1.0 Introduction

The study involves probabilistic seismic hazard mapping for South Carolina. A hazard model is developed which defines the sources for potential earthquakes and earthquake recurrence relations. Seismic hazard, expressed as maps of motion intensity corresponding to 4 probabilities of exceedance, are derived from calculations at 1247 site locations within and adjacent to South Carolina. The motions are defined in terms of pseudo-spectral acceleration (PSA) oscillator response for frequencies 0.5, 1.0, 2.0, 3.3, 5.0, 6.7 and 13 Hz, for 5% critical damping and peak horizontal ground acceleration (PGA). The 4 probability levels are 2%,5%,7% and 10% probability of exceedance for 50 year exposure periods. The seismic hazard for 1.0 Hz PSA and PGA are deaggregated for 19 cites and towns across South Carolina, to represent the contribution to seismic hazard from various magnitude earthquakes at various distances.

The approach used in this study is similar to that used by the U. S. Geological Survey (USGS) to develop the National Seismic Hazard Maps (Frankel et al., 1996, 2002). However, there are some important differences between the studies. Similar to the USGS approach, model uncertainty is incorporated using a logic tree. Important model elements involved in the logic tree analysis are alternative source configurations for earthquakes in the magnitude range ($5.0<M<7.0$), alternative source models for larger, characteristic type earthquakes ($7.0<M<7.5$) in the coastal areas of South Carolina, maximum magnitudes for the characteristic earthquakes in those areas, and 5 alternative ground motion prediction models adopted by the U. S. Geological Survey for the 2002 update of the National Seismic Hazard Maps.

A significant difference between the National Seismic Hazard Maps and the results presented here arises from our attempt to develop hazard maps reflecting actual geological conditions in South Carolina. Also, our aim is to provide results that may be directly used in conjunction with the current bridge design procedures implemented by SCDOT. Unfortunately, a generic site response model such as that adopted for the 1996 National Seismic Hazard Maps (and also used in the 2002 update) does not adequately represent the range of conditions in South Carolina. This is particularly the case for those coastal areas of the state where earthquake resistant design is most important from past experience. Providing a probabilistic mapping of seismic hazard in terms of motions that can be incorporated easily into current of design procedures requires treatment of wave propagation within the Coastal Plain sedimentary section.

To simplify matters as much as possible, we distinguish the results using only two conditions: 1) sites in the Atlantic Coastal Plain and 2) sites outside the Coastal Plain. In both cases, we predict ground motions that are consistent with the anticipated needs of SCDOT.

For sites in the Coastal Plain, we map ground motions for a hypothetical outcrop of "firm coastal plain sediment" (NEHRP B-C boundary, Vs=760 m/s). It is anticipated that material with this shear wave velocity will behave in an approximately linear manner to expected levels of strong motion at most sites in the state. These motions can serve as input for nonlinear dynamic analysis using shallow site specific geotechnical information, implemented with a program like SHAKE. Such an analysis would be straight-forward, requiring only an estimate of the depth at which the mapped outcrop motion would be applied in the soil/sediment column. In most cases this would be at depths of less than 50 m.

The motions mapped for sites outside the Coast Plain are to be interpreted as surface motions on "weathered southeastern U.S. Piedmont rock". This is very distinct from "weathered rock" in California. The mapped motions for sites outside the Coastal Plain represent surface motions on a velocity profile consisting of 250 m of material with shear wave velocity Vs=2,500 m/s, overlying a hard rock basement half-space with velocity 3,500 m/s. The quality factor for the weathered rock layer is 600. These velocities are higher than typically encountered at similar depths in California. Again, these motions may serve as input motions for dynamic analysis using a program such as SHAKE, if site investigations indicate significant soil or alluvial overburden.

This study also provides hazard calculations for hypothetical hard rock (basement) outcrop conditions (Vs=3.5 km/sec). The two suites of results together represent a definitive assessment of the nature of potential ground motion for design purposes, and provide a comprehensive basis for defining input ground motions for non-linear analysis using site-specific geotechnical information.

The results of this study are presented as hardcopy maps, EXCEL spreadsheets, and as interactive computer routines that provide the capability to interpolate the discrete results of the hazard calculations to any site location within South Carolina. The interactive programs provide the user with the means to generate times histories of horizontal ground acceleration for 4 probabilities of exceedance. The deaggreation analysis provides information for decisions regarding magnitude and distance combinations for these scenario time series.

The following sections of the report describe the modeling approach, present the results, and provide information on the use of the computer software and spreadsheet information developed in this study.

2.0 Probabilistic Seismic Hazard Model

The analysis methods used in this study are based on the approach developed by Cornell (1968). Basically, the earthquake processes that might potentially affect sites in South Carolina are modeled stochastically in both time and space. Seismic sources are defined. Within these sources, earthquakes are assumed to occur randomly, in terms of their epicentral locations, as well as in terms of their occurrence times. Temporally, the earthquakes are assumed to follow a simple Poisson process. The Poisson model is the most tractable model that can be applied to this type of analysis, and has been employed as a "standard" model for hazard analysis for many years. The most important assumption is that earthquakes associated with a given source have no "memory" of past earthquakes. The Poisson model is an approximation. Large earthquakes have been shown to occur in a time-dependent manner: i.e., the probability of a large shock in fact depends upon the time elapsed since the last large shock on a given fault, or in a given source area. Unfortunately, for the study area, the data necessary to estimate repeat times of large shocks remain sparse.

Important elements of the seismic hazard model are discussed below.

2.1 Seismic Sources

The specific geological features (faults) that are causally related to seismicity are not well defined in much of eastern North America. Hence, area sources based primarily on seismic history were used for analysis of non-characteristic events. Larger magnitude characteristic events with potential to occur in coastal South Carolina are modeled with a combination of area and fault sources. Earthquakes are assumed to occur with uniform probability in space, their locations having no dependence upon magnitude within the various area sources. Figure 1 shows the area sources defined in this study for the non-characteristic "background" events.

