# Chapter 11

# SOUTH CAROLINA GEOLOGY AND SEISMICITY

GEOTECHNICAL DESIGN MANUAL

*January 2022*

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# CHAPTER 11

# SOUTH CAROLINA GEOLOGY AND SEISMICITY

## 11.1 INTRODUCTION

This Chapter describes South Carolina's basic geology and seismicity within the context of performing geotechnical engineering for SCDOT. It is anticipated that the material contained in this Chapter will establish a technical framework by which basic geology and seismicity can be addressed. It is not intended to be an in-depth discussion of all the geologic formations and features found in South Carolina (SC) nor a highly technical discussion of the state's seismicity. The GEORs are expected to have sufficient expertise in these technical areas and to have the foresight and resourcefulness to keep up with the latest advancements in these areas.

The State of South Carolina is located in the Southeastern United States and is bounded on the north by the State of North Carolina, on the west and the south by the State of Georgia, and on the east by the Atlantic Ocean. The State is located between Latitudes 32° 4' 30" N and 35° 12' 00" N and between Longitudes 78° 0' 30" W and 83° 20' 00" W. The State is roughly triangular in shape and measures approximately 260 miles East-West and approximately 200 miles North-South at the states widest points. The South Carolina coastline is approximately 187 miles long. South Carolina is ranked 40th in size in the United States with an approximate total area of 31,189 square miles.

The geology of South Carolina is similar to that of the neighboring states of Georgia, North Carolina, and Virginia. These states have an interior consisting of the Appalachian Mountains with an average elevation of 3,000 feet. Just east of the Appalachian Mountains is the Piedmont region that typically ranges in elevation from 300 feet to 1000 feet. Continuing eastward from these highlands is a "Fall Line" which serves to transition into the Atlantic Coastal Plain. The Atlantic Coastal Plain gently slopes towards the Atlantic Ocean with few elevations higher than 300 feet.

The 1886 seismic event that occurred in the Coastal Plain near Charleston, South Carolina dominates the seismic history of the southeastern United States. It is the largest historic seismic event in the southeastern United States with an estimated moment magnitude ($M_w$) of 7.3. The damage area with a Modified Mercalli Intensity (MMI) scale of X, is an elliptical shape roughly 20 by 30 miles trending northeast between Charleston and Jedburg and including Summerville and roughly centered at Middleton Place. The intraplate epicenter of this seismic event and its magnitude is not unique in the Central and Eastern United States (CEUS). Other intraplate seismic events include those at Cape Ann, Massachusetts (1755) with an estimated $M_w$ of 5.9, and New Madrid, Missouri (1811-1812) with an estimated $M_w$ of at least 7.7.

The following Sections describe the basic geology of South Carolina and the seismicity that will be used to perform geotechnical engineering designs and analyses. The topics discussed in these Sections will be referenced throughout this Manual.

## 11.2 SOUTH CAROLINA GEOLOGY

South Carolina geology can be divided into 3 basic physiographic units: Blue Ridge Unit (Appalachian Mountains), Piedmont Unit, and the Coastal Plain Unit. The generalized locations of these physiographic units are shown in Figure 11-1.

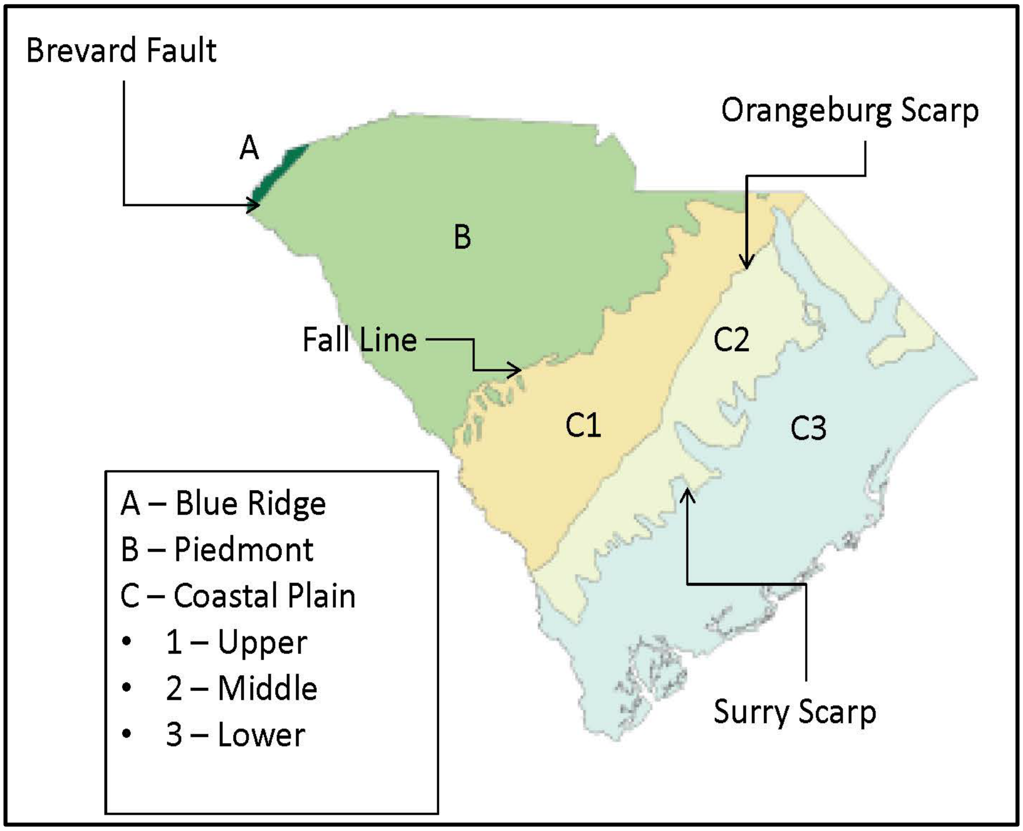



**Figure 11-1, South Carolina Physiographic Units (SCDNR (2013))**

The Blue Ridge Unit (Appalachian Mountains) covers approximately 2 percent of the state and is located in the northwestern corner of the state. The Blue Ridge Unit is separated from the Piedmont Unit by the Brevard Fault. The Piedmont Unit comprises approximately one-third of the state with the Coastal Plain Unit covering the remaining two-thirds of the state. The Piedmont and Coastal Plain Units are separated by the “Fall Line” as indicated in Figure 11-1. The geologic formations are typically aligned from the South-Southwest to the North-Northeast and parallel the South Carolina Atlantic coastline as shown in the generalized geologic map in Figure 11-2. The physiographic units in Figure 11-2 are broken down by the geologic time of the surface formations. South Carolina formations span in age from late Precambrian through the Quaternary period. The descriptions of events that have occurred over geologic time in South Carolina are shown in Figure 11-3. Please note that the term “Tertiary” is used in Figure 11-3; however, the Tertiary Period has been divided into the Paleogene and Neogene Periods by the International Commission on Stratigraphy, a subunit of the International Union of Geological Sciences. For the purposes of the GDM the term Tertiary Period will be deleted and replaced by Paleogene and Neogene Periods.

A description of the geologic formations, age, and geologic features for the Blue Ridge, Piedmont, and Coastal Plain Physiographic Units are provided in the following Sections.

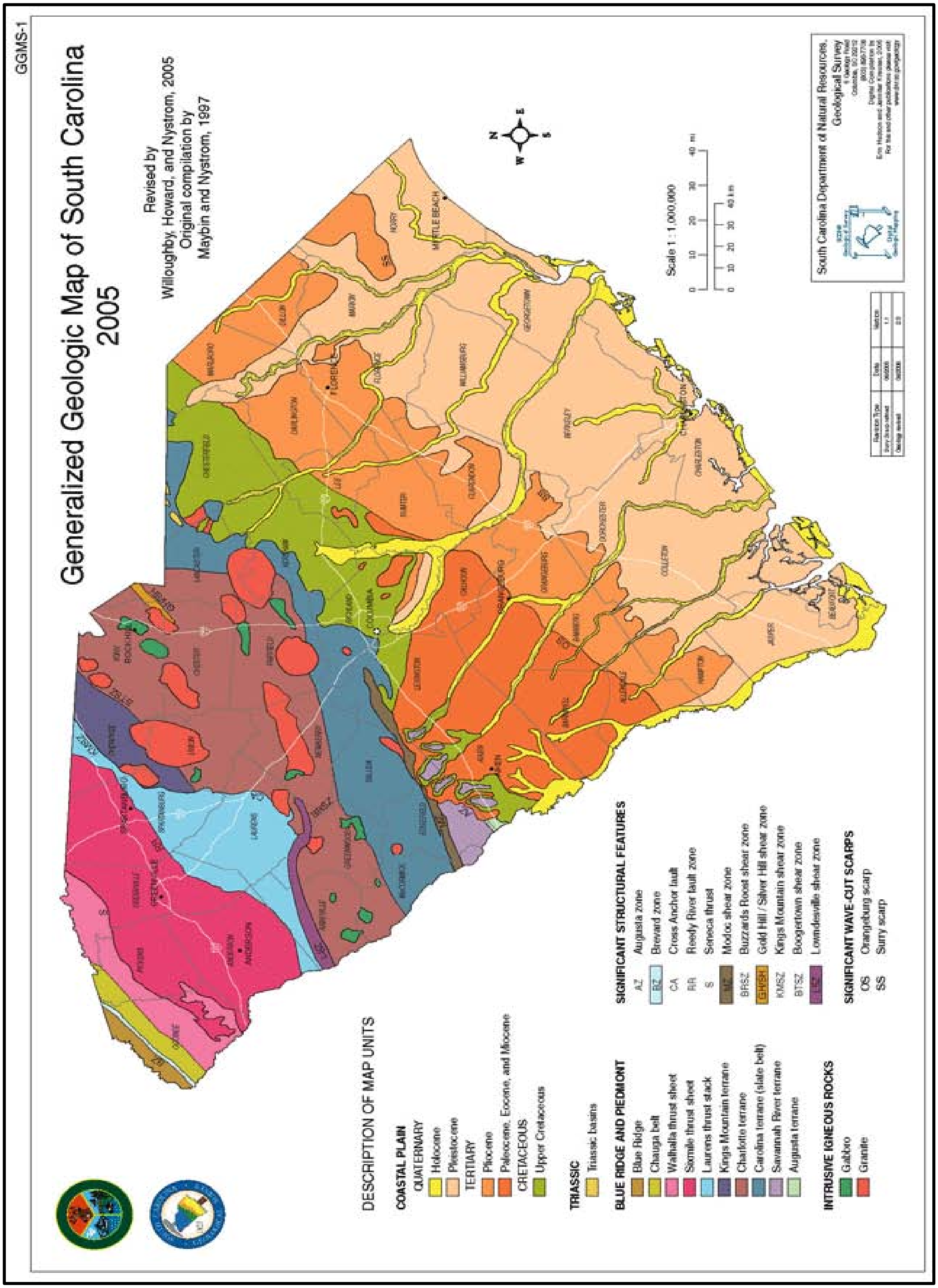



**Figure 11-2, Generalized Geologic Map of South Carolina (SCDNR (2005))**

# Geologic Time Scale for South Carolina

(not scaled for geologic time or thickness of deposits)

