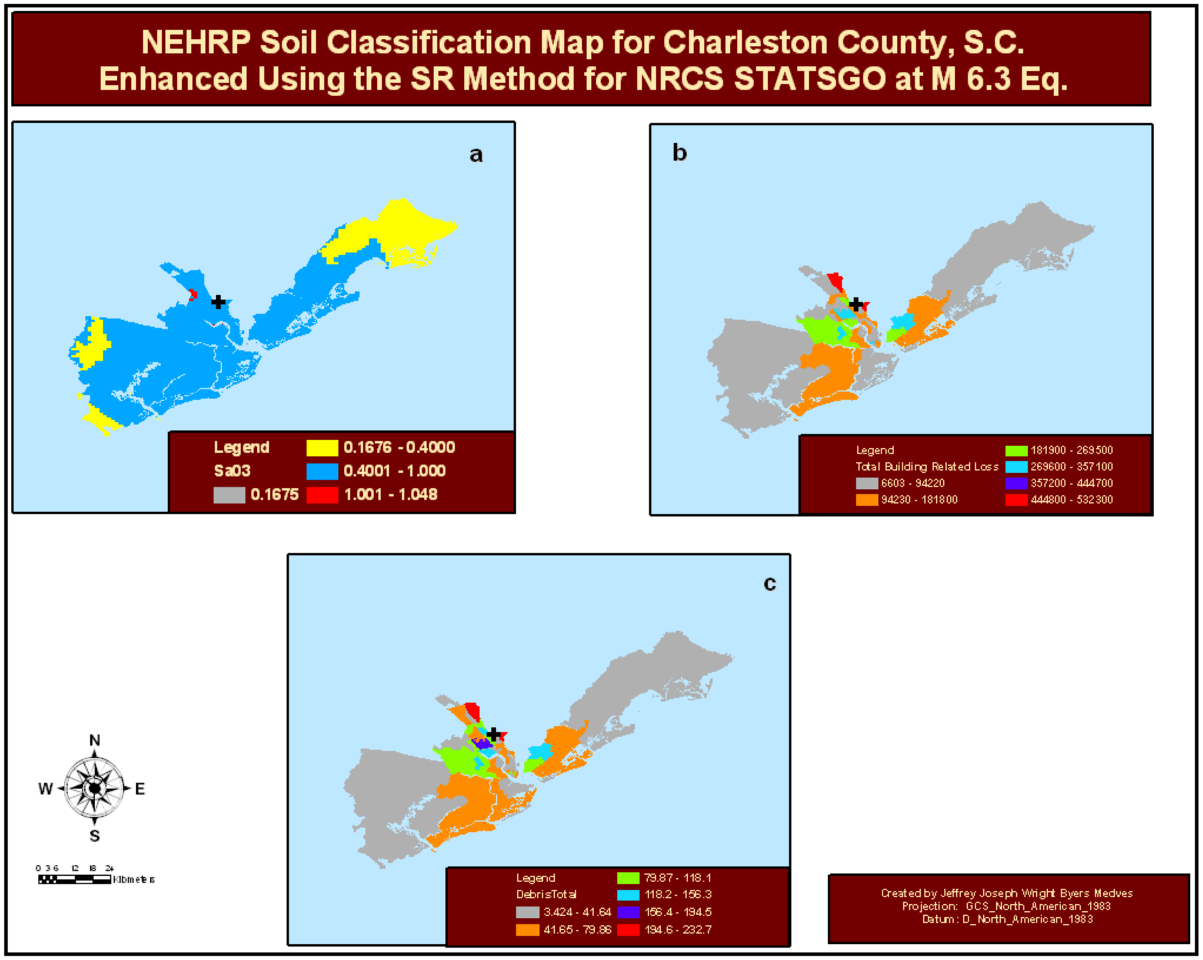


Figure 38 HAZUS-MH modeling results for the STATSGO SR M 6.3 Scenario.

The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).

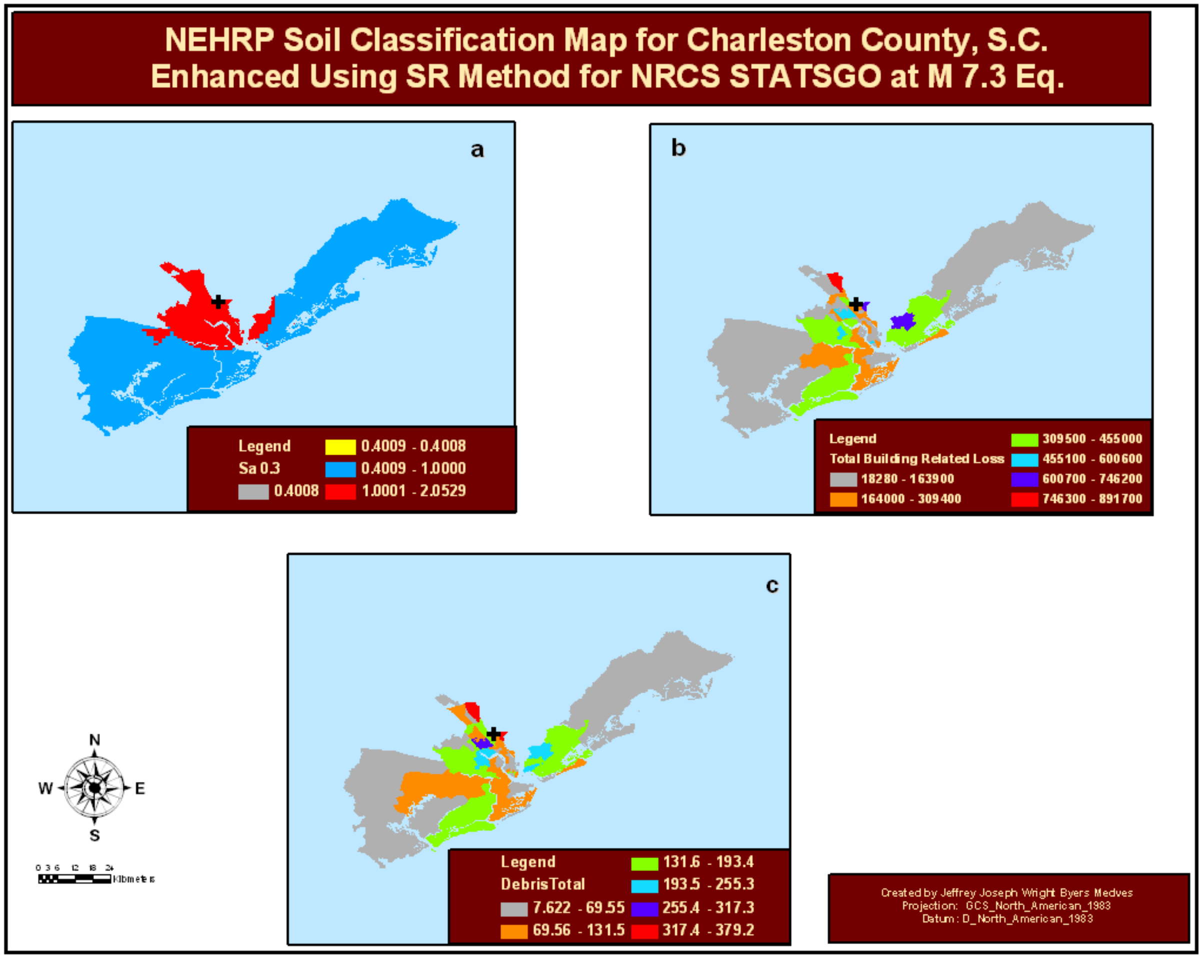
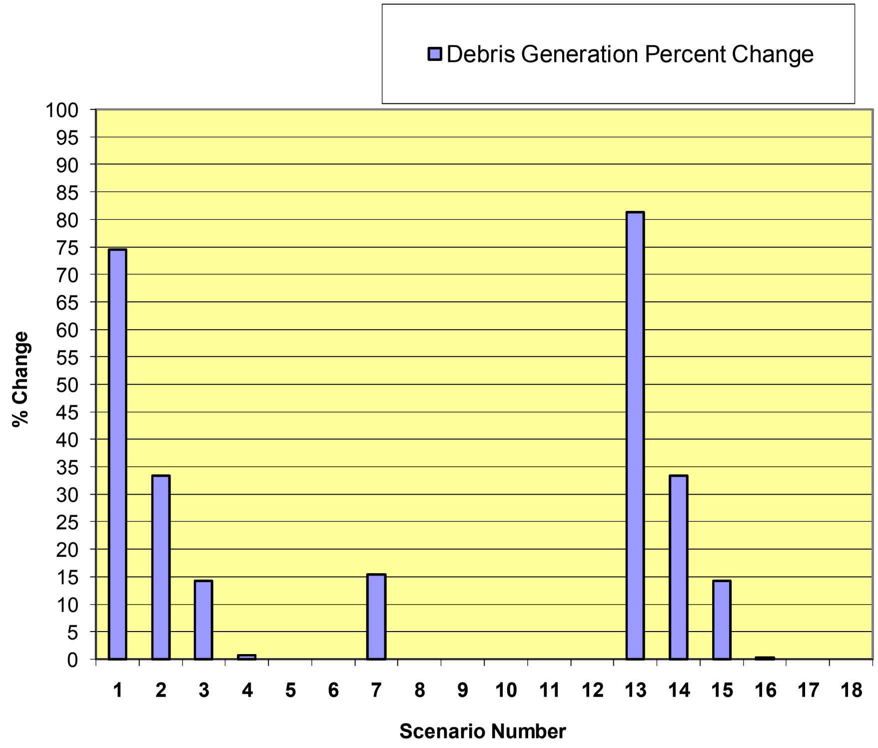


Figure 39 Illustration of the HAZUS-MH modeling results for the STATSGO SR M 7.3 Scenario.