We have also incorporated into the analysis a source delineation based of the concept of "smoothed seismicity" (Frankel et al., 1996) as an alternative to the delineation of area sources shown in Figure 1. This approach defines the rate of earthquakes contributing to hazard in terms of a geographically variable function that is estimated by counting the number of shocks in the historical catalog falling within a certain distance from a grid element location. The results of this discrete counting operation are then smoothed to develop a two-dimensional mapping of the frequency of earthquakes in the region. The approach removes the need for some arbitrary decisions concerning source area boundaries, and provides a highly reproducible input for the hazard analysis. However, it is not without a certain degree of arbitrariness. The choice of smoothing radius and density function are essentially arbitrary decisions. We have used the smoothed seismicity rates for South Carolina and adjacent areas developed for the 1996 National Seismic Hazard Maps by the USGS, and available at *http://geohazards.cr.usgs.gov/eq/html/rategrid.html*. Recurrence relationships for non-characteristic background earthquakes in the source areas south of latitude 40N and east of longitude 89W shown in Figure 1 were developed on the basis of the Virginia Tech Catalog of Seismicity for the Southeastern United States, available at *http://vtso.geol.vt.edu/outreach/vtso/* . Recurrence models for the remaining source areas were developed on the basis of the catalog assembled by the U.S. Geological Survey (Mueller et al., 1997). Figure 3 shows the instrumentally located earthquakes with magnitudes exceeding 3.0 occurring in the period 1977-present in the southeastern United States. Figure 4 shows the historical catalog of shocks with estimated magnitudes exceeding 3.0 in the region for the period 1600-1977.

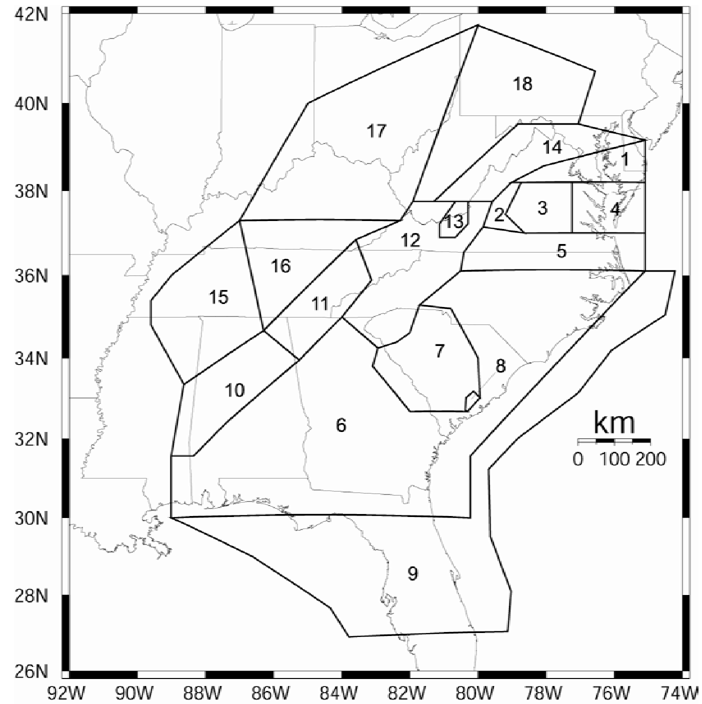

Figure 1. Source areas defined for non-characteristic events are indicated by the polygons.

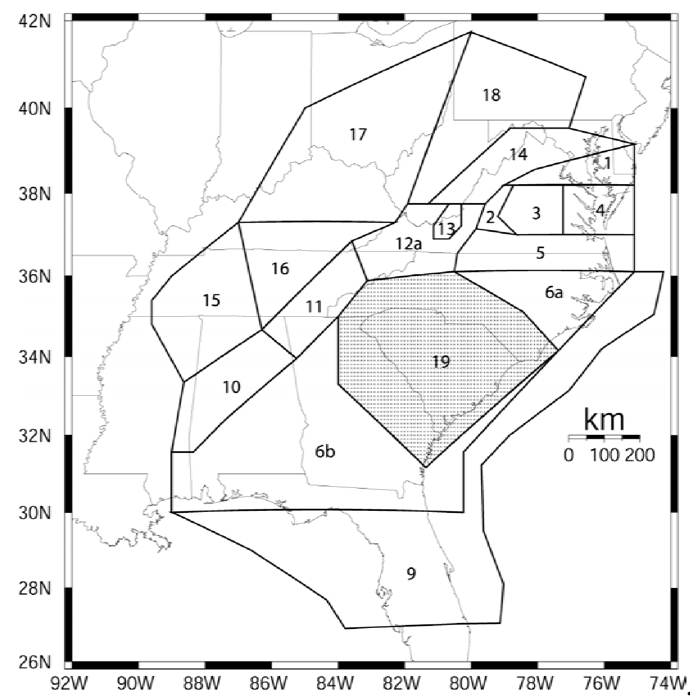

Figure 2. Alternative source areas defined for non-characteristic earthquakes. The source area including South Carolina and adjacent parts of surrounding states was modeled using the smoothed seismicity grid values of Frankel et al. (1996) as an alternative to the source area definition shown in Figure 1.

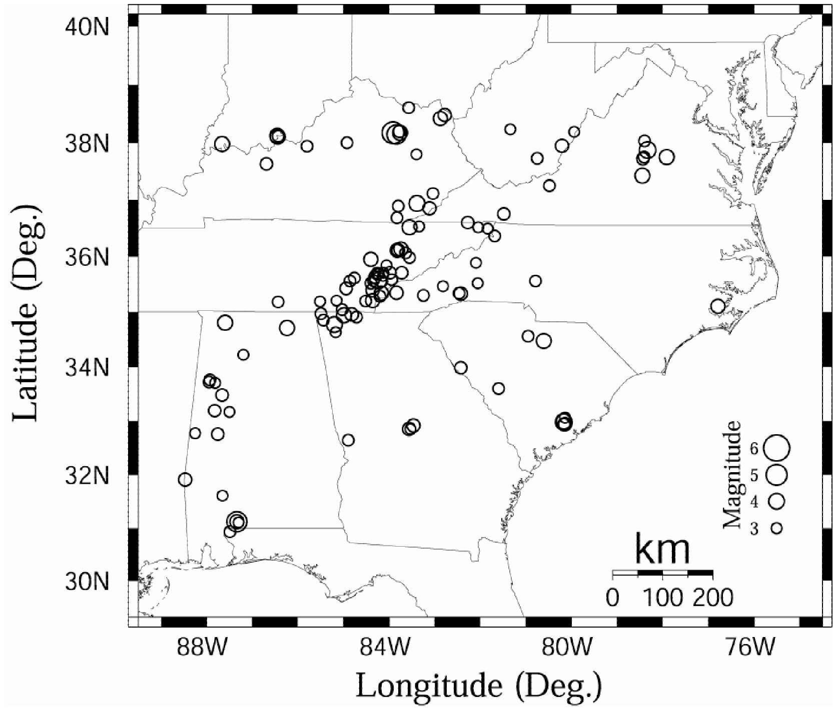

Figure 3. Circles indicate the epicenters of earthquakes with magnitudes greater than 3.0 contained in the Virginia Tech catalog of seismicity of the Southeastern United States, 1977-Present. The area covered by the catalog includes the states of KY, TN, AL, GA, FL, SC, NC, VA, WVA and MD.