| EON | ERA | PERIOD | EPOCH | Geologic Events in South Carolina | MYA* |
|---|---|---|---|---|---|
| PHANEROZOIC | CENOZOIC | QUATERNARY | HOLOCENE | Barrier Islands formed; flood plains of major rivers established. | 0.01 |
| PHANEROZOIC | CENOZOIC | QUATERNARY | PLEISTOCENE | Surficial deposits cover the underlying Coastal Plain formations. Carolina Bays develop; scarps form due to sea level rise and fall. | 1.6 |
| PHANEROZOIC | CENOZOIC | TERTIARY – NEOGENE | PLIOCENE | Coastal Plain sediments reflect large-scale regressive cycles. Off-lap of the ocean and scouring responsible for the Orangeburg scarp. | 5.3 |
| PHANEROZOIC | CENOZOIC | TERTIARY – NEOGENE | MIOCENE | Uplift and erosion of Piedmont and mountains. Fluvial sediments spread over the Coastal Plain. Sandhill dunes deposited. | 23 |
| PHANEROZOIC | CENOZOIC | TERTIARY – PALEOGENE | OLIGOCENE | Deposition of carbonates predominate. Arches and embayments continue to influence deposition of Coastal Plain formations. | 36.6 |
| PHANEROZOIC | CENOZOIC | TERTIARY – PALEOGENE | EOCENE | Sand deposited in upper Coastal Plain; limestone deposited in middle and lower Coastal Plain. Fault activity. | 53 |
| PHANEROZOIC | CENOZOIC | TERTIARY – PALEOGENE | PALEOCENE | Fluvial, marginal marine and marine Coastal Plain sediments deposited. | 65 |
| PHANEROZOIC | MESOZOIC | CRETACEOUS | | Development of the Cape Fear Arch and South Georgia Embayment influences deposition of Coastal Plain formations. Fault activity. | 135 |
| PHANEROZOIC | MESOZOIC | JURASSIC | | Renewed sea floor spreading; intrusion of N-S and NW-SE trending diabase (basaltic) dikes. Great North American intrusive event. | 205 |
| PHANEROZOIC | MESOZOIC | TRIASSIC | | Breakup of the supercontinent Pangea. Triassic rift-basins develop and fault activity. | 250 |
| PHANEROZOIC | PALEOZOIC | PERMIAN | | Alleghanian Orogeny - closing of the Iapetus Ocean accompanied by continental collision and formation of the supercontinent Pangea. Rocks related to South Carolina are folded and thrusted; some rocks may have been metamorphosed. | 290 |
| PHANEROZOIC | PALEOZOIC | PENNSYLVANIAN | Emplacement of igneous intrusions | Time of uplift and erosion. | 320 |
| PHANEROZOIC | PALEOZOIC | MISSISSIPPIAN | Emplacement of igneous intrusions | Time of uplift and erosion. | 355 |
| PHANEROZOIC | PALEOZOIC | DEVONIAN | Emplacement of igneous intrusions | Arcadian Orogeny - rocks related to South Carolina may have been folded, faulted, and metamorphosed. | 408 |
| PHANEROZOIC | PALEOZOIC | SILURIAN | Emplacement of igneous intrusions | Laurentia and western South America/Africa shear apart as the Gondwanian supercontinent breakup begins. | 438 |
| PHANEROZOIC | PALEOZOIC | ORDOVICIAN | Emplacement of igneous intrusions | Taconic Orogeny - collision of Laurentia with western South America/Africa; Gondwanian supercontinent forms. Rocks related to South Carolina are folded, sheared/faulted, and metamorphosed. | 510 |
| PHANEROZOIC | PALEOZOIC | CAMBRIAN | Emplacement of igneous intrusions | Deposition of volcanic and sedimentary rocks found in the Slate belt. | 570 |
| PRECAMBRIAN | PROTEROZOIC EON | | | Opening of the Iapetus Ocean (750 to 700 million years ago) and continental rifting of Laurentia's (North America) eastern margin. | 2,500 |
| PRECAMBRIAN | ARCHEAN EON | | | Grenville Orogeny (1,100 million years ago) metamorphosed basement rocks and rocks related to the Blue Ridge. Oldest rock dated in South Carolina is 1,200 million years old. | 3,800 |
| | | | | | 4,600 |
| | | | | Oldest known rock in U.S. - 3,600 million years old. Oldest known rock in world - 3,850 million years old. Formation of the Earth - 4,600 million years old. | |

* Estimated age in millions of years.

MYA = million years ago

Based on the 1989 Global Stratigraphic Chart, International Union of Geological Sciences.

**Figure 11-3, Geologic Time Scale for South Carolina (SCDNR (1998))**

## 11.3 BLUE RIDGE UNIT

The Blue Ridge Unit consists of mountains that are part of the Blue Ridge Mountains and is a southern continuation of the Appalachian Mountains. The Brevard Fault zone (depicted as the Brevard zone, BZ, in Figure 11-2) separates the Blue Ridge Unit from the Piedmont Unit. It consists of metamorphic and igneous rocks. The topography is rugged and mountainous and contains the highest elevations in the State of South Carolina with elevations ranging from 1,400 feet to 3,500 feet. Sassafras Mountain is the highest point in South Carolina with an elevation of 3,560 feet. The Appalachian Mountains were formed in the late Paleozoic Era, about 342 MYA. The basement rocks in the Blue Ridge Unit were formed in the late Precambrian time period (570 to 2,500 MYA). The oldest rock dated in South Carolina is 1,200 million years old.

The bedrock in this region is a complex crystalline formation that has been faulted and contorted by past tectonic movements. The rock has weathered to residual soils that form the mantle for the hillsides and hilltops. The typical residual soil profile in areas not disturbed by erosion or the activities of man consists of clayey soils near the surface where weathering is more advanced, underlain by sandy silts and silty sands. There may be colluvial (old land-slide) material on the slopes.

## 11.4 PIEDMONT UNIT

The Piedmont Unit is bounded on the west by the Blue Ridge Unit and on the east by the Coastal Plain Unit. The boundary between the Blue Ridge Unit and the Piedmont Unit is typically assumed to be the Brevard Fault zone (depicted as the Brevard zone, BZ, in Figure 11-2). The common boundary between the Piedmont Unit and the Coastal Plain Unit is the “Fall Line”. It is believed that the Piedmont is the remains of an ancient mountain chain that has been heavily eroded with existing elevations ranging from 300 feet to 1,400 feet. The Piedmont is characterized by gently rolling topography, deeply weathered bedrock, and relatively few rock outcrops. It contains monadnocks that are isolated outcrops of bedrock (usually quartzite or granite) that are a result of the erosion of the mountains. The vertical stratigraphic sequence consists of 5 to 70 feet of weathered residual soils at the surface underlain by metamorphic and igneous basement rocks (granite, schist, and gneiss). The weathered soils (saprolites) are physically and chemically weathered rocks that can be soft/loose to very hard and dense, or friable and typically retain the structure of the parent rock. The geology of the Piedmont is complex with numerous rock types that were formed during the Paleozoic Era (250 to 570 MYA).

The boundary between soil (i.e., completely decomposed rock) and parent bedrock is not sharply defined and is comprised of a transitional zone. The materials of this transitional zone may be comprised of soil, both completely decomposed as well as partially decomposed rock and pieces of the parent rock above the parent bedrock surface. The entire soil profile above the parent bedrock may be termed residual soil, since these soils have not be transported from one location to another location. The typical residual soil profile consists of clayey soils (completely decomposed rock) near the surface, where soil weathering is more advanced, underlain by sandy silts and silty sandsthat are normally found overlying the parent bedrock. In geotechnical engineering residual soil with Standard Penetration Test resistances exceeding 100 blows/foot is considered to be an Intermediate Geomaterial (IGM) (see Chapter 6 for more discussion of IGM). Weathering is facilitated by fractures, joints, and by the presence of less resistant rock types. Consequently, the profile of the completely decomposed rock and the parent bedrock is quite irregular and erratic, even over short horizontal distances. Also, it is not unusual to find lenses and boulders of parent bedrock and zones of partially decomposed rock within the soil mantle, well above the parent bedrock level.

## 11.5 FALL LINE

The Fall Line is an unconformity that marks the boundary between an upland region (bed rock) and a coastal plain region (sediment). In South Carolina the Piedmont Unit is separated from the Coastal Plain Unit by a “Fall Line” that begins near the Edgefield-Aiken County line and traverses to the northeast through Lancaster County. In addition to Columbia, SC many cities were built along the “Fall Line” as it runs up the east coast (Macon, Raleigh, Richmond, Washington D.C., and Philadelphia). The “Fall Line” generally follows the southeastern border of the Savannah River terrane formation and the Carolina terrane (slate belt) formation shown in Figure 11-2. Along the “Fall Line” between elevations 300 to 725 ft is the Sandhills formations that are the remnants of a prehistoric coastline. The Sandhills are unconnected bands of sand deposits that are remnants of coastal dunes that were formed during the Miocene Epoch (5.3 to 23 MYA). The land to the southeast of the “Fall Line” is characterized by a gently downward sloping elevation (2 to 3 feet per mile) as it approaches the Atlantic coastline as shown in Figure 11-4. Several rivers such as the Pee Dee, Wateree, Lynches, Congaree, N. Fork Edisto, and S. Fork Edisto flow from the “Fall Line” towards the Atlantic coast as they cut through the Coastal Plain sediments.