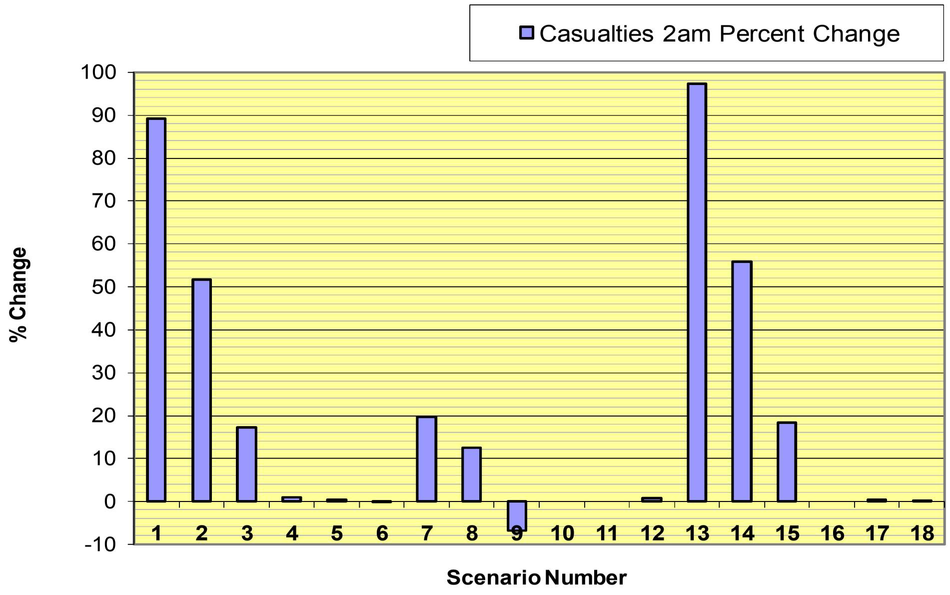
The Sa 0.3sec is shown in (a), total economic building loss is shown in (b), and the total debris generated is shown in (c).



Scenario Name	Scenario Number
geology sr 5.3	1
geology sr 6.3	2
geology sr 7.3	3
geology vsmrl 5.3	4
geology vsmrl 6.3	5
geology vsmrl 7.3	6
ssurgo sr 5.3	7
ssurgo sr 6.3	8
ssurgo sr 7.3	9
ssurgo vsmrl 5.3	10
ssurgo vsmrl 6.3	11
ssurgo vsmrl 7.3	12
statsgo sr 5.3	13
statsgo sr 6.3	14
statsgosr 7.3	15
statsgo vsmrl 5.3	16
statsgo vsmrl 6.3	17
statsgo vsmrl 7.3	18

Figure 40 Graph of all Enhanced Scenario Results for Debris Generation.

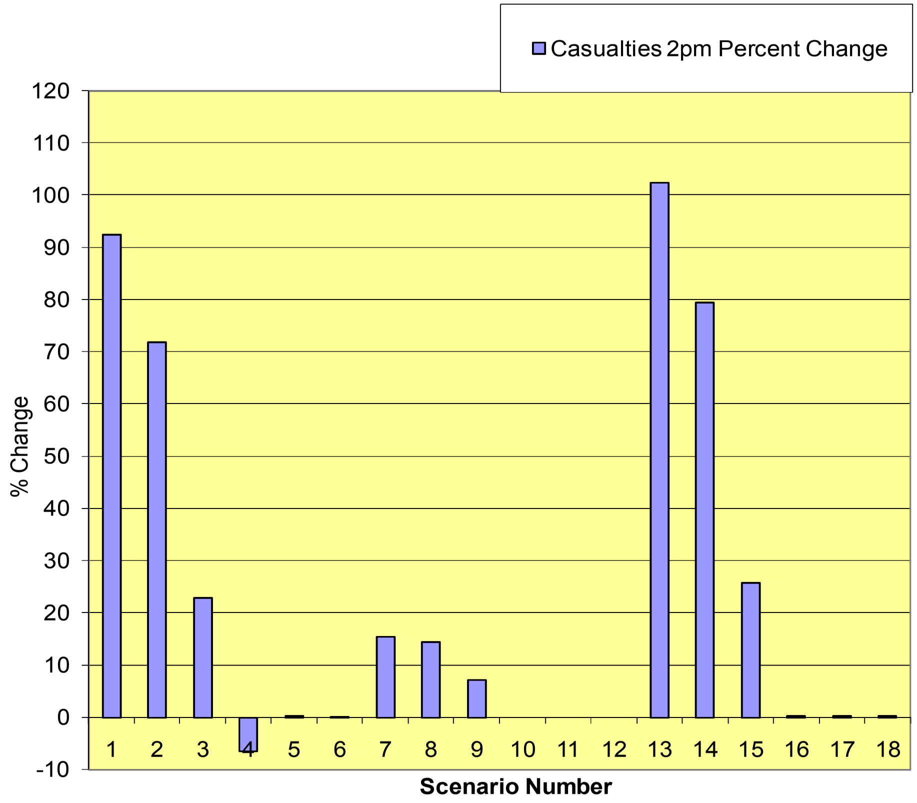
The figure represents the amount of change between the Enhanced and Baseline scenarios.



Scenario Name	Scenario Number
geology sr 5.3	1
geology sr 6.3	2
geology sr 7.3	3
geology vsmrl 5.3	4
geology vsmrl 6.3	5
geology vsmrl 7.3	6
ssurgo sr 5.3	7
ssurgo sr 6.3	8
ssurgo sr 7.3	9
ssurgo vsmrl 5.3	10
ssurgo vsmrl 6.3	11
ssurgo vsmrl 7.3	12
statsgo sr 5.3	13
statsgo sr 6.3	14
statsgosr 7.3	15
statsgo vsmrl 5.3	16
statsgo vsmrl 6.3	17
statsgo vsmrl 7.3	18

Figure 41 Graph of all Enhanced Scenario Results for 2am Casualties.

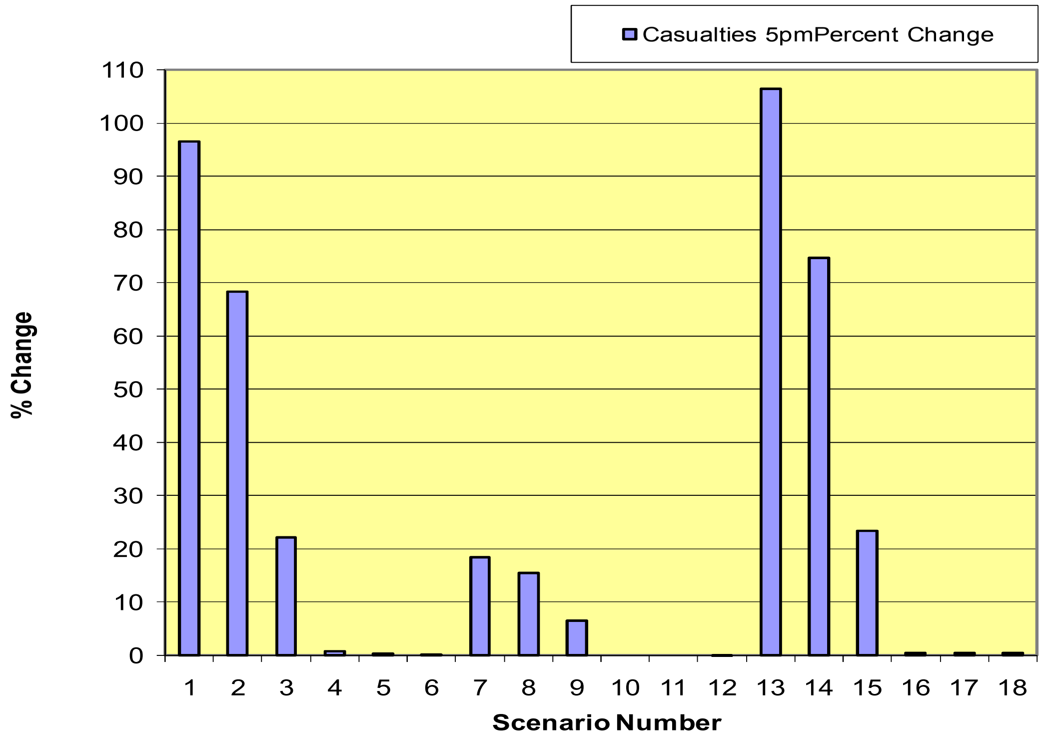
The figure represents the amount of change between the Enhanced and Baseline scenarios.