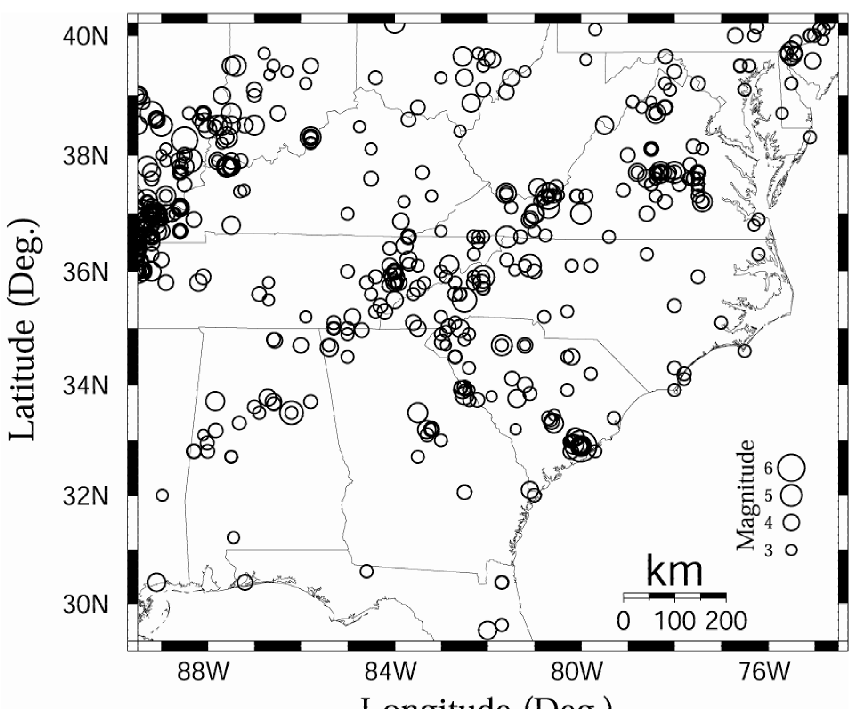

Figure 4. Earthquakes with magnitudes greater than 3.0, 1600-present, contained in the Va Tech catalog of seismicity of the Southeastern United States.

2.1.1: Non-Characteristic Earthquakes (5.0<M<7.0)

The 1886 Charleston, South Carolina earthquake dominates the seismic history for the entire southeastern region. Treatment of the 1886 event and similar shocks largely determines the estimate of seismic hazard at most sites, due to proximity to potential sources of such earthquakes in the future. The hazard represented by the potential of future occurrences of large magnitude events similar to the 1886 shock is treated using a "characteristic" earthquake model. This will be discussed in detail in a later section.

Although the potential for future shocks such as the 1886 event dominates the seismic hazard for South Carolina, the potential for smaller events located in South Carolina and elsewhere throughout the southeastern U.S. region also contributes, in varying degrees, to the total estimate of hazard. To estimate this hazard, earthquakes with magnitudes smaller than moment magnitude M=7.0 are termed "non-characteristic" and are treated as occurring at random within sources that are defined largely on the basis of the observed rate of historical and recent instrumentally recorded seismicity. The seismic hazard presented by these sources is proportional to the seismicity rate within the source and inversely proportional to the distance of the source to a given site. The individual sources for non-characteristic earthquakes are discussed in this section.

Earthquakes in the magnitude range (5.0<M<7.0) are assumed capable of occurring in all sources shown in Figures 1 and 2. Larger shocks (referred to below as "characteristic") are assumed capable of occurring only in a restricted area including parts of coastal South Carolina. The non-characteristic earthquakes are treated as forming a seismicity "background". The seismic hazard in South Carolina due to earthquake activity in the background was calculated using standard techniques, assuming a truncated Gutenberg-Richter recurrence model, with recurrences rates determined from the historical catalogs of earthquake activity cited above, or taken directly from the smoothed seismicity rate grid of Frankel et al., (1996).

Note that two alternative configurations of the non-characteristic background sources were used, and given equal weight in the analysis. One alternative involved the source areas shown in Figure 1. The second alternative involved the sources shown in Figure 2, which includes the spatially variable smoothed seismicity rate model of Frankel et al. (1996) for South Carolina and adjacent areas.

The rate of earthquakes per year is expressed in terms of the Gutenberg-Richter recurrence model for the background of non-characteristic events. The model is

$$\text{Log } N = a - b\, m \qquad (1)$$

where N is the number of earthquakes per year with magnitude greater than m. The parameters a and b are estimated from the historical record of pre-instrumental earthquakes, and from the catalog of more recent instrumentally recorded earthquakes. The Gutenberg-Richter model implies an exponential probability density function for earthquake magnitude.

There are several different magnitude scales in use. Two types are used in this study. The scale developed by Nuttli (1973) is based on the amplitude of the short-period Lg phase. It is the magnitude scale generally used in eastern North America for shocks recorded at regional distances. It is referred to in this study as m_{blg}. It is the magnitude scale adopted for most eastern U.S. earthquake catalogs. The recurrence relationships used in this study are developed in terms of this magnitude. The moment magnitude scale (Hanks and Kanamori, 1979) is based on seismic moment and is a better estimate of the physical "size". Here, it is used in the equations for ground motion prediction, in the definition of characteristic earthquakes and as the upper and lower truncation limits of the magnitude probability density functions. The values of a and b listed in Table 1 are in terms of mblg magnitude. The following conversion (Frankel et al., 1996; Johnston 1994) was used to convert from m_{blg} to moment magnitude M.

$$M \text{ (moment magnitude)} = 3.45 - 0.473\, m_{blg} + 0.145 m_{blg}^2 \quad (2)$$

A truncated form of the exponential probability density function for earthquake magnitude was developed from Equation 1 and used for calculation of hazard from the non-characteristic events. The minimum magnitude truncation (Mmin) was chosen to be moment magnitude M=5.0, because smaller earthquakes do not usually cause damage of engineering concern. This choice is consistent with current practice in construction of the USGS National Seismic Hazard Maps. The upper bound magnitude truncation (Mmax) can be a critical parameter for hazard analysis, and will be discussed in detail below in regard to the modeling of M>7.0 characteristic shocks in coastal South Carolina. The results of this study are not sensitive to the choice of upper bound magnitude truncation for the non-characteristic events, based on tests using values in the range M=6.5 to 7.0. On that basis, a value of M=7.0 was used for Mmax in all sources shown in Figures 1 and 2.