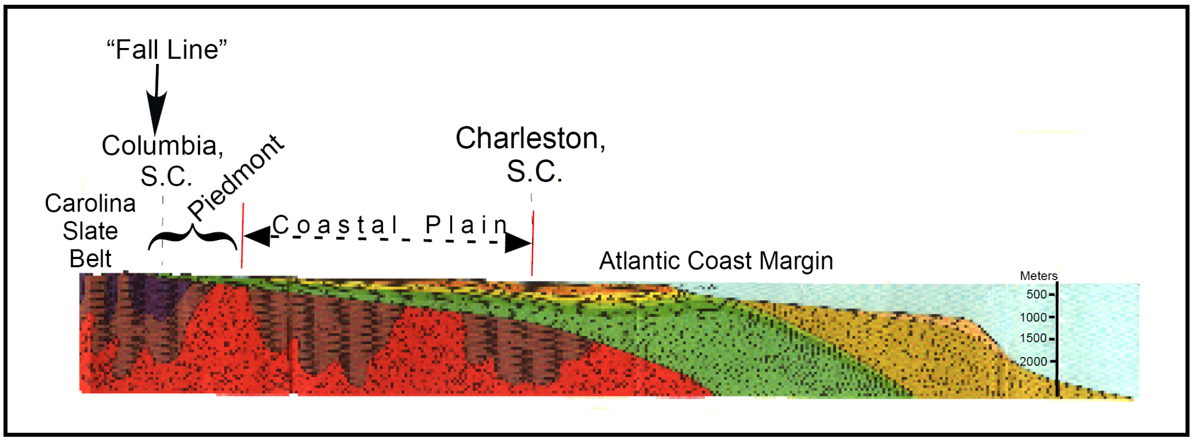
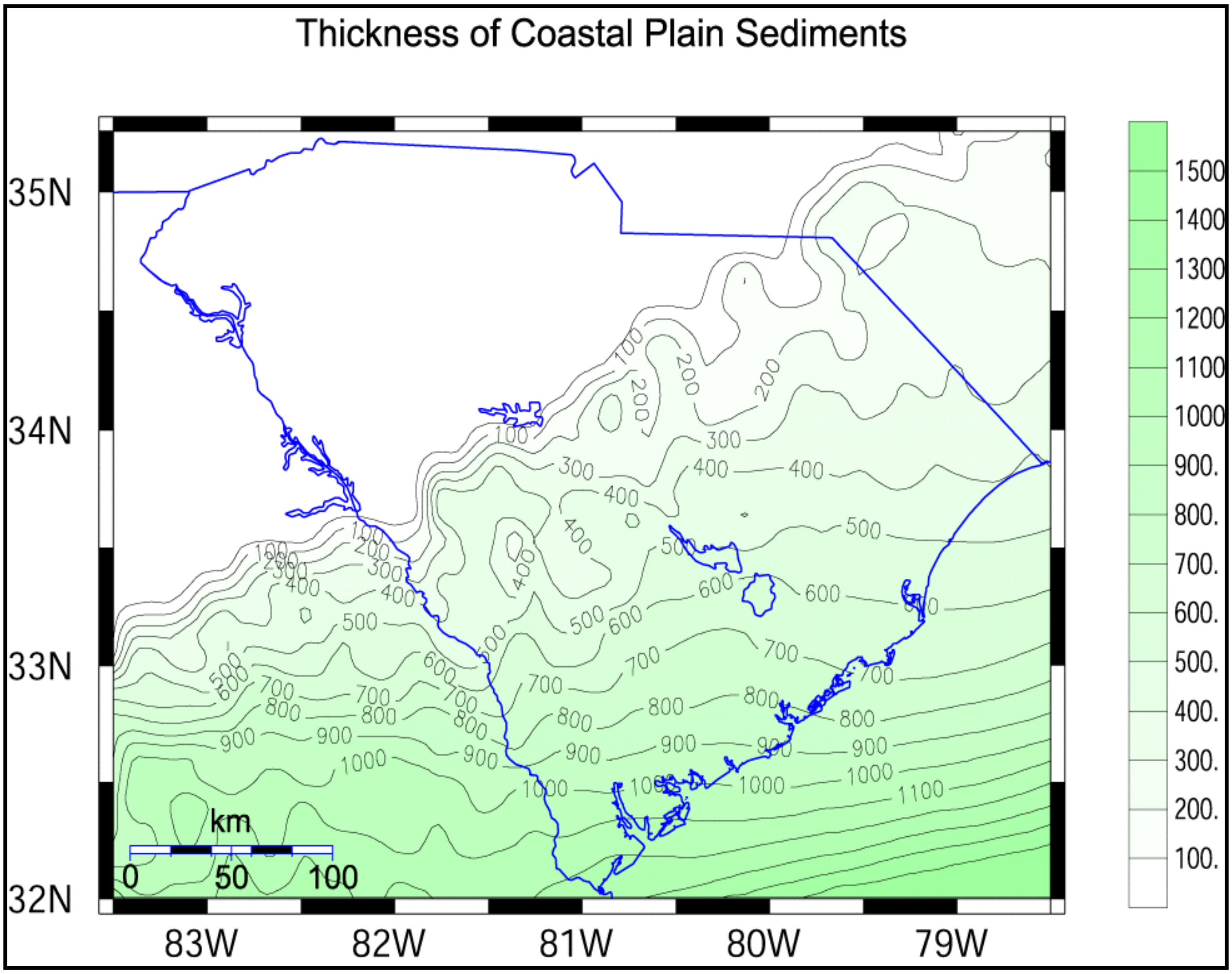



**Figure 11-4, South Carolina “Fall Line”**
**(Odum, Williams, Stephenson and Worley (2003))**

## 11.6 COASTAL PLAIN UNIT

The Coastal Plain Unit is a compilation of wedge shaped formations that begin at the “Fall Line” and dip towards the Atlantic Ocean with ground surface elevations typically less than 300 feet. The Coastal Plain is underlain by Mesozoic/Paleozoic basement rock. This wedge of sediment is comprised of numerous geologic formations that range in age from the late Cretaceous Period to Recent. The sedimentary soils of these formations consist of unconsolidated sand, clay, gravel, marl, cemented sands, and limestone that were deposited over the basement rock. The marl and limestone are considered in geotechnical engineering as a cohesive IGM as long as the criteria provided in Chapter 6 is met. The basement rock consists of granite, schist, and gneiss similar to the rocks of the Piedmont Unit. The thickness of the Coastal Plain sediments varies from zero at the “Fall Line” to more than 4,000 feet at the southern tip of South Carolina near Hilton Head Island. The thickness of the Coastal Plain sediments along the Atlantic coast varies from ~1,300 feet at Myrtle Beach to ~4,000 feet at Hilton Head Island. The top of the basement rock beneath the Coastal Plain has been mapped at selected locations where deep wells/borings were performed. The Seismic Hazard Study that was prepared for SCDOT developed contours of the top of the basement rock through interpretation of the available data. Predominantly, sediments lie in nearly horizontal layers; however, erosional episodes occurring between depositions of successive layers are often expressed by undulations in the contacts between the formations. The contours of the Coastal Plain sediment thickness shown in Figure 11-5 are in meters.




Contours in meters (1 meter = 3.28 feet)

**Figure 11-5, Contour Map of Coastal Plain Sediment Thickness (Chapman and Talwani (2002))**

This Coastal Plain Unit was formed during Quaternary, Neogene, Paleogene, and late Cretaceous geologic periods. The Coastal Plain can be divided into the following 3 subunits:

- Lower Coastal Plain
- Middle Coastal Plain
- Upper Coastal Plain

The Lower Coastal Plain comprises approximately one-half of the entire Atlantic Coastal Plain of South Carolina. The Surry Scarp (-SS-) depicted in Figures 11-1 and 11-2 separates the Lower Coastal Plain from the Middle Coastal Plain. The Surry Scarp is a seaward facing scarp with a toe elevation of 90 to 100 feet. The Middle Coastal Plain and the Upper Coastal Plain each compose approximately one fourth of the Coastal Plain area, each. The Orangeburg Scarp (-OS-) depicted in Figures 11-1 and 11-2 separates the Middle Coastal Plain from the Upper Coastal Plain. The Orangeburg Scarp is also a seaward facing scarp with a toe elevation of 250 to 270 feet.

### 11.6.1 Lower Coastal Plain

The Lower Coastal Plain is typically identified as the area east of the Surry Scarp below elevation 100 feet. However, as seen in Figures 11-1 and 11-2, the Lower Coastal Plain extends beyond both Surry and Orangeburg Scarps along some of the major river valleys in South Carolina. The 2 major river valleys where this occurs are the Pee Dee and Santee River systems. Therefore, Lower Coastal Plain soils may be found west of both scarps in the river valleys. The vertical stratigraphic sequence overlying the basement rock consists of unconsolidated Cretaceous, Paleogene, Neogene, and Quaternary sedimentary deposits. The surface deposits of the Lower Coastal Plain were formed during the Quaternary Period that began approximately 1.6 MYA and extends to present day. The Quaternary Period can be further subdivided into the Pleistocene Epoch (1.6 MYA to 10 thousand years ago) and the Holocene Epoch (10 thousand years ago to present day). The Pleistocene Epoch is marked by the deposition of the surficial soils, the formation of the Carolina Bays and the scarps found throughout the East Coast due to sea level rise and fall. Barrier islands and flood plains along the major rivers were formed during the Holocene Epoch. Preceding the Quaternary Period during the Eocene Epoch (53 to 36.6 MYA) of the Paleogene Period, limestone was deposited in the Lower Coastal Plain.

### 11.6.2 Middle Coastal Plain

The Middle Coastal Plain is typically identified as the area between the Surry Scarp and the Orangeburg Scarp and falls between elevation 100 feet and 270 feet. The vertical stratigraphic sequence overlying the basement rock consists of unconsolidated Cretaceous, Paleogene and Neogene sedimentary deposits. The surface deposits of the Middle Coastal Plain were formed during the Pliocene Epoch of the Neogene Period. During the Pliocene Epoch (5.3 to 1.6 MYA) of the Neogene Period, the Orangeburg Scarp was formed as a result of scouring from the regressive cycles of the Ocean as it retreated. During the Eocene Epoch (53 to 36.6 MYA) of the Paleogene Period, limestone was deposited in the Middle Coastal Plain.

### 11.6.3 Upper Coastal Plain

The Upper Coastal Plain is typically identified as the area between the Orangeburg Scarp and the “Fall Line” and has elevations between 270 feet and 300 feet. The Upper Coastal Plain was formed during the Paleogene, Neogene and late Cretaceous Periods. The Paleogene Period began approximately 65 MYA and ended approximately 23 MYA and is subdivided into the Paleocene, Eocene and Oligocene Epochs. The Neogene Period began approximately 23 MYA and ended approximately 1.6 MYA and is subdivided into the Miocene and Pliocene Epochs. The Miocene Epoch (23 to 5.3 MYA) is marked by the formation of the Sandhills dunes as a result of fluvial deposits over the Coastal Plain. During the early Paleogene Period (65 to 23 MYA) fluvial deposits over the Coastal Plain consisted of marine sediments, limestone, and sand. The Upper Coastal Plain is formed of older, generally well-consolidated layers of sands, silts, or clays that were deposited by marine or fluvial action during a period of retreating ocean shoreline. Due to their age, sediments exposed at the ground surface are often heavily eroded. Ridges and hills are either capped by terrace gravels or wind-deposited sands. Younger alluvial soils may mask these sediments in swales or stream valleys.

## 11.7 SOUTH CAROLINA SEISMICITY

### 11.7.1 Central and Eastern United States Seismicity

Even though seismically active areas in the United States are generally considered to be in California and the Western United States (WUS), historical records indicate that there have been major seismic events in the Central and Eastern United States (CEUS) that have not only been of equal or greater magnitude but that have shaken broader areas of the CEUS. The United States Geologic Survey (USGS) map shown in Figure 11-6 indicates seismic events that have caused damage within the United States between 1750 and 1996. Of particular interest to South Carolina is the 1886 seismic event in Charleston, SC that has been estimated to have an $M_w$ of approximately 7.3. In addition, the upstate of South Carolina underwent a moderate seismic event in 1913 in Union County, SC having an $M_w$ of approximately 5.5. Also of interest to the northwestern end of South Carolina is the influence of the New Madrid seismic zone, near New Madrid, Missouri, where historical records indicate that between 1811 and 1812 there were several large seismic events with an $M_w$ of at least 7.7.

The CEUS is located in the approximate middle of the North American tectonic plate. Specifically, Charleston, SC lies along the modern coastline with the Atlantic Ocean. Typically, seismic events occur along the margins of tectonic plates, where the plates either slide past each other; one plate overrides the adjoining plate (subduction); or the plates push apart with new plates being formed by volcanism (e.g., the mid-Atlantic Ridge). As indicated previously, South Carolina is located in the approximate middle of the North American Plate. The source of the seismic events in SC appears to be from partially formed rift valleys that have been infilled; therefore, covering and obscuring the rift valley (Stein, Pozzaglia, Meltzer, Wolin, Kafka and Berti (2013), Fillingim (1999)). The infilling of these ancient rift valleys has erased any evidence of the valley at the existing ground surface. Fillingim (1999) has also identified stress concentrations and high heat flow as possible causes of CEUS seismic events. Further evidence for faulting beneath SC is provided by Durá-Gómez and Talwani (2009) as the Zone of River Anomalies (ZRA) that appears to provide evidence that the faulting is strike-slip in nature. Unfortunately, this is all speculative given the lack of evidence at the existing ground surface.