Scenario Name	Scenario Number
geology sr 5.3	1
geology sr 6.3	2
geology sr 7.3	3
geology vsmrl 5.3	4
geology vsmrl 6.3	5
geology vsmrl 7.3	6
ssurgo sr 5.3	7
ssurgo sr 6.3	8
ssurgo sr 7.3	9
ssurgo vsmrl 5.3	10
ssurgo vsmrl 6.3	11
ssurgo vsmrl 7.3	12
statsgo sr 5.3	13
statsgo sr 6.3	14
statsgosr 7.3	15
statsgo vsmrl 5.3	16
statsgo vsmrl 6.3	17
statsgo vsmrl 7.3	18

Figure 42 Graph of all Enhanced Scenario Results for 2pm Casualties.

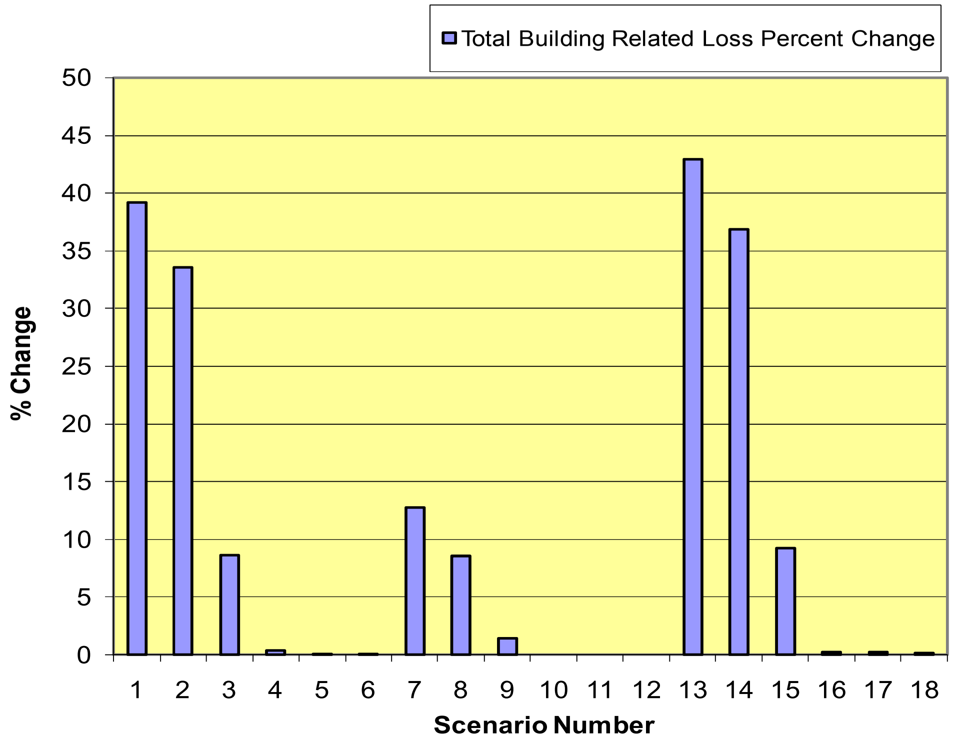
The figure represents the amount of change between the Enhanced and Baseline scenarios.



Scenario Name	Scenario Number
geology sr 5.3	1
geology sr 6.3	2
geology sr 7.3	3
geology vsmrl 5.3	4
geology vsmrl 6.3	5
geology vsmrl 7.3	6
ssurgo sr 5.3	7
ssurgo sr 6.3	8
ssurgo sr 7.3	9
ssurgo vsmrl 5.3	10
ssurgo vsmrl 6.3	11
ssurgo vsmrl 7.3	12
statsgo sr 5.3	13
statsgo sr 6.3	14
statsgosr 7.3	15
statsgo vsmrl 5.3	16
statsgo vsmrl 6.3	17
statsgo vsmrl 7.3	18

Figure 43 Graph of all Enhanced Scenario Results for 5pm Casualties.

The figure represents the amount of change between the Enhanced and Baseline scenarios.



Scenario Name	Scenario Number
geology sr 5.3	1
geology sr 6.3	2
geology sr 7.3	3
geology vsmrl 5.3	4
geology vsmrl 6.3	5
geology vsmrl 7.3	6
ssurgo sr 5.3	7
ssurgo sr 6.3	8
ssurgo sr 7.3	9
ssurgo vsmrl 5.3	10
ssurgo vsmrl 6.3	11
ssurgo vsmrl 7.3	12
statsgo sr 5.3	13
statsgo sr 6.3	14
statsgosr 7.3	15
statsgo vsmrl 5.3	16
statsgo vsmrl 6.3	17
statsgo vsmrl 7.3	18

Figure 44 Graph of all Enhanced Scenario Results for the Total Building Related Economic Loss.

The figure represents the amount of change between the Enhanced and Baseline scenarios.

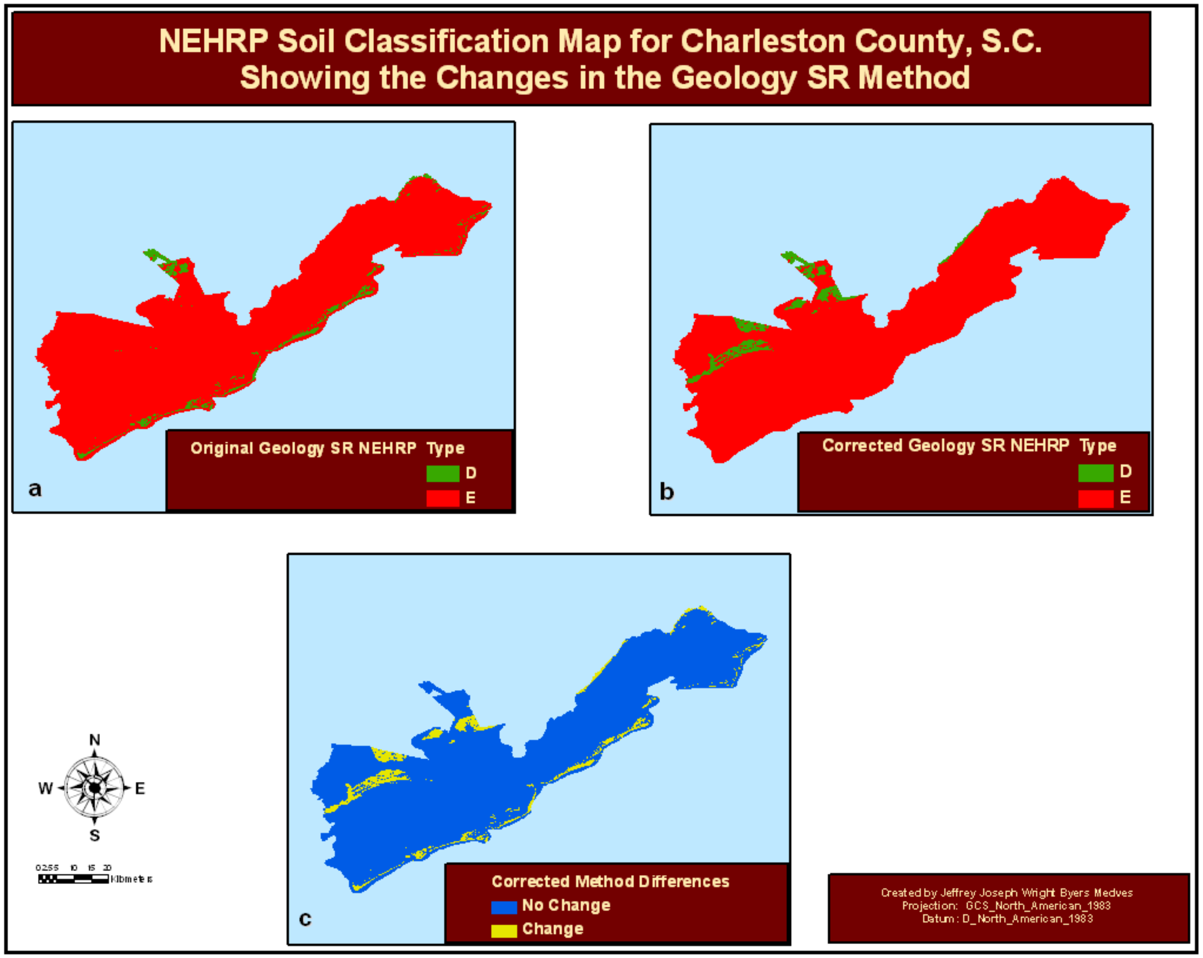


Figure 45 Corrected Methodology NEHRP classification maps for the USGS Geology SR Method.