Table 1 lists the parameters in Equation 1, as well the areas and Mmax values, in terms of m_{blg} and M, for the background sources for non-characteristic seismicity according to the numbering scheme shown in Figures 1 and 2. The non-characteristic sources contributing significantly to hazard in South Carolina are further discussed in the following sections.

2.1.1.1 Source Area 12: Southern Appalachian Zone

This source includes southwestern Virginia, western North Carolina, northeastern Tennessee, and northwestern South Carolina. Instrumental data from shocks in this area suggest that the earthquakes occur beneath the Appalachian thrust sheets, in Precambrian basement rock, as in Giles County, Virginia and the adjoining eastern Tennessee seismic zones, discussed below. The region overlies the inferred Eocambrian margin of North America, and reactivation of extensional faults that originally developed during the opening of the proto-Atlantic ocean may be responsible for modern seismicity (Bollinger and Wheeler, 1988).

The largest historical shock in this source area occurred on February 21, 1916. The epicenter of this shock is uncertain: it was strongly felt in Waynesville, North Carolina, which is the attributed epicenter. However, the shock was also strongly felt on the western side of the Smoky Mountains, in Sevierville, Tennessee. Stover and Coffman (1993) list a magnitude value of 5.2 (m_{blg}), based on felt area.

This source area is modified as source 12a and used in conjunction with source area 19 (Figure 2), for implementing the alternative source configuration based on the smoothed seismicity rates of Frankel et al. (1996).

2.1.1.2 Source Area 11: Eastern Tennessee Seismic Zone

The Valley and Ridge province of eastern Tennessee has been the most seismically active area in the southeastern United States since instrumental monitoring of the region became approximately uniform in the early 1980's. The pattern of epicenters defines a northeast trending zone, which correlates with regional scale potential field anomalies (King and Zietz, 1978; Nelson and Zietz, 1983, Powell et al., 1994, Vlahovic et al., 1998). The earthquakes in eastern Tennessee show similarities to the seismicity in Giles County Virginia and elsewhere along the Valley and Ridge province of the Southern Appalachians (Bollinger et al., 1991, Chapman et al., 1997). Focal depths are beneath the Appalachian sedimentary section in Precambrian basement.

An important aspect of the eastern Tennessee seismicity is apparent in Figure 3. The epicentral locations of the earthquakes define a major northeast trending seismic zone, over 300 km in length. This suggests the possibility of a major shock, if the zone is viewed as defining a through-going basement fault. Focal mechanisms and the spatial locations of the seismicity have revealed much information concerning this important issue, but the seismic hazard posed by this seismic zone remains uncertain (Johnston et al., 1985; Bollinger et al., 1991, Chapman et al., 1997). In the hazard calculations, the maximum magnitude earthquake potential for the eastern Tennessee seismic zone is assumed equivalent to that of surrounding areas in the Appalachians (M=7.0).

2.1.1.3 Source Area 13: Giles County Virginia

The "Giles County" seismic zone is an area of concentrated seismicity near the West Virginia-Virginia border, lying mostly within Giles County, Virginia. This is the location of the second largest earthquake to have occurred in the southeastern United States during the historical period. It occurred on May 31, 1897, with an estimated magnitude of 5.8 (m_{blg}). It caused intensity VIII MM damage in the epicentral area, near Pearisburg. The largest shock in recent times was m_{blg} 4.6 on November 11, 1969.

As in eastern Tennessee, earthquakes occur at depths between 5 and 25 km and appear to a define a 40 km long, steeply dipping structure which trends NNE, about 20 degrees counterclockwise to the trend of the detached sedimentary structures mapped at the surface. The earthquakes are apparently unrelated to structure exposed at the surface, and are confined to the Grenville basement beneath the Paleozoic detachment. It has been proposed that seismicity in the zone is the result of reactivation of one or more Eocambrian extensional faults.

2.1.1.4 Source Area 10: Alabama

The Valley and Ridge of Alabama is similar to the eastern Tennessee area in terms of seismicity. In past decades it has not experienced the high occurrence rates of small shocks that characterize the Eastern Tennessee seismic zone.

2.1.1.5 Source Area 7: South Carolina Piedmont

The Piedmont and Atlantic Coastal Plain areas exclusive of South Carolina and central Virginia have exhibited a very low level of seismicity in comparison to the Appalachian Mountain region to the northwest. The Piedmont of South Carolina, like central Virginia, has experienced a substantially higher level of seismicity than in the Piedmont-Coastal Plain region as a whole. Probably the largest shock to affect the entire Piedmont region occurred near Union, South Carolina on January 1, 1913. That shock threw down numerous chimneys in the epicentral area. The magnitude is estimated as 4.8 (Stover and Coffman, 1993). Source Area 7 is defined here on the basis of historical and recent levels of seismicity. The geological causes of earthquakes in this area are complex. Many recently recorded shocks are near-surface events, possibly related to stress concentrations near plutons. High near-surface stresses are also indicated by numerous cases of reservoir induced seismicity.

Because of the sensitivity of the hazard estimates to the definition of this source area, we have included an alternative approach in which local a and b values are estimated entirely on the geographic distribution of epicenters of past earthquakes. Seismicity rates and b values for the area indicated as Source 19 in Figure 2 are taken from the smoothed seismicity rate values estimated by Frankel et al. (1996).

2.1.1.6 Source Area 6: Piedmont and Coastal Plain

This source area has been defined on the basis of a lack of historical seismicity. Very few shocks of known tectonic origin have occurred in this large region. However, the uncertainty in the hazard for sites in South Carolina lying near or within this source is large, due to the essentially arbitrary boundary separating Source Area 6 from Area 7. This is the main motivation for including an alternative source scenario (source area 19 in Figure 2) that uses a grid of smoothed seismicity rates based on the geographic distribution of epicenters in the historical seismicity catalog (Frankel et al. 1996). Sources 6a and 6b in Figure 2 are used in conjunction with source 19 to represent this alternative hazard model.

2.1.1.7 Source Area 9: Florida and Continental Margin

This area has not experienced sufficient historical seismicity so as to permit quantification of recurrence models. Recurrence models for this source area are defined on the basis of the seismicity rate per unit area derived from Source Area 6. The geographic extent of the source area is defined to include the offshore areas with transitional continental crust.