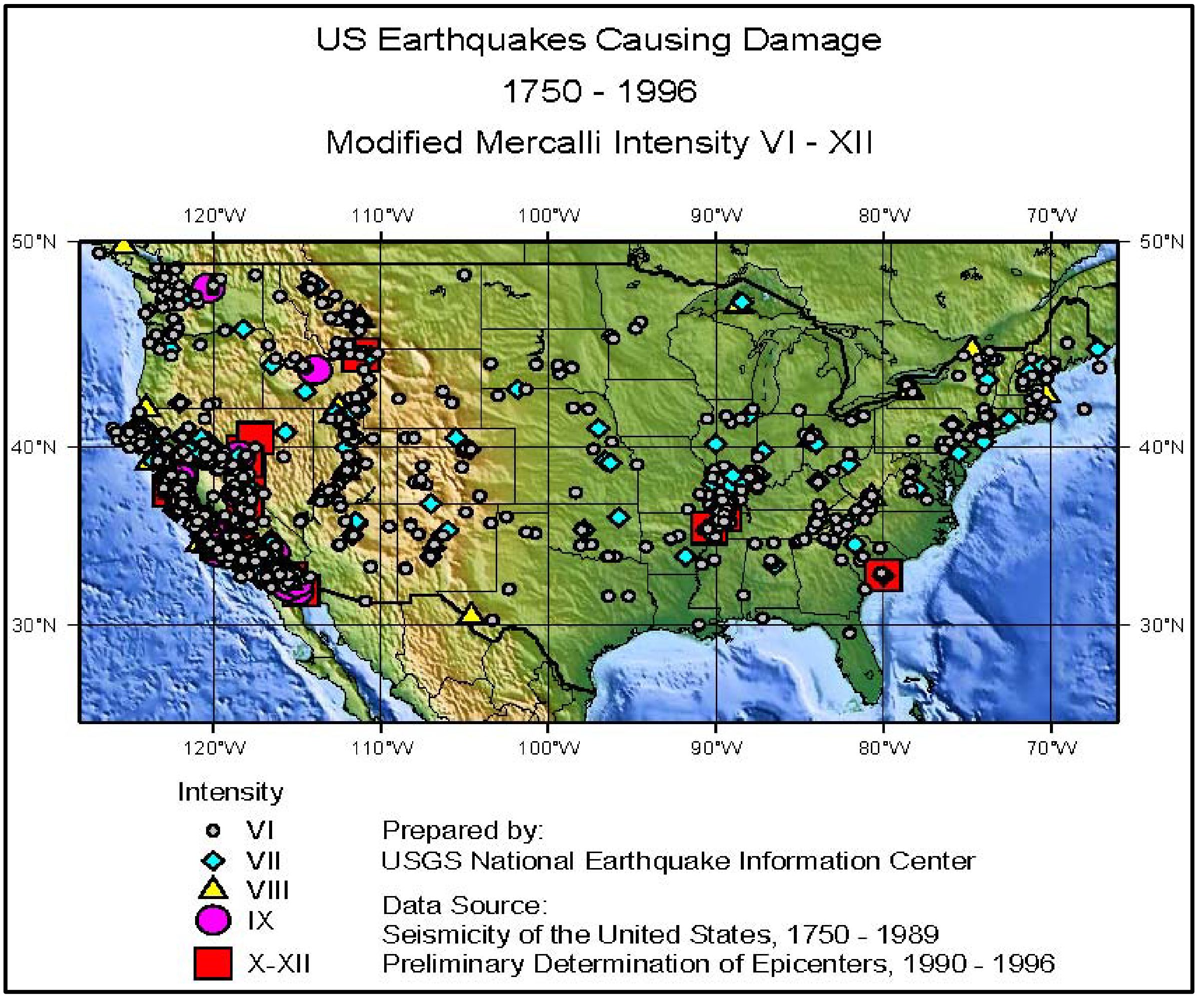



**Figure 11-6, U.S. Seismic Events Causing Damage 1750 – 1996 (USGS Website (2012b))**

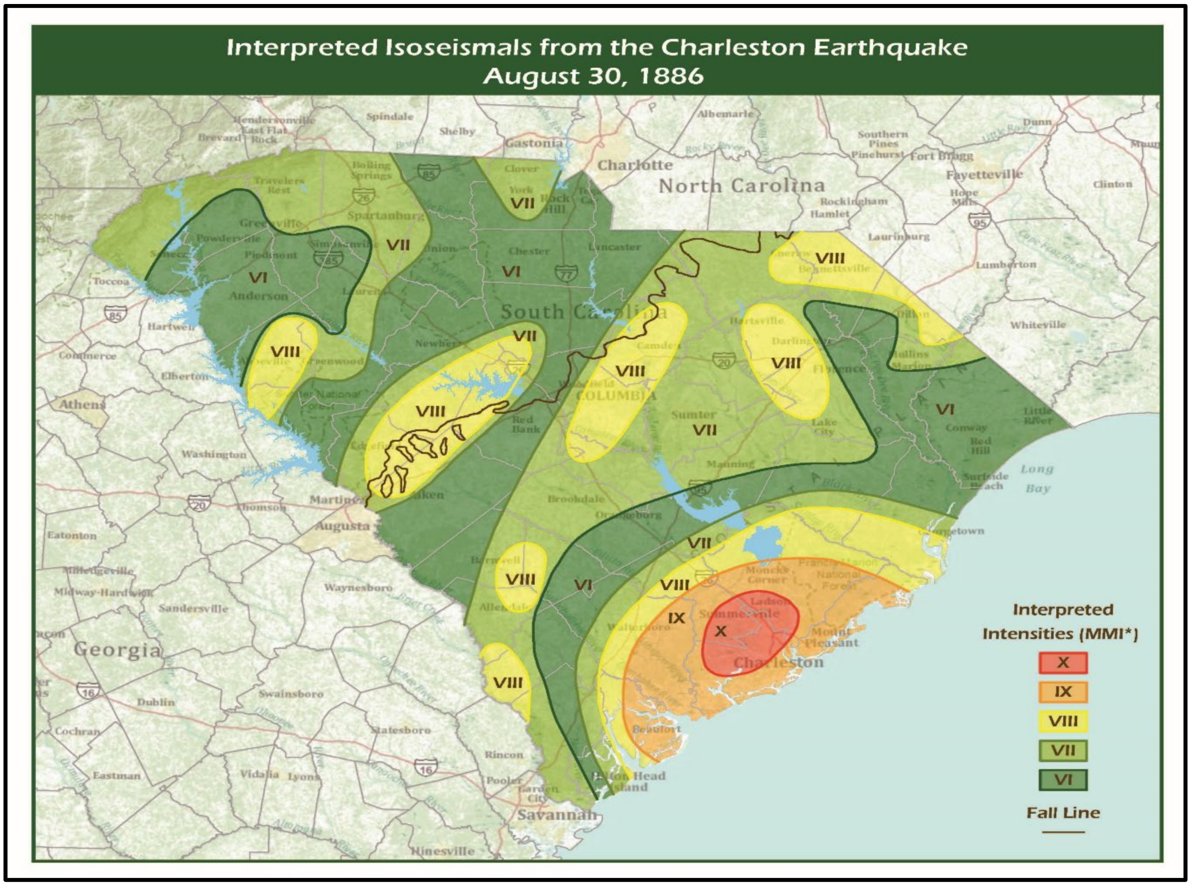
### 11.7.2 SC Seismic Event Intensity

The Modified Mercalli Intensity (MMI) scale is a qualitative measure of the strength of ground shaking at a particular site that is used in the United States. Each seismic event large enough to be felt will have a range of intensities. Typically the highest intensities are measured near the seismic event epicenter and lower intensities are measured farther away. The MMI scale is used to distinguish how the ground shaking is felt at different geographic locations as opposed to the moment magnitude scale that is used to compare the energy released by the seismic event. Roman numerals are used to identify the MMI scale of ground shaking with respect to shaking and damage felt at a geographic location as shown in Table 11-1.

**Table 11-1, Modified Mercalli Intensity Scale**

| **INTENSITY** | **I** | **II – III** | **IV** | **V** | **VI** | **VII** | **VIII** | **IX** | **X+** |
|---|---|---|---|---|---|---|---|---|---|
| **SHAKING** | Not Felt | Weak | Light | Moderate | Strong | Very Strong | Severe | Violent | Extreme |
| **DAMAGE** | None | None | None | Very Light | Light | Moderate | Moderate / Heavy | Heavy | Very Heavy |

Figure 11-7 shows a map developed by the South Carolina Geological Survey (SCGS) with interpreted isoseismals of seismic intensities based on the MMI scale. These intensities (MMI) are for the August 31, 1886, Charleston, S.C. seismic event ($M_w \approx 7.3$). Figure 11-8 shows a map also developed by the SCGS with seismic event intensities, by county, based on the anticipated MMI. The intensities shown on this map are the highest likely under the most adverse geologic conditions that would be produced by a combination of the August 31, 1886, Charleston ($M_w \approx 7.3$) and the January 1, 1913, Union County, S.C., ($M_w \approx 5.5$) seismic events. These maps are for informational purposes only and are not intended as a design tool, but reflect the potential for damage based on seismic events similar to the Charleston seismic event.




See Table 11-1 Modified Mercalli Intensity Scale definitions.

**Figure 11-7, Interpreted MMI for the 1886 Charleston Seismic Event (SCDNR (2012a))**

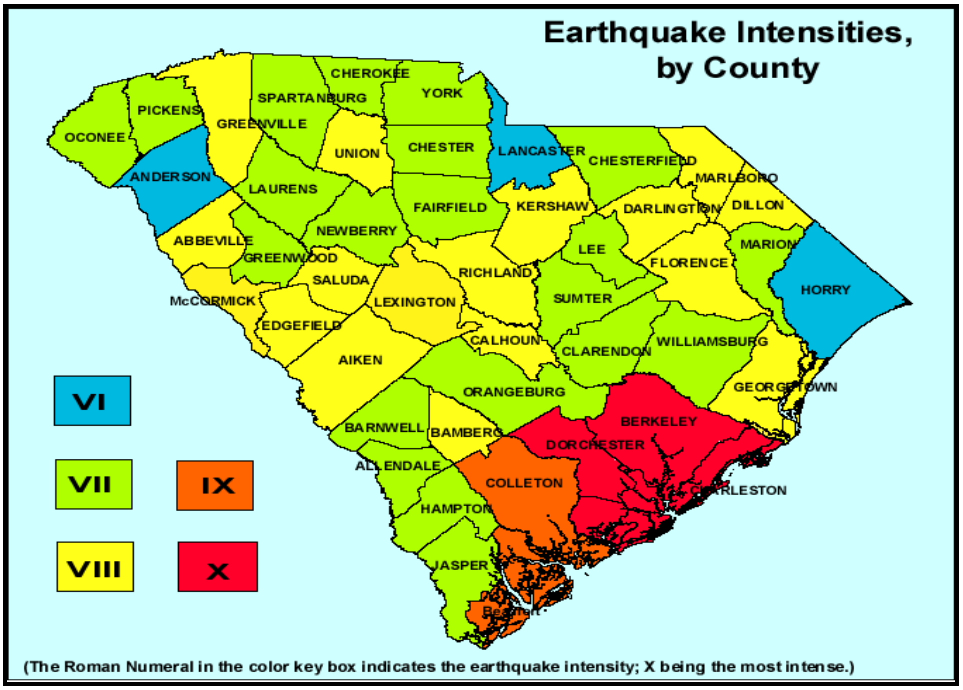



**Figure 11-8, Interpreted Seismic Event MMI by County (SCDNR (2012b))**

## 11.8 SOUTH CAROLINA SEISMIC SOURCES

Sources of seismicity are not well defined in much of the CEUS. However, based on recent studies in the geology and seismology of the CEUS, it appears that the source of the seismic events may be infilled rift valleys (Stein, et al. (2013)). It is noted that the rift valleys along the Atlantic seaboard are not fully formed such as the Great Rift Valley in northeast Africa. Since the presence of these rift valleys cannot be accurately confirmed; the South Carolina seismic sources have been defined based on seismic history in the Southeastern United States. The “Seismic Hazard Mapping for Bridge and Highway Design in South Carolina” (Seismic Hazard Mapping) study (Chapman and Talwani, 2002) has identified 2 types of seismic sources: Non-Characteristic Seismic Sources and Characteristic Seismic Sources.