The original method is shown in (a), corrected method shown in (b), and illustration of the changed units in (c).

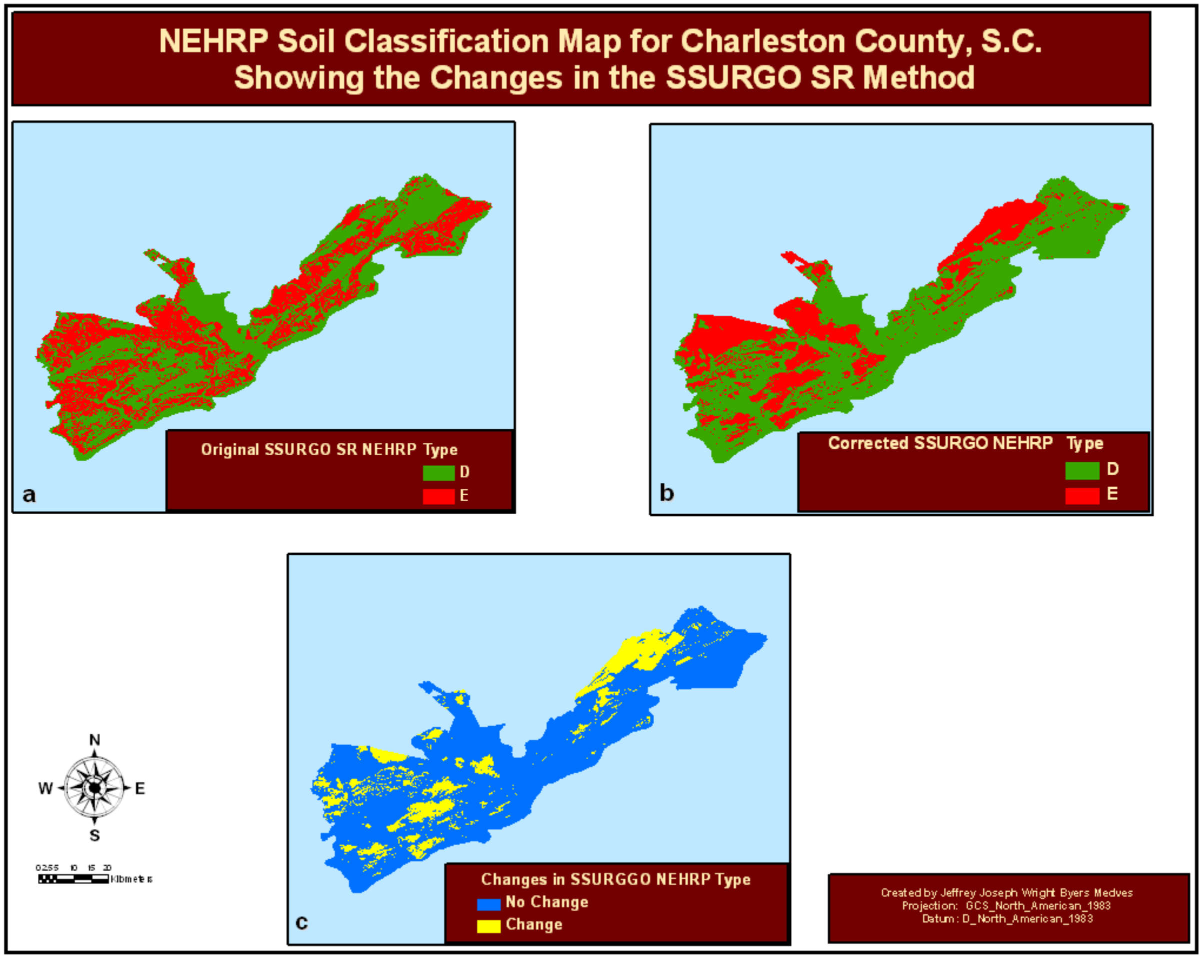


Figure 46 Corrected Methodology NEHRP classification maps for the NRCS SSURGO SR Method.

The original method is shown in (a), corrected method shown in (b), and illustration of the changed units in (c).

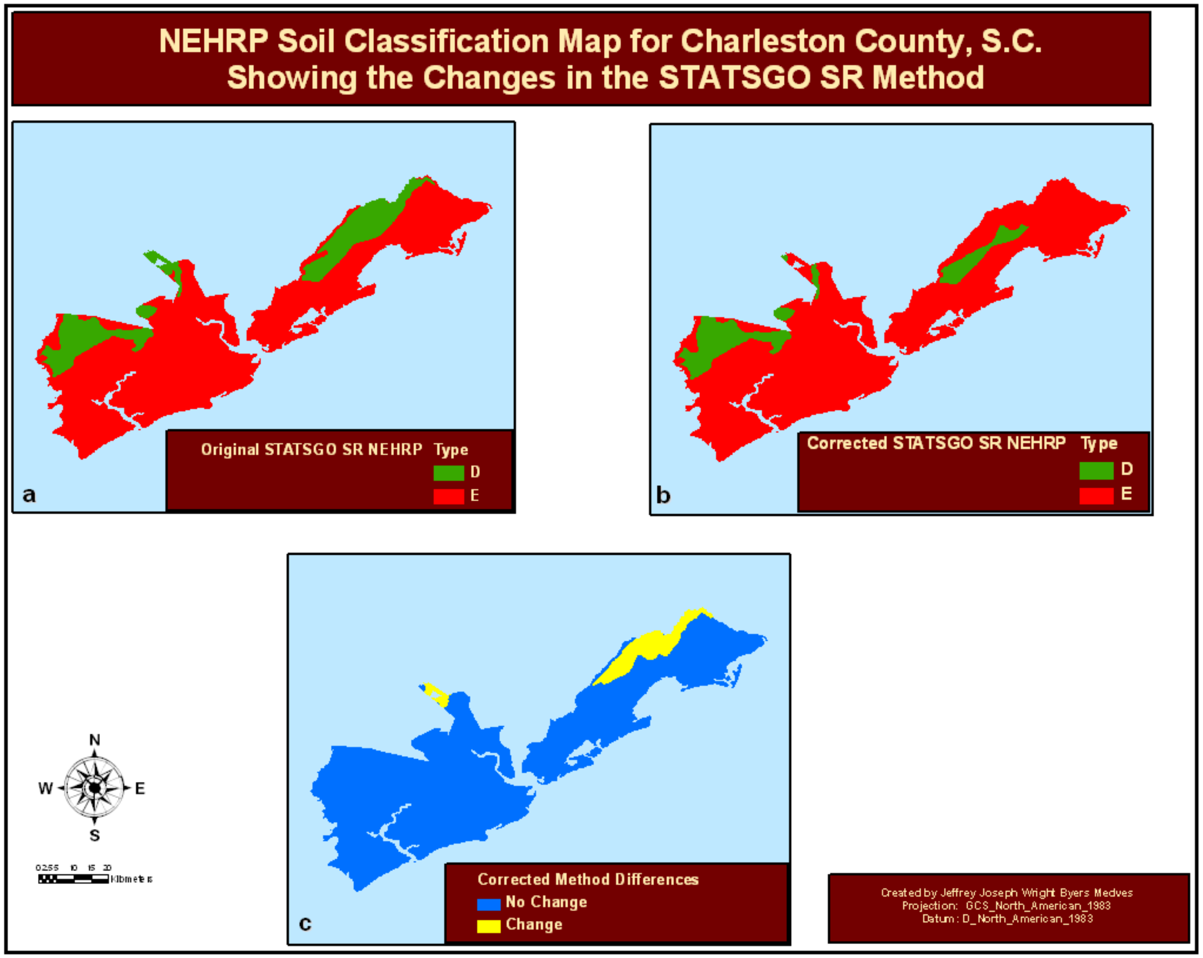


Figure 47 Corrected Methodology NEHRP classification maps for the NRCS STATSGO SR Method.

The original method is shown in (a), corrected method shown in (b), and illustration of the changed units in (c).