2.1.1.8 Source Area 8: Middleton Place Seismic Zone, South Carolina

The epicentral area of the 1886 shock near Middleton Place, SC continues to be seismically active. This source area is designed to model the non-characteristic events inferred from the historical and instrumentally defined seismicity catalog. As is done with all other source areas discussed above, the recurrence models for this source are based on the observed frequency of occurrence of historical earthquakes within the source. The geographic extent of Source Area 8 is taken to include the epicenters of recent, instrumentally located shocks in the area, as well as the majority of paleoliquefaction features induced by the 1886 shock and several earlier earthquakes. Source area 8 is replaced by source 19 (Figure 2) in the alternative configuration using the Frankel et al. (1996) smoothed seismicity rates.

Table 1
Seismicity Parameters for Non-Characteristic Background Source Areas

		Area km^2	a	b	Mmax m_{blg}	Mmax M
1	Zone1	21,064	0.242	0.84	6.84	7.00
2	Zone2	6,411	-0.27	0.84	6.84	7.00
3	Central Virginia	19,977	1.184	0.64	6.84	7.00
4	Zone4	25,088	0.319	0.84	6.84	7.00
5	Zone5	47,525	0.596	0.84	6.84	7.00
6	Piedmont and Coastal Plain	417,274	1.537	0.84	6.84	7.00
6a	Pied&CP NE	48,731	0.604	0.84	6.84	7.00
6b	Pied&CP SW	248,260	1.312	0.84	6.84	7.00
7	South Carolina Piedmont	57,622	2.220	0.84	6.84	7.00
8	Middleton Place	1,178	1.690	0.77	6.84	7.00
9	Florida and continental margin	285,856	1.371	0.84	6.84	7.00
10	Alabama	52,466	1.800	0.84	6.84	7.00
11	Eastern Tennessee	37,345	2.720	0.90	6.84	7.00
12	Southern Appalachian	75,715	2.420	0.84	6.84	7.00
12a	Southern Appalachian North	44,118	2.185	0.84	6.84	7.00
13	Giles County, VA	5,129	1.070	0.84	6.84	7.00
14	Central Appalachians	43,195	1.630	0.84	6.84	7.00
15	West Tennessee	76,837	2.431	1.00	6.84	7.00
16	Central Tennessee	53,431	2.273	1.00	6.84	7.00
17	Ohio-Kentucky	151,475	2.726	1.00	6.84	7.00
18	West Va-Pennsylvania	88,187	2.491	1.00	6.84	7.00
19	USGS (1996) gridded seismicity rates and b value			0.95	6.84	7.00

2.1.2 Characteristic Events

Coastal South Carolina experienced a major earthquake on the evening of August 31, 1886, one of the largest shocks to affect eastern North America in historical times. To this day, it remains the most deadly and damaging seismic event ever experienced east of the Rocky Mountains. Current estimates of the magnitude of this earthquake are in the range M =7.0 to 7.5 (Johnston, 1996). The available evidence indicates that the source of this earthquake had dimensions on the order of several tens of kilometers, and was located to the west and northwest of Charleston (Dutton, 1889, Bollinger, 1973, 1977, 1992, Bollinger et al., 1993). Modern seismicity near Middleton Place has been monitored by the University of South Carolina since 1975. Most of the earthquakes define a dense cluster that has been interpreted to represent an intersection of basement faults (e.g., Talwani 1982; Madabhushi and Talwani 1993; Talwani 1999). The seismicity involves the upper crust, to a depth of approximately 15 km.

The coastal South Carolina area received intense multidisciplinary investigation during the late 1970's and early 1980's. The results of those studies have proven to be equivocal (e.g., Rankin 1977, Gohn, 1983). The source of the 1886 earthquake has not yet been definitively identified (see, for example, Marple and Talwani, 1992, 1993, and 2000).

Although the exact faulting scenario involved in 1886 remains debatable, new information provides important constraints on the occurrence rates of larger shocks in the coastal South Carolina region. These data allow development of alternative models of potential sources for future large shocks in the area.

The Middleton Place seismic zone is situated within the area experiencing the maximum shaking intensity and ground deformation of the 1886 event. Talwani (1982, 1985, 1988, 1989, 1999; Talwani et al., 1997) have interpreted the data to indicate the existence of two (possibly 3) fault segments that intersect in the Middleton Place seismic zone. Talwani's interpretation for the source of the 1886 shock involves rupture on a NE trending "Woodstock" fault and rupture on a northwest trending "Ashley River" fault. More recent studies (Marple and Talwani, 1993, 1999) suggest that the Woodstock fault may be a member of a larger, NE trending system that extends to near the North Carolina border, and possibly further to the Virginia border. This larger feature has been termed the "East Coast Fault System" as it is defined by interpretation of geomorphic data, including stream gradients and offsets of drainage patterns. In South Carolina, the feature is referred to as the "Zone of River Anomalies" (ZRA).

The spatial distribution and age of paleoliquefaction features in the coastal South Carolina area constrains possible locations and recurrence rates for larger shocks (Obermeier and others, 1985, 1990, Amick et al., 1990, Amick et al., 1991, Rajendran and Talwani, 1993, Talwani and Cox, 1985, Talwani et al., 1999). Recent work by Talwani et al. (1999) and Talwani and Schaeffer (2001) considers two possible scenarios for the prehistoric seismicity. In one scenario, there are 3 possible sources located near

Charleston, Georgetown (to the northeast) and Bluffton (to the southwest). In the second scenario, all prehistoric events occurred near Charleston (i.e., within or near the Middleton Place seismic zone). Age dating techniques provide the following dates for the occurrences of these prehistoric events: A, 546+/-17 yrbp; B, 1001+/-33; C, 1648+/-74;D, 1966 +/-212; C', 1683+/-70; E, 3548+/-66; F, 5038+/-166; G, 5800+/-500.

In Scenario 1, events A,B,E,F occurred near Charleston, events C and D occurred at a northern site, and event D occurred at the southern site. In Scenario 2, events A, B, C' (and C),E,F and G all were large shocks near Charleston (M7+). Scenario 1 admits the possibility that events C and D were smaller in magnitude (6+).

By considering the above uncertainties on the age determinations as well as the 2 alternative scenarios, it is possible to derive average recurrence times of about 550 years for scenario 2 and approximately 900-1000 years for scenario 1.