### 11.8.1 Non-Characteristic Seismic Sources

Seismic histories were used to establish seismic area sources for analysis of non-characteristic background events. The study by Chapman and Talwani (2002) modified the Frankel, et al. (1996) source area study to develop the seismic source areas shown in Figures 11-9 and 11-10.

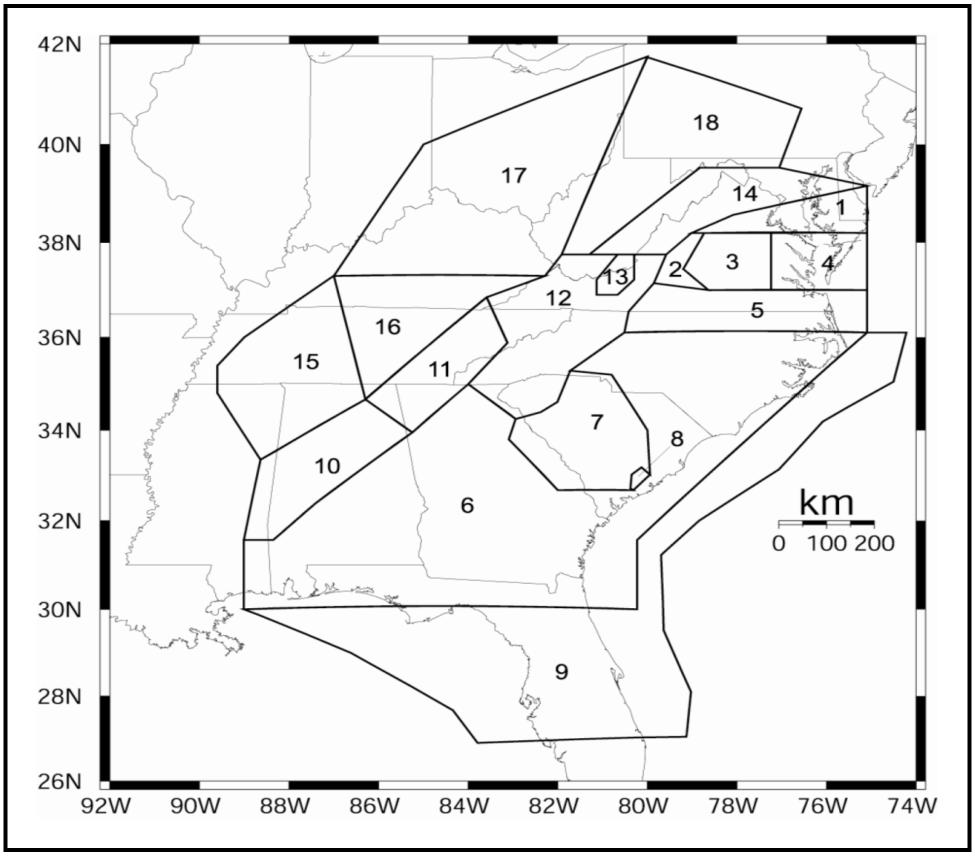



**Figure 11-9, Source Areas for Non-Characteristic Seismic Events (Chapman and Talwani (2002))**

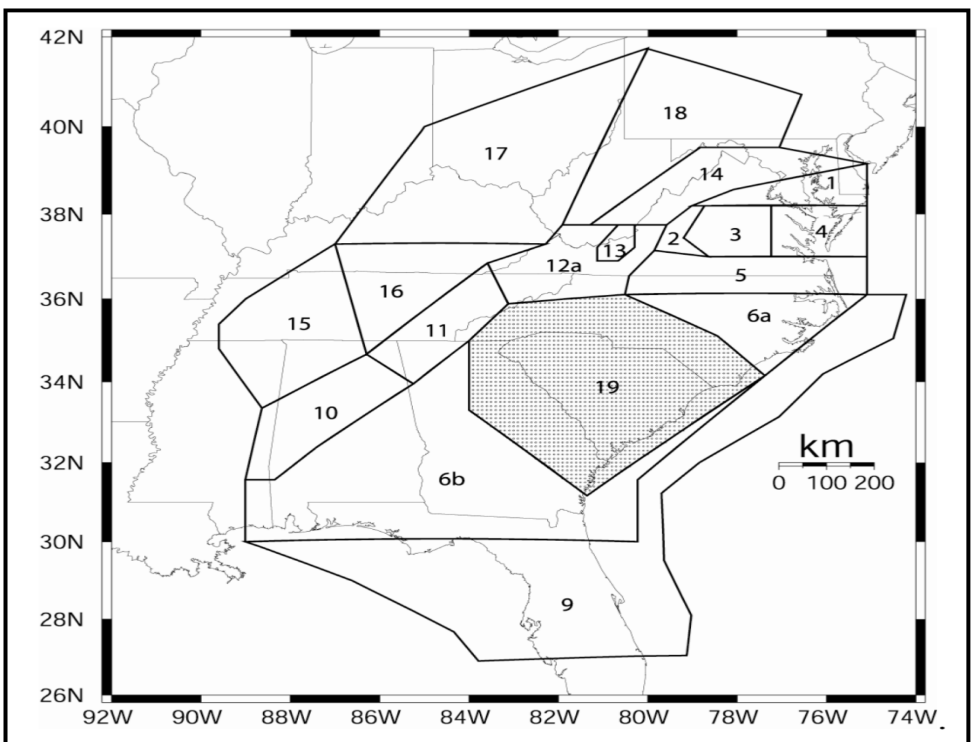



**Figure 11-10, Alternative Source Areas for Non-Characteristic Seismic Events (Chapman and Talwani (2002))**

The source areas listed in Figures 11-9 and 11-10 are described in Table 11-2.

**Table 11-2, Source Areas for Non-Characteristic Background Events (Chapman and Talwani (2002))**

| Area No. | Description | Area (sq.miles) | Area No. | Description | Area (sq.miles) |
|---|---|---|---|---|---|
| **1** | Zone 1 | 8,133 | **10** | Alabama | 20,257 |
| **2** | Zone 2 | 2,475 | **11** | Eastern Tennessee | 14,419 |
| **3** | Central Virginia | 7,713 | **12** | Southern Appalachian | 29,234 |
| **4** | Zone 4 | 9,687 | **12a** | Southern Appalachian N. | 17,034 |
| **5** | Zone 5 | 18,350 | **13** | Giles County, VA | 1,980 |
| **6** | Piedmont and Coastal Plain | 161,110 | **14** | Central Appalachians | 16,678 |
| **6a** | Piedmont & CP NE | 18,815 | **15** | West Tennessee | 29,667 |
| **6b** | Piedmont & CP SW | 95,854 | **16** | Central Tennessee | 20,630 |
| **7** | SC Piedmont | 22,248 | **17** | Ohio – Kentucky | 58,485 |
| **8** | Middleton Place | 455 | **18** | West VA-Pennsylvania | 34,049 |
| **9** | Florida/Continental Margin | 110,370 | **19** | USGS Gridded Seis.-1996 | --- |

Figure 11-11 shows additional historical seismic information obtained from the Virginia Tech catalog of seismicity in the Southeastern United States from 1600 to present that was used to model the non-characteristic background events in the source areas.

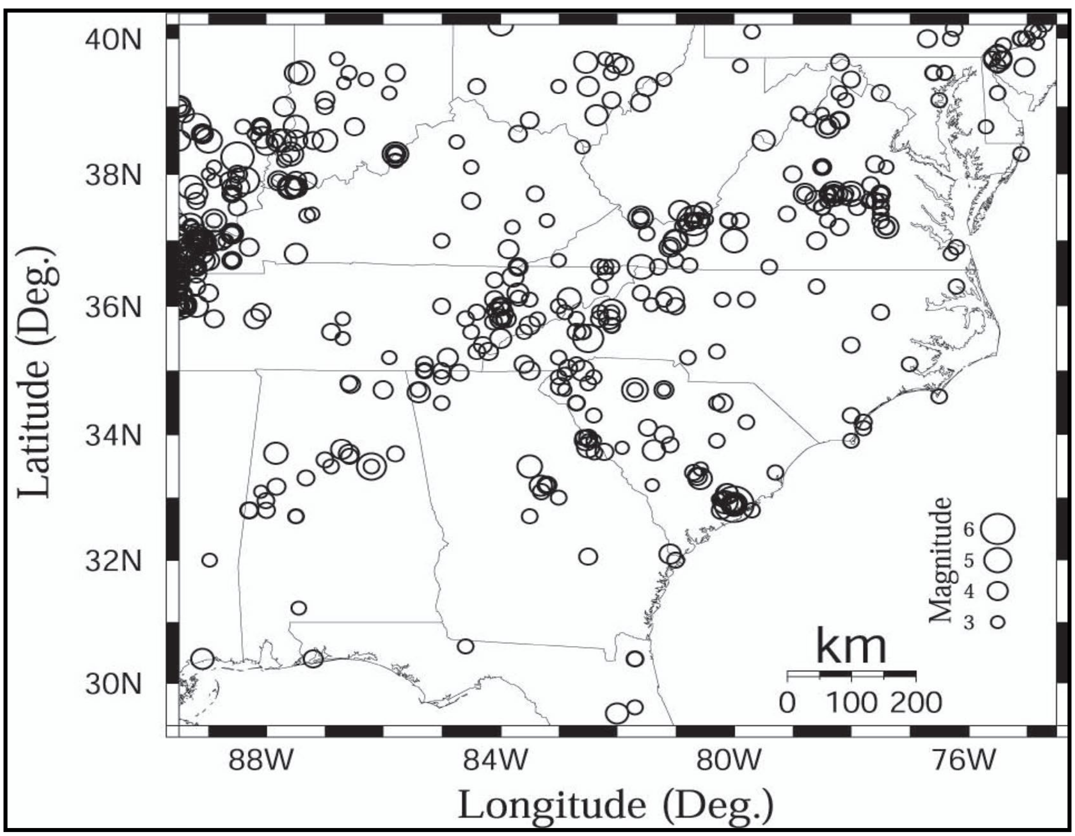



**Figure 11-11, Southeastern U.S. Seismic Events ($M_W$ > 3.0 from 1600 to Present) (Chapman and Talwani (2002))**

### 11.8.2 Characteristic Seismic Sources

The single most severe seismic event that has occurred in South Carolina's recorded human history occurred in Charleston, South Carolina, in 1886. It was one of the largest, seismic events to affect the CEUS in historical times. The $M_w$ of this seismic event has been estimated to range from 7.0 to 7.5. It is typically assigned an $M_w$ of 7.3. The faulting source that was responsible for the 1886 Charleston seismic event remains uncertain to date.