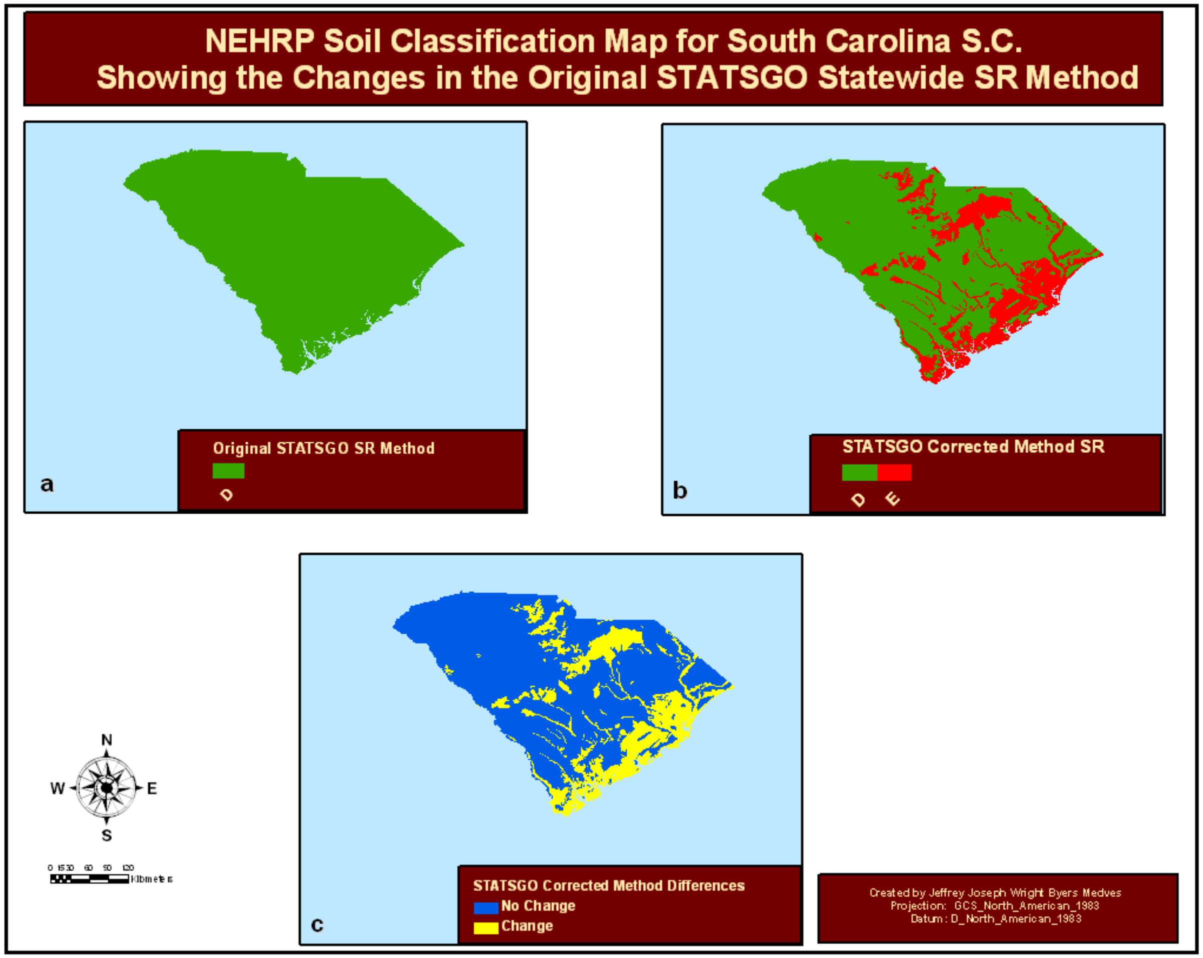
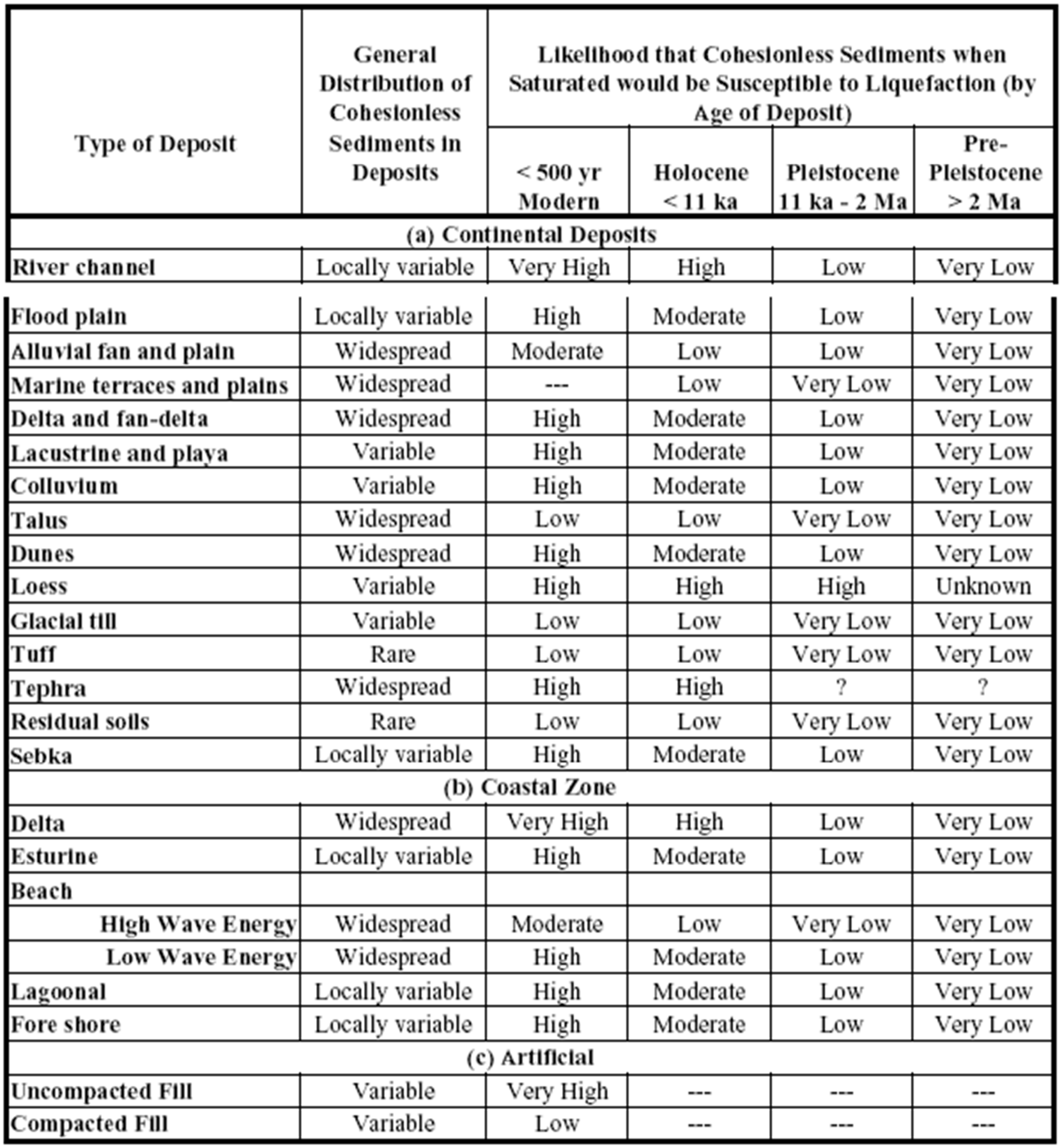


Figure 48 Corrected Methodology NEHRP classification maps for the NRCS STATSGO Statewide SR Method.

The original method is shown in (a), corrected method shown in (b), and illustration of the changed units in (c).

Site Class	**Site Class Description**	**Minimum Vs (m/sec)**	**Maximum Vs (m/sec)**
A	**HARD ROCK** Only	**1500**	
B	**ROCK**	**760**	**1500**
C	**VERY DENSE SOIL AND SOFT ROCK** Undrained shear strength $u_s \geq$ 2000psf ($u_s \geq$ 100 kPa) or N ≥ 50 blows/ft	**360**	**760**
D	**STIFF SOILS** Stiff soil with undrained shear strength 1000psf ≤ $u_s \leq$ 2000psf (50 kPa ≤ $u_s \leq$ 100 kPa) or 15 ≤ N ≤ 50 blows/ft	**180**	**360**
E	**SOFT SOILS** Profile with more than 10 ft (3 m) of soft clay defined as soil with plasticity index PI > 20, moisture content *w* > 40% and undrained shear strength u_s < 1000 psf (50 kPa) (N < 15 blows/ft)		**180**
F	Table 1 NEHRP GUIDLEINES illustrating the different NEHRP classifications (HAZUS MH MR-III Technical Manual, 2007) **SOILS REQUIRING SITE SPECIFIC EVALUATIONS** 1.**Soils vulnerable to potential failure or collapse under seismic loading:** e.g. liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. **2. Peats and/or highly organic clays** (10 ft (3 m) or thicker layer) **3. Very high plasticity clays:** (25 ft (8 m) or thicker layer with plasticity index > 75) **4. Very thick soft/medium stiff clays:** (120 ft (36 m) or thicker layer)		

Table 1 NEHRP GUIDLEINES illustrating the different NEHRP classifications (HAZUS MH MR-III Technical Manual, 2007).