The hazard model developed in this study seeks to give weight to several key elements of the problem discussed above. The characteristic event model pertains only to earthquakes with moment magnitudes in the range 7.0 to 7.5. These events are modeled as occurring only within the coastal area of South Carolina according to a Poisson process with mean return period of 550 years. All smaller earthquakes, with magnitudes ranging from M=5.0 to 7.0, are modeled as occurring within the various area sources discussed above, at ranges to 500 km from sites in South Carolina. As discussed above in Section 2.1.1, the return periods of the M=5.0 to 7.0 events are unconstrained by paleoseismic data, and follow the Gutenberg-Richter recurrence model (Equation 1) with parameters determined from the observed rates of historical seismicity in the respective source areas (Table 1).

The characteristic event model for the M=7.0 to 7.5 events is defined by 3 source alternatives. These alternative scenarios are considered to be statistically independent. Figure 5 shows the fault and area sources defining the three scenarios, which are discussed in the following sections.

Finite fault rupture is modeled in the hazard calculations for two of the characteristic scenarios. This implies that the source to site distance is a function of earthquake magnitude. The magnitude-fault length relationship assumes a 25 km thickness of seismogenic crust, and a vertical strike-slip rupture. Fault length to width aspect ratio of 2:1 is assumed, conditional on width<25 km. The rupture area as a function of magnitude is based on the Brune (1970) source model, with static stress drop of 100 bars. The characteristic magnitude is treated as a discrete random variable that can assume values of M=7.1, 7.3 and 7.5 (moment magnitude). The probabilities (weights) of these values used in the hazard analysis are 0.2, 0.6 and 0.2, respectively. This distribution was designed to represent the range of magnitude estimates of the 1886 Charleston shock proposed by Johnston (1996). The characteristic magnitude distribution used here differs slightly from that finally adopted by the U. S. Geological Survey for the 2002 update of the National Maps. The USGS uses M=6.8 (0.2 wt), M=7.1 (0.2 wt), M=7.3 (0.45 wt) and M=7.5 (0.15 wt) (Frankel et al. 2002). These different modeling assumptions concerning the characteristic magnitude distributions contribute very little to the differences in final hazard estimates between the two studies.

2.1.2.1 Fault Sources for 1886-Type Rupture on the Woodstock-Ashley River Faults

This scenario represents essentially a re-occurrence of the 1886 earthquake. It is assumed that rupture occurred on the proposed Woodstock and/or on the Ashley River faults. The Woodstock fault is inferred to be a NE trending, strike-slip fault, whereas the Ashley River fault is inferred to be a shorter, NW trending thrust that may offset a north easterly continuation of the Woodstock fault in a compressional stepover (Talwani 1982; Madabhushi and Talwani 1993; Talwani 1999). This complex scenario is modeled using 3 independent finite fault sources. The faults are 74 km in length, and parallel to each other. Each fault is modeled capable of rupturing fully to produce a M=7.5 shock, or in a portion of the total length to produce M=7.1 or M=7.3 events. They lie within the area of maximum shaking intensity defined by Dutton (1889). The Woodstock fault can be considered spatially represented by either one of the three model faults, due to uncertainty in the exact location of that feature. The inferred NW trending Ashley River fault is thought likely to be much shorter than the Woodstock fault (approx. 20 km) and is not represented in the model as a discrete feature. However, the geographic effect on seismic hazard due to a NW trending source is modeled here by the NW-SE offset of the three parallel faults in the model scenario (Figure 5).

While is it possible that the 1886 event involved coeval slip on both NE and NW trending faults, the hazard model does not incorporate the possibility of statistical dependence among the faults modeling this scenario. Each fault is assumed to act independently of the others. The recurrence constraint provided by the paleoliquefaction data is an average of one characteristic event occurring in a 550 year period. This value was adopted by the U. S. Geological Survey for the mean return period of characteristic events in the coastal region of South Carolina. For this scenario, we assume a Poisson process with mean rate 1/550 yr^{-1}, and divide this activity rate equally among the three faults. Thus, the mean return period for a characteristic earthquake ($7.0<M<7.5$) on any one fault is 1,650 years.

2.1.2.2 ZRA Fault Source

The possible existence of an extended fault zone associated with the "Zone of River Anomalies" (ZRA) defined by Marple and Talwani (1993, 1999) is modeled by a 234 km NE trending finite fault source. In this source model, earthquakes with magnitude in the range ($7.0<M<7.5$) with maximum rupture lengths of approximately 74 km (for M=7.5) can occur along various segments of the total fault model. In comparison to the Woodstock-Ashley River scenario, the ZRA scenario tends to dilute seismic hazard in the epicentral area of the 1886 shock, and increase hazard to the northeast and southwest. The recurrence constraint of activity on the ZRA is a mean return period of 550 years ($7.0<M<7.5$), based on the paleoliquefaction data (Talwani and Schaeffer (2001).

2.1.2.3 Characteristic Area Source

This area source is similar to that used in the 1996 National Seismic Hazard Maps (Frankel et al., 1996). It models the possibility that a network of faults has been active in the coastal South Carolina region, and that our knowledge of all individual fault locations is not precise. In this model, characteristic magnitude events ($7.0<M<7.5$) can occur at random within a large area of the coastal region, with mean return period 550 years. Given that each occurrence would represent the rupture of a fault of up to 74 km in length, the source area represents the loci of the points of nearest fault rupture to any specific site.