Large magnitude seismic events with the potential to occur in coastal South Carolina are considered characteristic seismic events. These seismic events are modeled as a combination of fault sources and a seismic Area Source. The Seismic Hazard Mapping study used the 1886 Seismic Event fault source, also known as the Middleton Place seismic zone, and ZRA fault source. For the 1886 Seismic Event fault source it is assumed that rupture occurred on the NE trending "Woodstock" fault and on the NW trending "Ashley River" fault. The 1886 Seismic Event fault source is modeled as 3 independent parallel faults.

Recent studies (Marple and Talwani, (1993, 2000)) suggest that the "Woodstock" fault may be a part of larger NE trending fault system that extends to North Carolina and possibly Virginia, referred to in the literature as the "East Coast Fault System". The ZRA fault source is the term used for the portion of the "East Coast Fault System" that is located within South Carolina. The ZRA fault system is modeled by a 145-mile long fault with a NE trend. The characteristic seismic Area Source is the same as is used in the 1996 National Seismic Hazard Maps. It models a network of individual faults no greater than 46 miles in length within the Lower Coastal Plain. The fault sources and area sources used to model the characteristic seismic sources in the Seismic Hazard Mapping study are shown in Figure 11-12.

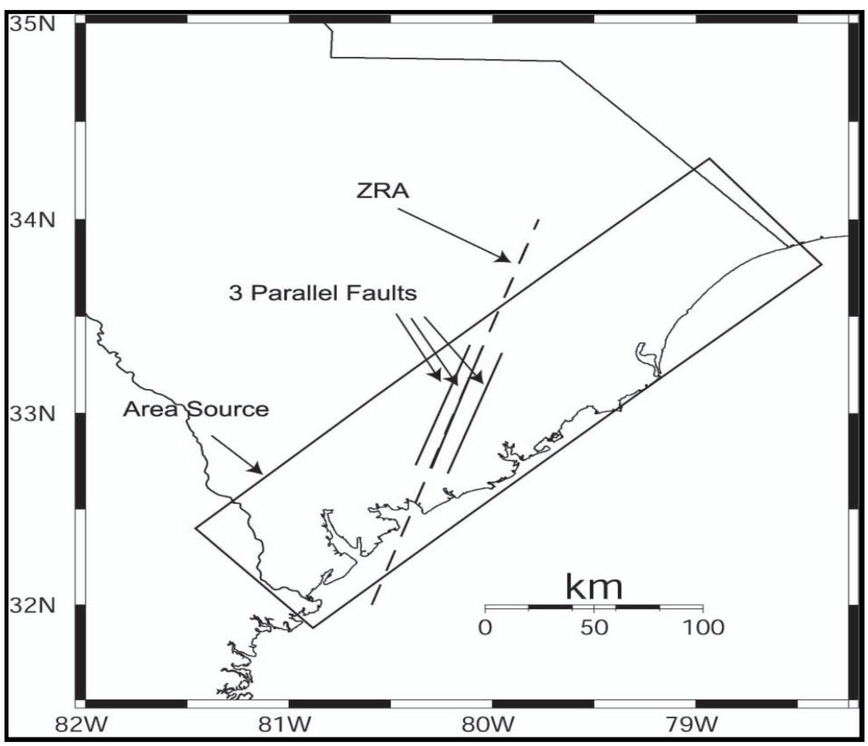



**Figure 11-12, South Carolina Characteristic Seismic Sources (Chapman and Talwani (2002))**

## 11.9 SOUTH CAROLINA SEISMIC HAZARDS

### 11.9.1 Design Seismic Events

SCDOT uses the FEE and the SEE to design transportation infrastructure in South Carolina. The FEE represents a small ground motion that has a likely probability of occurrence within the life of the structure being designed. The SEE represents a large ground motion that has a relatively low probability of occurrence within the life of the structure. The 2 levels of seismic events have been chosen for South Carolina because SEE spectral accelerations can be as much as 3 to 4 times higher than FEE spectral accelerations in the CEUS. In contrast, the California SEE spectral accelerations can be the same or as much as 1.8 times the FEE spectral accelerations. Because of the large variation between FEE and SEE design events it is necessary to perform geotechnical seismic engineering analyses for each event and compare the resulting performance with the SCDOT Performance Limits established in Chapter 10. The design life for transportation infrastructure is typically assumed to be 75 years when evaluating the design seismic events, regardless of the actual design life specified in Chapter 10.

### 11.9.2 Probabilistic Seismic Hazard Maps

The seismic hazard of South Carolina is estimated from the probabilistic pseudo-spectral accelerations (PSA) maps for SCDOT (Chapman and Talwani (2002), Chapman (2006)) assuming a geologically realistic rock model for the State and the 2 $P_E$ conditions. The motions are defined in terms of PSA at frequencies of 0.5, 1.0, 2.0, 3.3, 5.0, 6.67, and 13.0 Hz, for a damping ratio of 0.05 (5%) and the peak horizontal ground acceleration (PGA or PHGA). Please note that period is the inverse of frequency, therefore, the frequencies previously indicated become periods of 2.0, 1.0, 0.50, 0.303, 0.20, 0.15, and 0.077 seconds. The accelerations were developed for the geologically realistic site conditions as well as for the hypothetical hard-rock basement outcrop. The motions are termed the Uniform Hazard Spectrum (UHS) at the respective geologic condition (i.e., geologically realistic or hard-rock). All of the PSAs contained in the UHS have the same $P_E$. The geologically realistic site condition is a hypothetical site condition that was developed by using a transfer function of a linear response. South Carolina has been divided into 2 zones as shown in Figure 11-13: Zone I – Physiographic Units Outside of the Coastal Plain and Zone II – Coastal Plain Physiographic Unit. The delineation between these 2 zones has been shown linearly in Figure 11-13 but in reality it should follow the “Fall Line.” Because of the distinct differences between these 2 physiographic units, a geologically realistic model has been developed for each zone.

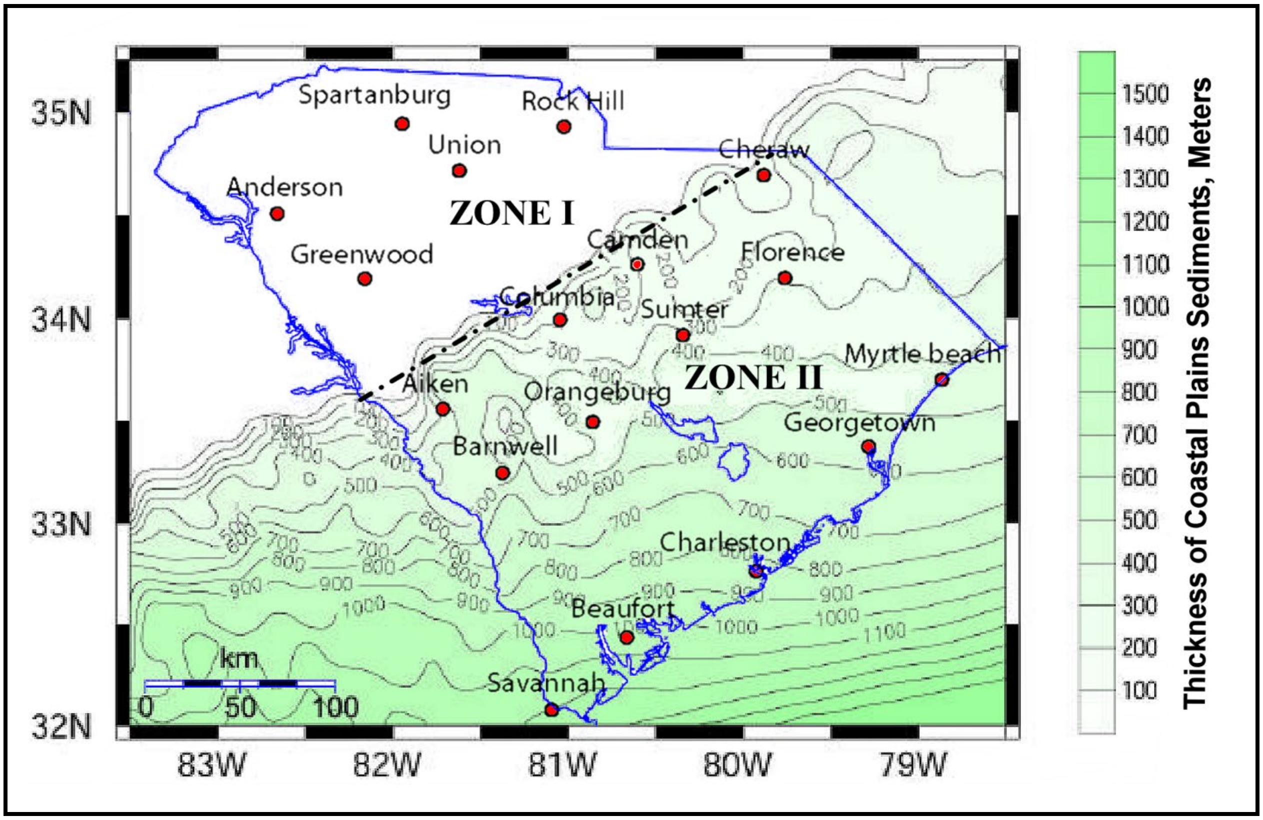



**Figure 11-13, SCDOT Site Condition Selection Map (Modified Chapman and Talwani (2002))**

The Coastal Plain geologically realistic site condition consists of 2 layers, the shallowest layer consists of Coastal Plain sedimentary soil (Q=100) and weathered rock (Q=600), over a half-space of unweathered Mesozoic and Paleozoic sedimentary, and metamorphic/igneous rock, assuming vertical shear wave incidence. The variable Q is called the Quality Factor and is a measure of the energy dissipation during a seismic event due to absorption of the energy by the soil. A higher Q results in lower energy dissipation (i.e., less soil grains bumping into each). The soil/rock properties for the Coastal Plain geologically realistic model are shown in Table 11-3.

The Piedmont geologically realistic site condition consists of 1 layer of weathered rock (Q=600) over a half-space of unweathered Mesozoic and Paleozoic sedimentary, and metamorphic/igneous rock, assuming vertical shear wave incidence. The soil/rock properties for the Piedmont geologically realistic model are shown in Table 11-4.