Type of Deposit	General Distribution of Cohesionless Sediments in Deposits	Likelihood that Cohesionless Sediments when Saturated would be Susceptible to Liquefaction (by Age of Deposit)			
		< 500 yr Modern	Holocene < 11 ka	Pleistocene 11 ka - 2 Ma	Pre-Pleistocene > 2 Ma
(a) Continental Deposits					
River channel	Locally variable	Very High	High	Low	Very Low
Flood plain	Locally variable	High	Moderate	Low	Very Low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very Low
Marine terraces and plains	Widespread	---	Low	Very Low	Very Low
Delta and fan-delta	Widespread	High	Moderate	Low	Very Low
Lacustrine and playa	Variable	High	Moderate	Low	Very Low
Colluvium	Variable	High	Moderate	Low	Very Low
Talus	Widespread	Low	Low	Very Low	Very Low
Dunes	Widespread	High	Moderate	Low	Very Low
Loess	Variable	High	High	High	Unknown
Glacial till	Variable	Low	Low	Very Low	Very Low
Tuff	Rare	Low	Low	Very Low	Very Low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very Low	Very Low
Sebka	Locally variable	High	Moderate	Low	Very Low
(b) Coastal Zone					
Delta	Widespread	Very High	High	Low	Very Low
Esturine	Locally variable	High	Moderate	Low	Very Low
Beach					
High Wave Energy	Widespread	Moderate	Low	Very Low	Very Low
Low Wave Energy	Widespread	High	Moderate	Low	Very Low
Lagoonal	Locally variable	High	Moderate	Low	Very Low
Fore shore	Locally variable	High	Moderate	Low	Very Low
(c) Artificial					
Uncompacted Fill	Variable	Very High	---	---	---
Compacted Fill	Variable	Low	---	---	---

Table 2 Liquefaction Susceptibility Chart showing the relationship of age to liquefaction potential (HAZUS-MH MR III Technical Manual, 2007)

Map Unit	Avg VsMRL Velocity	Depth to Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation	AGE
af	194	63	D	E	(24 m/s) (156-204)	> 300 years old
ps	193	63	D	E	(24 m/s) (156-204)	> 300 years old
Qal	171	102	E	E	(24 m/s) (156-204)	Holocene 0-12 ka (thousand)
Qhm	187	36	D	E	(24 m/s) (156-204)	Holocene-Pleistocene (12ka-1.6ma)
Qhs	205	100	D	D	(24 m/s) (156-204)	Holocene 0-12 ka (thousand)
Qhsi	247	97	D	D	(24 m/s) (156-204)	Unknown
Qht	190	72	D	E	(24 m/s) (156-204)	Holocene 0-12 ka (thousand)
Qlc	209	70	D	D	(24 m/s) (156-204)	Pleistocene (250-750 ka) (thousand)
Qls	232	148	D	D	(24 m/s) (156-204)	Pleistocene (250-750 ka) (thousand)
Qpc	204	62	D	D	(24 m/s) (156-204)	Pleistocene (750ka-1.25ma) (thousand)
Qpf	223	53	D	D	(24 m/s) (156-204)	Pleistocene (750ka-1.25ma) (thousand)
Qps	158	58	E	D	(24 m/s) (156-204)	Pleistocene (750ka-1.25ma) (thousand)
Qsbc	188	41	D	E	(24 m/s) (156-204)	Pleistocene (33-85 ka) (thousand)
Qsbr	157	97	E	E	(24 m/s) (156-204)	Pleistocene (33-85 ka) (thousand)
Qsbs	193	53	D	E	(24 m/s) (156-204)	Pleistocene (33-85 ka) (thousand)

Table 3 Geologic Units Used in the Project

Map Unit	Avg VsMRL Velocity	Depth to Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation	AGE
Qtc	182	51	D	E	(24 m/s) (156-204)	Pleistocene (200-240 ka) (thousand)
Qtf	232	139	D	D	(24 m/s) (156-204)	Pleistocene (200-240 ka) (thousand)
Qts	190	115	D	E	(24 m/s) (156-204)	Pleistocene (200-240 ka) (thousand)
Qw	157	43	E	E	(24 m/s) (156-204)	Pleistocene (70-130 ka) (thousand)
Qwc	181	49	D	E	(24 m/s) (156-204)	Pleistocene (70-130 ka) (thousand)
Qwlc	207	54	D	D	(24 m/s) (156-204)	Pleistocene (33-85 ka) (thousand)
Qwls	195	63	D	E	(24 m/s) (156-204)	Pleistocene (70-130 ka) (thousand)
Qwr	157	47	E	E	(24 m/s) (156-204)	Pleistocene (70-130 ka) (thousand)
Qws	200	70	D	E	(24 m/s) (156-204)	Pleistocene (70-130 ka) (thousand)
Ta	216	87	D	D	(24 m/s) (156-204)	Oligocene (30 ma) (million)
Tcb	218	69	D	D	(24 m/s) (156-204)	Oligocene (30 ma) (million)
Tgc	230	201	D	D	(24 m/s) (156-204)	Pliocene (3.5ma) (million)
water	205	70	D	E	(24 m/s) (156-204)	Holocene 0-12 ka (thousand)

Table 3 Geologic Units Used in the Project

Site response calculations will be applied only to the samples that fall within the first order standard deviation of the Avg. Vs for the sample. All of the samples that do not fall within the standard deviation will keep their VsMRL rating for the SR classification
If age is greater than or equal to(>=) 250ka (thousand years), sample classified as a "D" Soil
If age is less than (<) 80k, sample classified as an "E" soil
If age falls between 250ka and 80ka, depth to water table (dwtbl) method is used
If water table depth is greater (deeper/larger value) than or equal to (>=) 1m, then the soil is classified as a "D" soil
If water table depth is less than (<) 1m, then the soil is classified as a "E" soil

Table 4 USGS Site Response MODEL showing the model parameters

Taxonomic Class Name	Avg. VsMRL Velocity	Avg. Depth To Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation
Null	207	194	D	D	(19 m/s) (161-199)
Aeric Alaquods, sandy, siliceous, thermic	212	30	D	D	(19 m/s) (161-199)
Aeric Endoaquults, fine mixed, semiactive, thermic	243	31	D	D	(19 m/s) (161-199)
Aeric Ochraquults, fine-loamy, siliceous, thermic	240	38	D	D	(19 m/s) (161-199)
Aeric Ochraquults, sandy, mixed, thermic	205	30	D	D	(19 m/s) (161-199)
Aquic Hapludults, fine, mixed, thermic	223	80	D	D	(19 m/s) (161-199)
Aquic Hapludults, fine-loamy, siliceous, thermic	190	61	D	E	(19 m/s) (161-199)
Aquic Quartzipsamments, thermic, coated	206	69	D	D	(19 m/s) (161-199)
Aquultic Hapludalfs, coarse-loamy, mixed, thermic	197	84	D	E	(19 m/s) (161-199)
Arenic Hapludults, loamy, siliceous, thermic	189	122	D	D	(19 m/s) (161-199)
Fluvaquentic Endoaquepts, fine, mixed, semiactive, acid, thermic	257	0	D	D	(19 m/s) (161-199)
Glossaquic Hapludalfs, coarse-loamy, siliceous, thermic	194	61	D	E	(19 m/s) (161-199)

Table 5 SSURGO Units used in the study

Taxonomic Class Name	Avg. VsMRL Velocity	Avg. Depth To Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation
Terric Haplosaprists, sandy or sandy-skeletal, siliceous, dysic, thermic	184	0	D	E	(19 m/s) (161-199)
Typic Albaqualfs, fine-loamy, siliceous, thermic	200	11	D	D	(19 m/s) (161-199)
Typic Argiaquolls, fine-loamy, mixed, thermic	200	15	D	D	(19 m/s) (161-199)
Typic Haplaquods, sandy, siliceous, thermic	204	15	D	D	(19 m/s) (161-199)
Typic Haplohumods, sandy, siliceous, thermic	205	61	D	D	(19 m/s) (161-199)
Typic Hapludults, fine-loamy, siliceous, subtractive, thermic	176	114	E	D	(19 m/s) (161-199)
Typic Humaquepts, sandy, siliceous, thermic	206	1	D	D	(19 m/s) (161-199)
Typic Ochraqualfs, fine-loamy, mixed, thermic	184	15	D	E	(19 m/s) (161-199)
Typic Ochraquults, fine-loamy, siliceous, thermic	237	8	D	D	(19 m/s) (161-199)
Typic Paleaquults, fine-loamy, siliceous, thermic	226	0	D	D	(19 m/s) (161-199)
Typic Paleudults, fine-loamy, siliceous, thermic	205	91	D	D	(19 m/s) (161-199)
Typic Psammaquents, siliceous, thermic	186	28	D	E	(19 m/s) (161-199)
Typic Quartzipsamments, thermic coated	200	136	D	D	(19 m/s) (161-199)
Typic Quartzipsamments, thermic, uncoated	204	201	D	D	(19 m/s) (161-199)