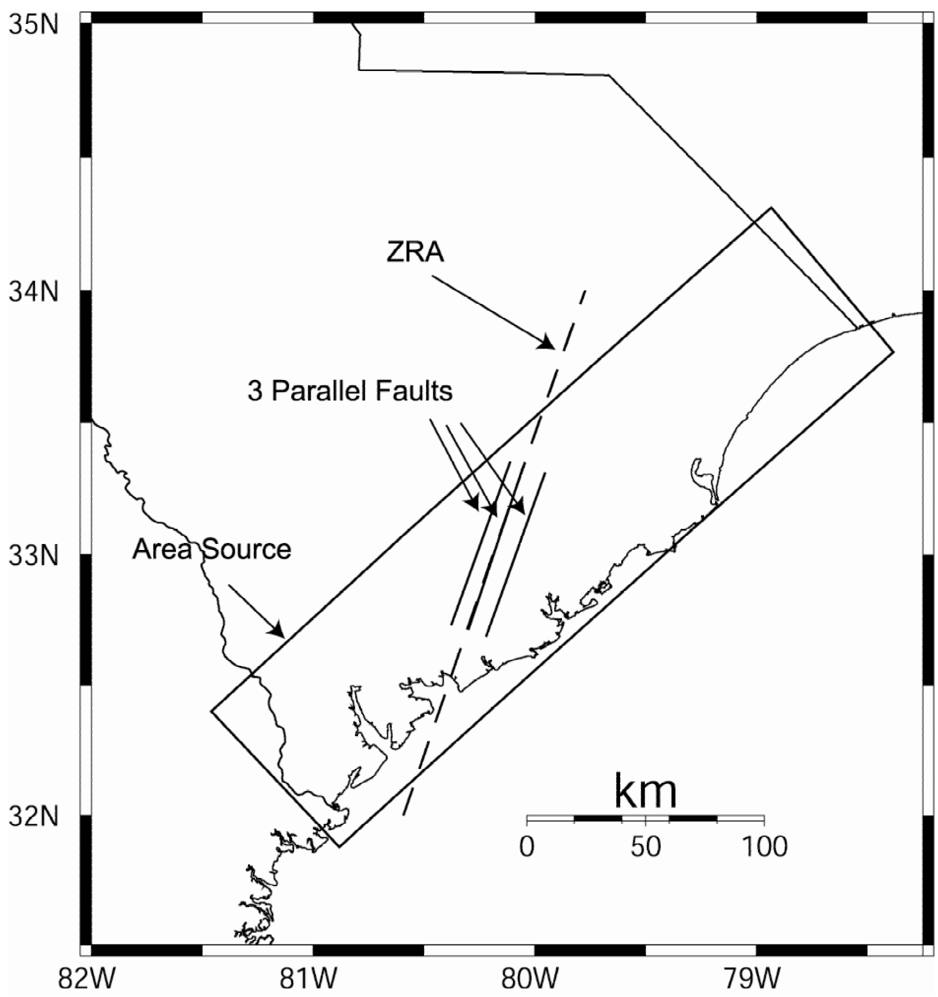

Figure 5. Sources for characteristic earthquakes. The dashed line indicates the fault source representing the "Zone of River Anomalies" scenario. The short solid lines representing 3 parallel faults model the combined Woodstock-Ashley River fault scenario, and the area source (rectangle) models the third scenario wherein characteristic shocks can occur at random locations in the coastal area of South Carolina.

2.2 Ground Motion Prediction

The hazard calculation requires the prediction of ground motion or harmonic oscillator response at a given distance from earthquakes of specific magnitudes. This prediction is made using an "attenuation model." The predictions used in this study are based on the results of recent work involving both empirical and theoretical modeling of eastern North American strong ground motion. The strong motion database for the east is small compared to that for the western United States. However, the available data indicate that high frequency ground motions attenuate more slowly in the east than in the west.

A small eastern North American strong motion data set has been obtained, and significant advances in understanding the generation and propagation of strong motion have taken place. The work of Hanks and McGuire (1981) showed that high frequency motion could be successfully predicted using a simple model of the earthquake source and random vibration theory. Boore and Atkinson (1987) and Toro and McGuire (1987) used this approach, now referred to as the "stochastic model" to predict ground motions in eastern North America. Joyner and Boore (1988), Atkinson and Boore (1990), Atkinson (1990) and Atkinson and Boore (1995) describe the development and evolution of the method as applied in the east.

An important unresolved issue is the nature of the S wave Fourier amplitude spectrum at the source. The commonly used stochastic models differ in respect to this element. The model of Atkinson and Boore (1995) uses a "two-corner frequency" source spectrum. Another widely used model, by Toro et al., (1997), effectively uses a standard one-corner frequency model. The main distinction between those two models results from the assumed source spectrum: the two-corner model causes smaller spectral amplitudes in the important mid-period band (approximately 1-sec. period).

Frankel et al. (1996) developed a stochastic model based on the ω^{-2} (one-corner frequency) source model for the 1996 National Seismic Hazard Maps. More recently, Sommerville et al., (2001) have developed a prediction model for motions from finite fault ruptures in eastern North America. The Sommerville et al. model is applicable to earthquakes in the magnitude range $6.0<M<7.5$. It models extended ruptures on faults with variable slip distributions, rather than assuming that the radiation is produced at a point with an idealized source spectral shape, as in the case of earlier published models for eastern North America based on the stochastic model. Campbell (2002) has developed a semi-empirical prediction model for eastern North America that modifies existing empirical prediction models derived from the western U.S. strong motion data base using adjustment factors that take into account differences in wave propagation known to exist between average rock sites in eastern and western North America.

2.2.1 Motions on Hard Rock

This study uses the prediction equations of Toro et al. (1997), Frankel et al. (1996), Atkinson and Boore (1995), Somerville et al., (2001) and Campbell (2002), with respective weights of 0.143, 0.143, 0.143, 0.286 and 0.286, for the characteristic events ($7.0<M<7.5$). The Somerville et al. model was not used for the non-characteristic events ($M<7.0$): in that case, the four remaining models were given equal weight (0.25). These models are used to predict motion for hard rock site conditions. The predictions are then modified as described in the following section to account for spatially variable geological conditions within South Carolina.

For comparison with this study, Frankel et al. (2002) use, for the characteristic events, Toro et al. (wt. 0.25), Frankel et al. 1996, (wt. 0.25), Atkinson and Boore (1995; wt. 0.25), Somerville et al. (2001; wt. 0.125) and Campbell (2002; wt. 0.125). For the non-characteristic events, Frankel et al. (2002) use Toro et al. (1997; wt. 0.286), Frankel et al. (1996; wt. 0.286), Atkinson and Boore (1995; wt. 0.286) and Campbell (2002; wt. 0.143). For the 2002 National Seismic Hazard Maps, the rock motions were modified to predict motions for a generic NEHRP B-C boundary site condition (average shear wave velocity = 760 m/s for the uppermost 30 m of material). The 2002 National Seismic Hazard Maps assume the same velocity versus depth profile to 8 km at all locations in South Carolina.

2.2.2 Development of Motions Accounting for Variable Geological Conditions

The amplitudes of seismic waves traveling from source to receiver are affected by contrasts in the velocity and density encountered along the full length of the transmission path. The largest velocity and density contrasts along the raypath are typically found at the shallow depths, for receivers on the surface and located within a few tens of kilometers from the focus of a crustal earthquake. Often, the velocity contrast between a thin soil layer and underlying bedrock, within a few meters of the surface, represents the largest velocity contrast found along the entire path of the seismic energy transmission. For this reason, the earthquake engineering community has coined the term "site response" in reference to the often dramatic effect that shallow geological conditions may impose on the incoming seismic wavefield. However, it is important to recognize that material properties along the entire raypath determine the motion at the ground surface, not necessarily those in the shallow subsurface (e.g. upper 30 meters) beneath a site.