**Table 11-3, Coastal Plain Geologically Realistic Model**

| Soil Layer | Mass Density, ρ | Total Unit Weight, γ | Shear Wave Velocity, $V_S$ |
|---|---|---|---|
| | slug[a]/ft[3] | pcf | ft/sec |
| Layer 1 – Sedimentary Soils | 3.88 | 125 | 2,300 |
| Layer 2 – Weathered Rock | 4.81 | 155 | 8,200 |
| Half-Space – Basement Rock | 5.12 | 165 | 11,200 |

[a]slug = ($lb_f*s^2$)/ft

**Table 11-4, Geologically Realistic Model Outside of Coastal Plain**

| Soil Layer | Mass Density, ρ | Total Unit Weight, γ | Shear Wave Velocity, $V_S$ |
|---|---|---|---|
| | slug[a]/ft³ | pcf | ft/sec |
| Layer 1 – Weathered Rock | 4.81 | 155 | 8,200 |
| Half-Space - Basement Rock | 5.12 | 165 | 11,200 |

[a]slug = $(lb_f * s^2)/ft$

The transfer functions were computed using the one-quarter wavelength approximation of Boore and Joyner (1991). For more information on the development of the transfer function refer to Chapman and Talwani (2002).

The selection of the appropriate site condition is very important in the generation of probabilistic seismic hazard motions in the form of PSA and (PGA or PHGA). The available site conditions for use in generating probabilistic seismic hazard motions are defined in Table 11-5. The selection of the appropriate site condition should be based on the results of the geotechnical site investigation, geologic maps, and any available geologic or geotechnical information from past projects in the area. Generally speaking the geologically realistic site condition should be used in the Coastal Plain. In areas outside of the Coastal Plain such as the Piedmont / Blue Ridge Physiographic Units and along the “Fall Line” the use of the geologically realistic site condition should be evaluated carefully. The geotechnical investigation in these areas should be sufficiently detailed to determine depth to weathered rock having a shear wave velocity of approximately 8,000 to 8,200 ft/sec or to define the basement rock outcrop having a shear wave greater than 11,000 ft/sec.

**Table 11-5, Site Conditions**

<table>
<tr><th rowspan="2">South Carolina Zones</th><th colspan="2">Site Condition</th></tr>
<tr><th>Geologically Realistic</th><th>Hard-Rock Basement Outcrop</th></tr>
<tr><td>Zone I – Physiographic Units Outside of the Coastal Plain</td><td>Hypothetical outcrop of “Weathered Southeastern U.S. Piedmont Rock” that consist of an 820-foot thick weathered formation of shear wave velocity, $V_s$ = 8,200 ft/s overlying a hard-rock formation having shear wave velocity, $V_s$ = 11,500 ft/s.</td><td rowspan="2">A hard-rock basement outcrop formation having shear wave velocity, $V_s$ = 11,500 ft/s.</td></tr>
<tr><td>Zone II – Coastal Plain Physiographic Unit</td><td>Hypothetical outcrop of “Firm Coastal Plain Sediment” having a shear wave velocity, $V_s$ = 2,500 ft/s.</td></tr>
</table>

The seismic hazard computations use the seismic sources listed in Section 11.8, the design seismic event in Section 11.9.1, and the ground motions described in Section 11.9.4.

The PGA and PSA can be obtained for any location in South Carolina by specifying a Latitude and Longitude. The Latitude and Longitude of a project site may be obtained from the plans or by using an Interactive Internet search tool. Typical Latitude and Longitude for select South Carolina cities are provided in Table 11-6 for reference.

**Table 11-6, Latitude and Longitude for South Carolina Cities**

| SC City | Latitude | Longitude[a] | SC City | Latitude | Longitude[a] |
|---|---|---|---|---|---|
| Anderson, SC | 34.50 | -82.72 | Greenwood, SC | 34.17 | -82.12 |
| Beaufort, SC | 32.48 | -80.72 | Myrtle Beach, SC | 33.68 | -78.93 |
| Charleston, SC | 32.90 | -80.03 | Nth Myrtle B, SC | 33.82 | -78.72 |
| Columbia, SC | 33.95 | -81.12 | Orangeburg, SC | 33.50 | -80.87 |
| Florence, SC | 34.18 | -79.72 | Rock Hill, SC | 34.98 | -80.97 |
| Georgetown, SC | 33.83 | -79.28 | Spartanburg, SC | 34.92 | -81.96 |
| Greenville, SC | 34.90 | -82.22 | Sumter, SC | 33.97 | -80.47 |

[a]Longitude is negative indicating west.

The site-specific hazard PGA and PSA are generated by the OES/GDS for every project using Scenario_PC (2006) (Chapman (2006)). Scenario_PC (2006) generates seismic hazard data (UHS) in a similar format as that generated by the USGS.

A sample of the Seismic Hazard information generated by Scenario_PC (2006) for Columbia, SC is shown in Figure 11-14.

```
THIS FILE CONTAINS THE RESULTS FROM ONE EXECUTION
 OF PROGRAM scenario_pc (Martin Chapman, 2006).

THE NAME OF THE DIRECTORY CONTAINING THIS FILE
 AND ALL ASSOCIATED OUTPUT FILES IS: Columbia_SEE


 2% PROBABILITY OF EXCEEDANCE (For 50 year Exposure)
      FOR GEOLOGICALLY REALISTIC SITE CONDITION


 RESULTS OF INTERPOLATION

     Site Location: 33.9500 N 81.1200 W
Nearest Grid Point: 34.0000 N 81.1250 W Distance From Site:   5.56 Km
Thickness of sediments, meters:   262.2

                    PSA and PGA as Percentage of g
  0.5Hz     1.0Hz     2.0Hz     3.3Hz     5Hz       6.7Hz     13Hz      PGA
 6.44409  19.45698  32.21224  44.23877  52.80246  53.29054  56.02329  30.17862
```

**Figure 11-14, Scenario_PC (2006) Sample Output for Columbia, SC**

Note: 2% Probability of Exceedance (for 50-year Exposure) is equal to 3% Probability of Exceedance (for 75-year Exposure)

As indicated previously, the PSAs generated by Scenario_PC (2006) all have the same $P_E$. Figure 11-15 shows the seismic hazard curves for Charleston for seismic events having $P_E$s of 0.0004 (3%/75yr (2%/50yrs)), 0.0010 (7.5%/75yr (5%/50yr)), 0.0014 (10.5%/75yr (7%/50yr)) and 0.0020 (15%/75yr (10%/50yr)). Also shown is a line indicating a $P_E$ of 0.0004 (3%/75yr (2%/50yr)), the PGA and PSAs that are indicated by this line are used to create the UHS for the SEE (3%/75yr) depicted in Figure 11-17. In order to provide the designer with an overview of South Carolina's UHS, for the FEE and SEE, the PGA and PSAs (generated by Scenario_PC (2006)) for selected cities in South Carolina have been plotted at either the geologically realistic (B-C boundary) or hard rock basement outcrop in Figures 11-16 and 11-17. <u>The UHS curves for various cities are provided for information only and shall not be used for design of any structures in South Carolina.</u>