Table 5 SSURGO Units used in the study

Taxonomic Class Name	Avg. VsMRL Velocity	Avg. Depth To Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation
Typic Sulfaquents, fine, mixed, nonacid, thermic	188	0	D	E	(19 m/s) (161-199)
Typic Sulfaquents, fine, mixed, superactive,nonacid, thermic	199	0	D	E	(19 m/s) (161-199)
Typic Umbraqualfs, fine, mixed, thermic	199	0	D	E	(19 m/s) (161-199)
Typic Umbraqualfs, fine-loamy, siliceous, thermic	210	0	D	D	(19 m/s) (161-199)
Typic Umbraquults, fine, mixed, thermic	169	80	E	E	(19 m/s) (161-199)
Udothents	197	201	D	E	(19 m/s) (161-199)
Umbric Ochraqualfs, fine-loamy, mixed, thermic	187	0	D	E	(19 m/s) (161-199)

Table 5 SSURGO Units used in the study

Taxonomic Class Name	Avg. VsMRL Velocity	Avg. Depth To Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation
Null	207	194	D	D	(19 m/s) (161-199)
Aeric Alaquods, sandy, siliceous, thermic	212	30	D	D	(19 m/s) (161-199)
Aeric Endoaquults, fine mixed, semiactive, thermic	243	31	D	D	(19 m/s) (161-199)
Aeric Ochraquults, fine-loamy, siliceous, thermic	240	38	D	D	(19 m/s) (161-199)
Aeric Ochraquults, sandy, mixed, thermic	205	30	D	D	(19 m/s) (161-199)
Aquic Hapludults, fine, mixed, thermic	223	80	D	D	(19 m/s) (161-199)
Aquic Hapludults, fine-loamy, siliceous, thermic	190	61	D	E	(19 m/s) (161-199)
Aquic Quartzipsamments, thermic, coated	206	69	D	D	(19 m/s) (161-199)
Aquultic Hapludalfs, coarse-loamy, mixed, thermic	197	84	D	E	(19 m/s) (161-199)
Arenic Hapludults, loamy, siliceous, thermic	189	122	D	D	(19 m/s) (161-199)
Fluvaquentic Endoaquepts, fine, mixed, semiactive, acid, thermic	257	0	D	D	(19 m/s) (161-199)
Glossaquic Hapludalfs, coarse-loamy, siliceous, thermic	194	61	D	E	(19 m/s) (161-199)
Terric Haplosaprists, sandy or sandy-skeletal, siliceous, dysic, thermic	184	0	D	E	(19 m/s) (161-199)

Table 6 STATSGO Units used in the study

Taxonomic Class Name	Avg. VsMRL Velocity	Avg. Depth To Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation
Typic Albaqualfs, fine-loamy, siliceous, thermic	200	11	D	D	(19 m/s) (161-199)
Typic Argiaquolls, fine-loamy, mixed, thermic	200	15	D	D	(19 m/s) (161-199)
Typic Haplaquods, sandy, siliceous, thermic	204	15	D	D	(19 m/s) (161-199)
Typic Haplohumods, sandy, siliceous, thermic	205	61	D	D	(19 m/s) (161-199)
Typic Hapludults, fine-loamy, siliceous, subtractive, thermic	176	114	E	D	(19 m/s) (161-199)
Typic Humaquepts, sandy, siliceous, thermic	206	1	D	D	(19 m/s) (161-199)
Typic Ochraqualfs, fine-loamy, mixed, thermic	184	15	D	E	(19 m/s) (161-199)
Typic Ochraquults, fine-loamy, siliceous, thermic	237	8	D	D	(19 m/s) (161-199)
Typic Paleaquults, fine-loamy, siliceous, thermic	226	0	D	D	(19 m/s) (161-199)
Typic Paleudults, fine-loamy, siliceous, thermic	205	91	D	D	(19 m/s) (161-199)
Typic Psammaquents, siliceous, thermic	186	28	D	E	(19 m/s) (161-199)
Typic Quartzipsamments, thermic coated	200	136	D	D	(19 m/s) (161-199)
Typic Quartzipsamments, thermic, uncoated	204	201	D	D	(19 m/s) (161-199)

Table 6 STATSGO Units used in the study

Taxonomic Class Name	Avg. VsMRL Velocity	Avg. Depth To Water Table (cm)	NEHRP Vs MRL	NEHRP SR	Standard Deviation
Typic Sulfaquents, fine, mixed, nonacid, thermic	188	0	D	E	(19 m/s) (161-199)
Typic Sulfaquents, fine, mixed, superactive,nonacid, thermic	199	0	D	E	(19 m/s) (161-199)
Typic Umbraqualfs, fine, mixed, thermic	199	0	D	E	(19 m/s) (161-199)
Typic Umbraqualfs, fine-loamy, siliceous, thermic	210	0	D	D	(19 m/s) (161-199)
Typic Umbraquults, fine, mixed, thermic	169	80	E	E	(19 m/s) (161-199)
Udothents	197	201	D	E	(19 m/s) (161-199)
Umbric Ochraqualfs, fine-loamy, mixed, thermic	187	0	D	E	(19 m/s) (161-199)

Table 6 STATSGO Units used in the study

Site response calculations will be applied only to the samples that fall within the first order standard deviation of the Avg. Vs for the sample. All of the samples that do not fall within the standard deviation will keep their VsMRL rating for the SR classification
For surface soils (SSURGO and STATSGO), the age factor is negated, and only Avg. VsMRL and Avg. Depth to Water Table are used
If water table depth is greater (deeper/larger value) than or equal to (>=) 1m, then the soil is classified as a "D" soil
If water table depth is less than (<) 1m, then the soil is classified as a "E" soil

Table 7 NRCS Soils Site Response Method model parameters

Scenario Name	Debris Generation Tons (thousands)	Debris Generation Tons (millions)	Casualties 2am	Casualties 2pm	Casualties 5pm	Total Building Related Loss (millions of $)
baseline 5.3	279	0.279	223	278	233	1061.34
baseline 6.3	3000	3.000	3386	5626	4684	6803.45
baseline 7.3	7000	7.000	9930	16593	13892	15600.81

Table 8 HAZUS-MH scenario results for the baseline data values

Scenario Name	Scenario Number	Debris Generation Tons (thousands)	Debris Generation Tons (millions)	Casualties 2am	Casualties 2pm	Casualties 5pm	Total Building Related Loss (millions of $)
geology sr 5.3	1	487	0.487	422	535	458	1477.14
geology sr 6.3	2	4000	4.000	5137	9666	7887	9088.04
geology sr 7.3	3	8000	8.000	11646	20402	16963	16941.90
geology vsmrl 5.3	4	281	0.281	225	260	235	1064.66
geology vsmrl 6.3	5	3000	3.000	3401	5647	4700	6806.76
geology vsmrl 7.3	6	7000	7.000	9928	16608	13908	15608.39

Table 9 HAZUS-MH scenario results for the USGS Geology data values

Scenario Name	Scenario Number	Debris Generation Tons (thousands)	Debris Generation Tons (millions)	Casualties 2am	Casualties 2pm	Casualties 5pm	Total Building Related Loss (millions of $)
ssurgo sr 5.3	7	322	0.322	267	321	276	1196.81
ssurgo sr 6.3	8	3000	3.000	3811	6443	5413	7386.77
ssurgo sr 7.3	9	7000	7.000	9248	17797	14797	15820.76
ssurgo vsmrl 5.3	10	279	0.279	223	278	233	1061.34
ssurgo vsmrl 6.3	11	3000	3.000	3386	5626	4684	6803.45
ssurgo vsmrl 7.3	12	7000	7.000	10010	16593	13894	15600.81

Table 10 HAZUS-MH scenario results for the NRCS SSURGO data values

Scenario Name	Scenario Number	Debris Generation Tons (thousands)	Debris Generation Tons (millions)	Casualties 2am	Casualties 2pm	Casualties 5pm	Total Building Related Loss (millions of $)
statsgo sr 5.3	13	506	0.506	440	563	481	1516.93
statsgo sr 6.3	14	4000	4.000	5281	10093	8184	9312.53
statsgosr 7.3	15	8000	8.000	11748	20862	17142	17041.09
statsgo vsmrl 5.3	16	280	0.280	223	279	234	1063.40
statsgo vsmrl 6.3	17	3000	3.000	3400	5639	4708	6817.93
statsgo vsmrl 7.3	18	7000	7.000	9956	16638	13969	15625.72

Table 11 HAZUS-MH scenario results for the NRCS STATSGO data values

Scenario Name	Scenario Number	Debris Generation Percent Change	Casualties 2am Percent Change	Casualties 2pm Percent Change	Casualties 5pm Percent Change	Total Building Related Loss Percent Change
geology sr 5.3	1	75	89	92	97	39
geology sr 6.3	2	33	52	72	68	34
geology sr 7.3	3	14	17	23	22	9
geology vsmrl 5.3	4	1	1	-6	1	<1
geology vsmrl 6.3	5	<1	<1	<1	<1	<1
geology vsmrl 7.3	6	<1	<1	<1	<1	<1

Table 12 HAZUS-MH scenario results for the USGS Geology data values, compared to the Baseline output values in order to determine the amount of change that occurred as a result of the enhanced scenario.

Scenario Name	Scenario Number	Debris Generation Percent Change	Casualties 2am Percent Change	Casualties 2pm Percent Change	Casualties 5pm Percent Change	Total Building Related Loss Percent Change
ssurgo sr 5.3	7	15	20	15	18	13
ssurgo sr 6.3	8	<1	13	15	16	9
ssurgo sr 7.3	9	<1	-7	7	7	1
ssurgo vsmrl 5.3	10	<1	<1	<1	<1	<1
ssurgo vsmrl 6.3	11	<1	<1	<1	<1	<1
ssurgo vsmrl 7.3	12	<1	1	<1	<1	<1

Table 13 HAZUS-MH scenario results for the NRCS SSURGO data values, compared to the Baseline output values in order to determine the amount of change that occurred as a result of the enhanced scenario.

Scenario Name	Scenario Number	Debris Generation Percent Change	Casualties 2am Percent Change	Casualties 2pm Percent Change	Casualties 5pm Percent Change	Total Building Related Loss Percent Change
statsgo sr 5.3	13	81	97	103	106	43
statsgo sr 6.3	14	33	56	79	75	37
statsgosr 7.3	15	14	18	26	23	9
statsgo vsmrl 5.3	16	<1	<1	<1	<1	<1
statsgo vsmrl 6.3	17	<1	<1	<1	1	<1
statsgo vsmrl 7.3	18	<1	<1	<1	1	<1

Table 14 HAZUS-MH scenario results for the NRCS STATSGO data values, compared to the Baseline output values in order to determine the amount of change that occurred as a result of the enhanced scenario.

Map_Unit	NEHRP 30m	NEHRP Vs MRL	NEHRP SR	NEHRP SR Methods Corrected With Age
af	D	D	E	E
ps	D	D	E	E
Qal	D	E	E	E
Qhm	D	D	E	E
Qhs	D	D	D	E
Qhsi	D	D	D	E
Qht	D	D	E	E
Qlc	D	D	D	D
Qls	D	D	D	D
Qpc	D	D	D	D
Qpf	D	D	D	D
Qps	D	E	D	D
Qsbc	D	D	E	E
Qsbr	D	E	E	E
Qsbs	D	D	E	E
Qtc	D	D	E	E
Qtf	D	D	D	D
Qts	D	D	E	D
Qw	D	E	E	E
Qwc	D	D	E	E
Qwlc	D	D	D	E
Qwls	D	D	E	E
Qwr	D	E	E	E
Qws	D	D	E	E
Ta	D	D	D	D
Tcb	D	D	D	D
Tgc	D	D	D	D
water	D	D	E	E

Table 15 Corrected Model results for the USGS Geology SR method.

Taxonomic Class Name	NEHRP Vs MRL	NEHRP SR	NEHRP SR Method Correction
Null	D	D	D
Aeric Alaquods, sandy, siliceous, thermic	D	D	E
Aeric Endoaquults, fine mixed, semiactive, thermic	D	D	E
Aeric Ochraquults, fine-loamy, siliceous, thermic	D	D	E
Aeric Ochraqualfs, sandy, mixed, thermic	D	D	E
Aquic Hapludults, fine, mixed, thermic	D	D	E
Aquic Hapludults, fine-loamy, siliceous, thermic	D	E	E

Table 16 Corrected Model results for the NRCS SSURGO SR method.

Taxonomic Class Name	NEHRP Vs MRL	NEHRP SR	NEHRP SR Method Correction
Aquic Quartzipsamments, thermic, coated	D	D	E
Aquultic Hapludalfs, coarse-loamy, mixed, thermic	D	E	E
Arenic Hapludults, loamy, siliceous, thermic	D	D	D
Fluvaquentic Endoaquepts, fine, mixed, semiactive, acid, thermic	D	D	E
Glossaquic Hapludalfs, coarse-loamy, siliceous, thermic	D	E	E
Terric Haplosaprists, sandy or sandy-skeletal, siliceous, dysic, thermic	D	E	E
Typic Albaqualfs, fine-loamy, siliceous, thermic	D	D	E
Typic Argiaquolls, fine-loamy, mixed, thermic	D	D	E
Typic Haplaquods, sandy, siliceous, thermic	D	D	E

Table 16 Corrected Model results for the NRCS SSURGO SR method.

Taxonomic Class Name	NEHRP Vs MRL	NEHRP SR	NEHRP SR Method Correction
Typic Haplohumods, sandy, siliceous, thermic	D	D	E
Typic Hapludults, fine-loamy, siliceous, subtractive, thermic	E	D	E
Typic Humaquepts, sandy, siliceous, thermic	D	D	E
Typic Ochraqualfs, fine-loamy, mixed, thermic	D	E	E
Typic Ochraquults, fine-loamy, siliceous, thermic	D	D	E
Typic Paleaquults, fine-loamy, siliceous, thermic	D	D	E
Typic Paleudults, fine-loamy, siliceous, thermic	D	D	E
Typic Psammaquents, siliceous, thermic	D	E	E
Typic Quartzipsamments, thermic coated	D	D	D

Table 16 Corrected Model results for the NRCS SSURGO SR method.

Taxonomic Class Name	NEHRP Vs MRL	NEHRP SR	NEHRP SR Method Correction
Typic Quartzipsamments, thermic, uncoated	D	D	E
Typic Sulfaquents, fine, mixed, nonacid, thermic	D	E	E
Typic Sulfaquents, fine, mixed, superactive,nonacid, thermic	D	E	E
Typic Umbraqualfs, fine, mixed, thermic	D	E	E
Typic Umbraqualfs, fine-loamy, siliceous, thermic	D	D	E
Typic Umbraquults, fine, mixed, thermic	E	E	E
Udothents	D	E	E
Umbric Ochraqualfs, fine-loamy, mixed, thermic	D	E	E

Table 16 Corrected Model results for the NRCS SSURGO SR method.

Taxonomic Class Name	NEHRP Vs MRL	NEHRP SR	NEHRP SR Method Correction
Null	D	E	E
Aeric Alaquods, sandy, siliceous, thermic	D	D	E
Aquic Paleudults, claey, kaolinitic, thermic	E	D	D
Fluvaquentic Dystrochrepts, fine kaolinitic, thermic	D	D	E
Typic Albaqualfs, fine-loamy, siliceous, thermic	E	E	E
Typic Albaquults, clayey, mixed, thermic	D	E	E
Typic Endoaqualfs, fine, mixed, thermic	D	E	E
Typic Endoaqualfs, fine-loamy, siliceous, thermic	D	D	E
Typic Hapludults, fine-loamy, siliceous, thermic	E	D	D
Typic Humaquepts, sandy, siliceous, thermic	D	E	E
Typic Hydraquents, fine, mixed acid, thermic	D	D	E
Typic Quartzipsamments, thermic, coated	D	E	E
Typic Sulfaquents, fine, mixed, nonacid, thermic	D	E	E
Typic Umbraquults, clayey, mixed thermic	E	E	E
Umbric Ednoaqualfs, fine-loamy, mixed, thermic	D	E	E

Table 17 Corrected Model results for the NRCS STATSGO Clipped SR method.

Taxonomic Order Name	NEHRP Vs MRL	NEHRP SR	NEHRP SR Corrected Method
NULL	D	D	D
Alfisols	D	D	E
Entisols	D	D	E
Histosols	D	D	E
Inceptisols	D	D	D
Mollisols	D	D	E
Spodosols	D	D	E
Ultisols	D	D	D

Table 18 Corrected Model results for the NRCS STATSGO Statewide SR method.