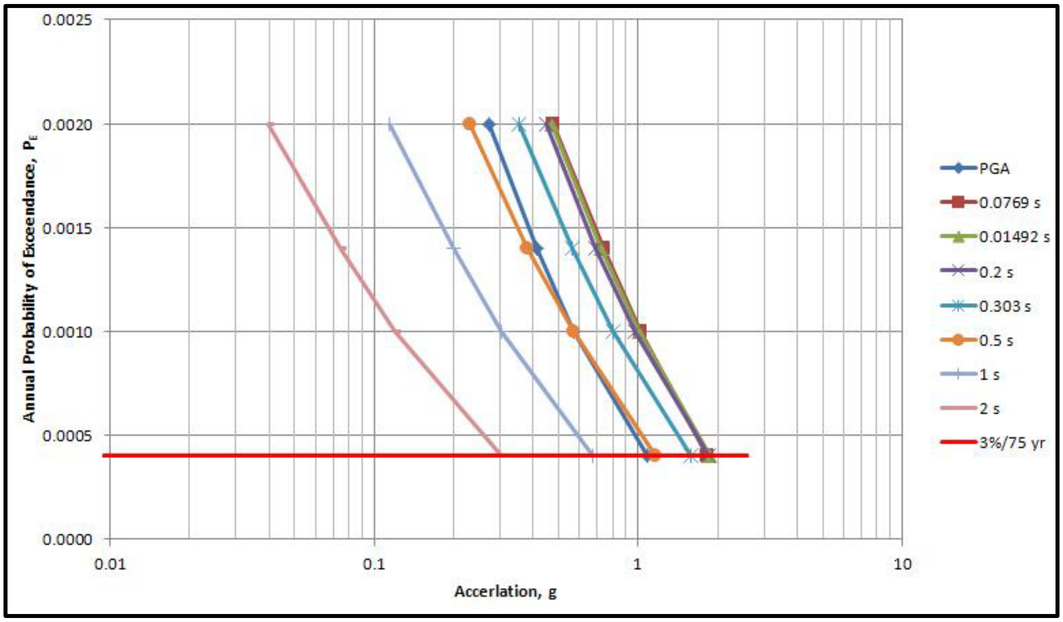



**Figure 11-15, SEE Seismic Hazard Curves for Various Periods**

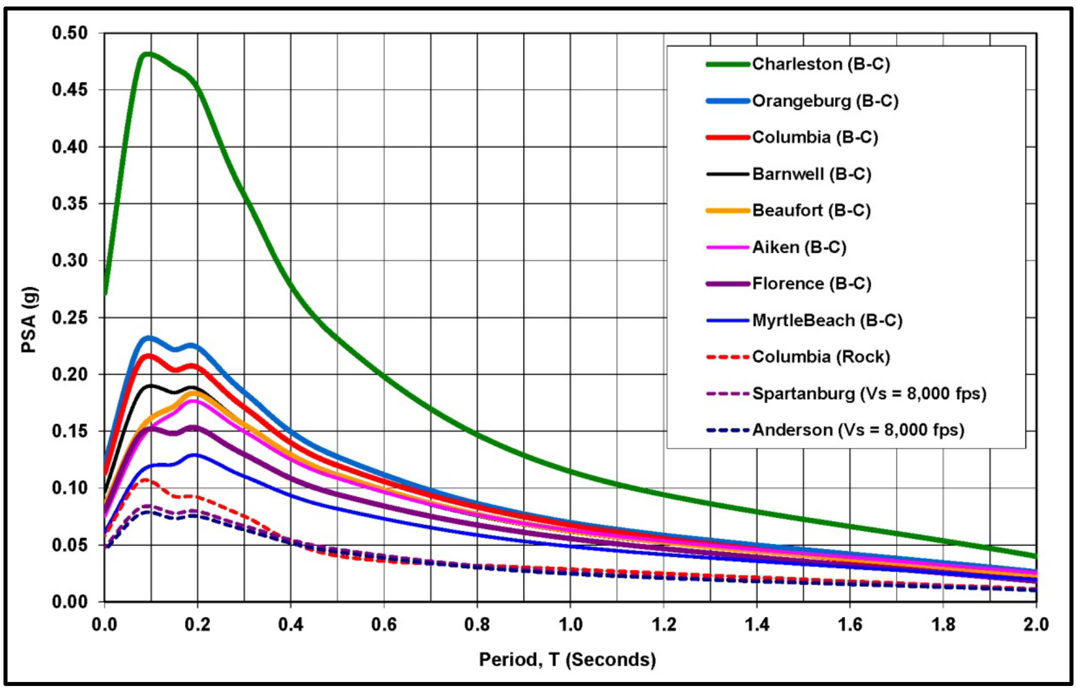



**Figure 11-16, FEE UHS Curves for Selected South Carolina Cities**

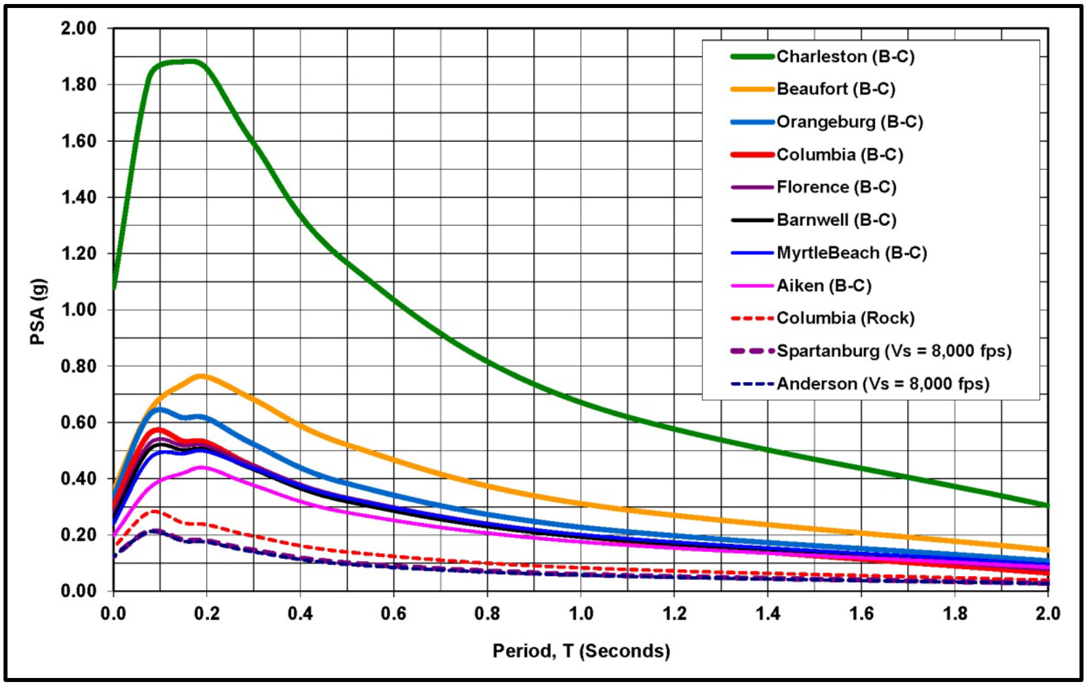



**Figure 11-17, SEE UHS Curves for Selected South Carolina Cities**

## 11.9.3 Seismic Event Deaggregation Charts

The ground motion hazard from a probabilistic seismic hazard analysis can be deaggregated to determine the predominant seismic event $M_w$ and distance (R) contributions from a hazard to guide in the selection of seismic event magnitude, site-to-source distance, and in development of appropriate time histories. On March 1, 2017, the USGS Interactive Earthquake Deaggregation program was taken off line by USGS and replaced with the either the 2008 or 2014 deaggregation maps. Scenario_PC (2006) is based on the 2002 deaggregation maps. The 2002 deaggregation maps were included in Scenario_PC (2006); therefore, deaggregation shall be based on the results contained in Scenario_PC (2006). Scenario_PC (2006) generates the interpolated results from the USGS Deaggregation 2002 data. A sample deaggregation output is provided in Figure 11-18 that was generated along with the SC Seismic Hazard results shown in Figure 11-14.

Interpolated results from USGS Deaggregation 2002

| Freq. | R(mean) km | mag(mean) | eps0(mean) | R(modal) km | mag(modal) | eps0(modal) |
|---|---|---|---|---|---|---|
| PGA | 58.6 | 6.31 | .44 | 125.4 | 7.31 | 1.23 |
| 5 Hz | 77.3 | 6.64 | .68 | 125.1 | 7.30 | 1.05 |
| 1 Hz | 113.1 | 7.06 | .74 | 125.0 | 7.30 | .81 |

**Figure 11-18, Scenario_PC (2006) Deaggregation – Columbia, SC**

The seismic event deaggregations typically provide the source category, percent contribution of the source to the hazard, R, mean and modal $M_w$, and epsilon ($\varepsilon$). Mean $M_w$ covers several sources that are typically not used and it is an overall average of seismic events from these other seismic sources and does not appropriately reflect magnitude of the hazard contribution within a specific seismic source. Mean $M_w$ values listed with respect to principal sources can be used. The $\varepsilon$ (esp0 in Figure 11-18) parameter is as important to understanding a ground motion as is the $M_w$ and the R values for the various sources. The $\varepsilon$ parameter is a measure of how close the ground motion is to the mean value in terms of standard deviation ($\sigma$). The $\varepsilon_o$ parameter is provided for ground motions having a fixed $P_E$. If a structure is designed for a seismic event with a magnitude $M_w$ that occurs a distance R from the site and the $\varepsilon_o = 0.0$, then the structure was designed to resist a median motion from this source. If the $\varepsilon_o = 1.0$, then the structure was designed to resist a motion one standard deviation ($+1\sigma$) greater than the median motion. Consequently, if the $\varepsilon_o = -1.0$, then the structure was designed to resist a motion one standard deviation ($-1\sigma$) less than the median motion. Predominance of a modal seismic source is generally indicated if the $\varepsilon$ is within $\pm1\sigma$.

## 11.9.4 Ground Motions

Ground motions are required when a site-specific seismic response analysis is being performed, see Chapter 12 for requirements, and/or, see the Seismic Specs for when a time history analysis is required. Time histories can be either recorded with seismographs or synthetically developed. Since the Charleston 1886 seismic event occurred, a seismic event with a magnitude of +7 has not occurred in South Carolina and therefore, no seismograph records are available for strong motion seismic events in South Carolina. The following Sections will outline the development of synthetic time histories and the selection of “real” time histories.

### 11.9.4.1 Synthetic Ground Motions

SCDOT has chosen to generate synthetic project-specific time histories based on the Seismic Hazard Mapping study completed for SCDOT. The ground motion predictions used in the study are based on the results of work involving both empirical and theoretical modeling of CEUS strong ground motion. Even though the strong motion database for the CEUS is small compared to the WUS, the available data indicate that high frequency ground motions attenuate more slowly in the CEUS than in the WUS. The Seismic Hazard Mapping study computer program Scenario_PC (2006) shall be used to generate synthetic ground motions.

A minimum of 7 time histories shall be required for either an equivalent-linear or a non-linear one-dimensional site-specific response analysis. See Chapter 12 for the type of site-specific analysis required (i.e., equivalent-linear or non-linear). As indicated previously, additional time histories may be needed based on the deaggregation results. Additional time histories may be required by SCDOT if project and site conditions warrant it. The time histories are generated based on project specific information using Scenario_PC (2006).

The method of scaling the time series to match a Uniform Hazard Spectrum (UHS), PGA, or a PSA frequency is primarily dependent on the results of the seismic deaggregation described in Section 11.9.3. When the uniform hazard is dominated by a well-defined modal seismic event, the method of scaling the time series should be to match the UHS. The seed number is used to start development of the ground motion process and shall be different for each ground motion required.

Synthetic ground motions are developed using an attenuation model. The ground motions on hard rock produced from the Seismic Hazard Mapping program Scenario_PC (2006) uses a stochastic model that uses weighted (w) attenuation relationships from Toro and McGuire (1987) (w=0.143), Frankel, et al. (1996) (w=0.143), Atkinson and Boore (1995) (w=0.143), Somerville, Collins, Abrahamson, Graves and Saikia (2001) (w=0.286), and Campbell (2003) (w=0.286) for the characteristic seismic events with magnitudes ranging from 7.0 to 7.5. For the non-characteristic seismic events with magnitudes less than 7.0, the following weighted prediction equations were used, Toro and McGuire (1987) (w=0.286), Frankel, et al. (1996) (w=0.286), Atkinson and Boore (1995) (w=0.286), and Campbell (2003) (w=0.143).

The location of the ground motion is dependent on the Site Condition (Geologically Realistic or Hard-Rock Basement Outcrop) selected in Section 11.9.2. Table 11-7 provides the location where the ground motions are computed based on the Site Condition selected and Geologic Unit.

**Table 11-7, Location of Ground Motion**

| Site Condition | Geologic Unit[1] | Location of Ground Motion |
|---|---|---|
| Geologically Realistic | Piedmont / Blue Ridge (Zone I) | Generated at a hypothetical outcrop of weathered rock (**$V_s$ = 8,200 ft/s**) |
| | Coastal Plain (Zone II) | Generated at a hypothetical outcrop of firm Coastal Plain sediment (**$V_s$ = 2,500 ft/s**) |
| Hard-Rock Basement Outcrop | Piedmont / Blue Ridge (Zone I) | Generated at a hard-rock basement outcrop (**$V_s$ = 11,500 ft/s**) |
| | Coastal Plain (Zone II) | |

[1]For geologic unit locations see Figure 11-1 and 11-2 and for Site Condition locations see Figure 11-13.

### 11.9.4.2 "Real" Ground Motions

Should a 3-dimensional site-specific response analysis be required, typically on "non-typical" SCDOT bridges, then 7 three-component (orthogonal directions) "real" time histories shall be required. "Real" time histories are recorded time histories from actual seismic events as opposed to the synthetic time histories generated by Scenario_PC (2006). The use of "real" time histories on "typical" bridges shall be determined by the OES/GDS on a project specific basis.

The "real" time histories shall be selected based on the following criteria:

- Tectonic environment
- Seismic magnitude, $M_w$
- Type of faulting
- Site-to-seismic source distance, R
- Local site conditions
- Design or expected ground-motion (time history) characteristics (including duration and energy content (Arias Intensity, $I_A$))

As indicated in this Chapter, South Carolina is located in the approximate middle of the North American tectonic plate with the type and distribution of faulting unknown. However, based on recent evidence (Virginia Seismic Event, August 2011), the tectonic environment is probably comprised of infilled rift valleys (Stein, et al. (2013)). These rift valleys appear to be located adjacent to the modern coastline of the CEUS, where the change in density between the overlying rock and the underlying rock is greatest (i.e., granite under the North American continent and basalt under the Atlantic Ocean). In addition, the thickness of the infill materials is also greatest adjacent to the coastline. These infill materials can cause downward pressure on the faults (i.e., similar to the New Madrid Seismic Zone), that can be uneven along the fault causing stress differentials along the rift valley that can lead to seismic shaking. Based on this evidence the tectonic environment used to select the “real” ground motion shall not include ground motions generated by a subduction zone seismic event.

According to Durá-Gómez and Talwani (2009), the faults located in the Charleston, South Carolina area appear to be strike-slip faults. Strike-slip faults are faults where the ground on either side of the fault moves laterally to each other. This type of faulting is evidenced by the ZRA as identified by Chapman and Talwani (2002).

The magnitude and distance shall be determined as previously indicated in this Chapter. The local site conditions shall be identified as either soil (typical of the Lower and Middle Coastal Plain) or rock (typical of the Piedmont). Rock as used here has a $V^*_{s,H}$ of greater than 11,500 feet per second ($V^*_{s,H}$ > 11,500 ft/sec). The selected seismic event should also match the estimated duration (see Section 12.9.3) as closely as possible. In addition, the selected seismic event should closely match the design UHS.

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