The sedimentary deposits of the Atlantic Coastal Plain present a complication for the prediction of ground motions in South Carolina, for reasons mentioned above. The southeastern half of the state is underlain by a wedge of sediments that increases in thickness from zero at the Fall Line to well over 1 km in southernmost South Carolina. The basement rocks immediately underlying the Cretaceous and Cenozoic Coastal Plain sediments have shear wave velocities in excess of 3 km/s. This (in some cases deep) velocity contrast has an important effect on the amplitudes of seismic waves. In addition, absorption and scattering within the thicker sections of the sediments alter the frequency content of the ground motion. Because the thickness of the sedimentary section varies state-wide from zero to over 1 km, a generic "site response" model has limited utility for hazard mapping.

We estimate ground motions that can be interpreted unambiguously as "input" motions for seismic design procedures. To simplify matters as much as possible, we distinguish the results using only two conditions: 1) sites in the Atlantic Coastal Plain and 2) sites outside that geologic province

For sites in the Coastal Plain, we map ground motions on a hypothetical outcrop of "firm coastal plain sediment" (NEHRP B-C boundary, Vs=760 m/s). It is anticipated that material with this shear wave velocity will behave in an approximately linear manner to expected levels of strong motion at most sites in the state. These motions can be used as input for nonlinear dynamic analysis using shallow site specific geotechnical information and implemented with a program like SHAKE. Such an analysis would be straight-forward, requiring only an estimate of the depth at which the mapped outcrop motion would be applied in the soil/sediment column. In most cases this would be at depths less than 50 m.

The motions mapped for sites outside the Coast Plain are to be interpreted as surface motions on "weathered southeastern U.S. Piedmont rock". This is very distinct from "weathered rock" in California. The mapped motions for sites outside the Coastal Plain represent surface motions on a velocity profile consisting of 250 m of material with shear wave velocity Vs=2,500 m/s, overlying a hard rock basement half-space with velocity 3,500 m/s. The quality factor for the weathered rock layer is 600. These velocities are higher than typically encountered at similar depths in California. Again, these motions may be interpreted as input motions for dynamic analysis using a program such as SHAKE. They will need to be modified if site investigations indicate the presence of significant soil or alluvial overburden.

2.2.2.1 Site Response Modeling

Figure 6 shows contours representing the depth to the top of Mesozoic/Paleozoic basement in South Carolina.

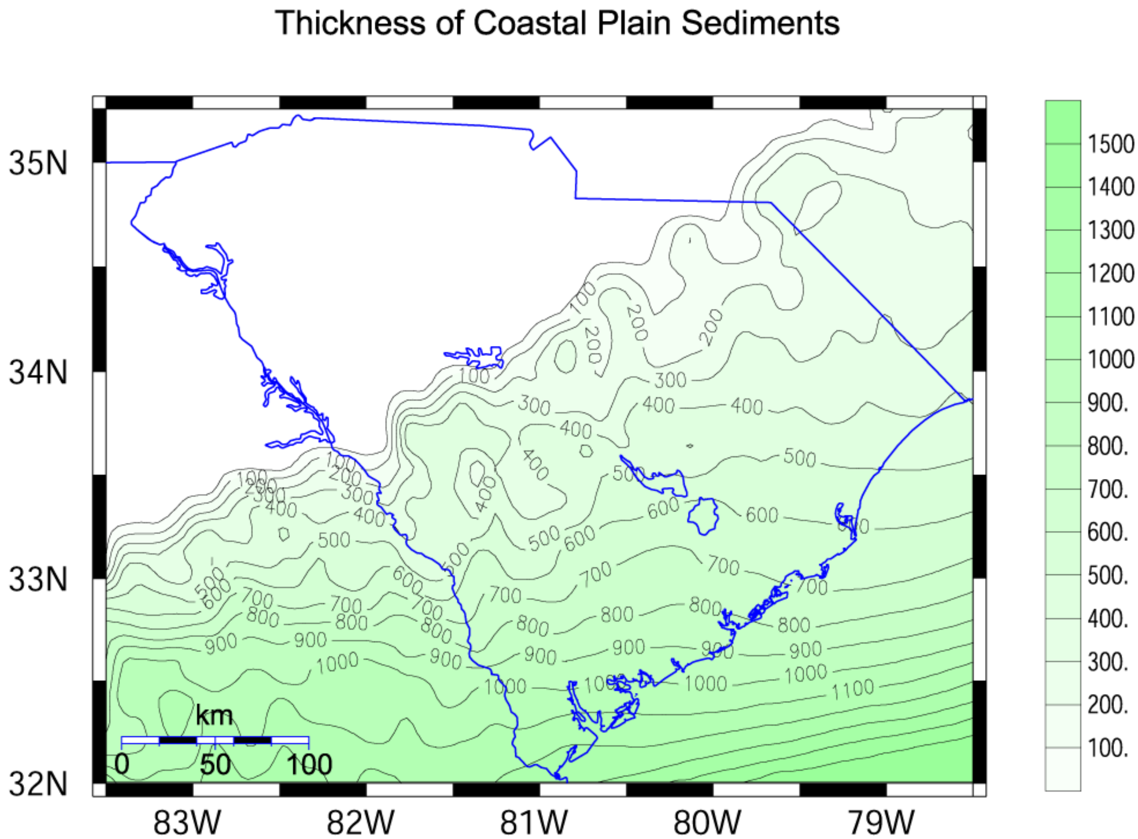

Figure 6. Contour map of Coastal Plain sediment thickness, in meters.

Figure 6 shows that the top-of-basement beneath the Coastal Plain section is a complex surface that generally deepens to the southeast and south. Thickness of sediments decreases to the northeast along the coast, representing a feature known as the "Cape Fear Arch". The general thickening to the sediments to the southwest along the coast represents a feature termed the "Southeast Georgia Embayment". The thickness contours shown in Figure 6 are derived by differencing the ground surface elevations of 1247 sites on a 0.025 x 0.025 degree grid, and the elevations of the basement surface at the same locations. The basement elevations were interpolated from a contour map developed from well data (P. Talwani, personal information). Ground surface elevations were taken from USGS SDTS format 7.5' Digital Elevation Models (DEM) (URL: http://mcmcweb.er.usgs.gov/sdts).

Transfer functions for the Coastal Plain section were developed on the basis of linear response of two layers over a half-space, assuming vertical SH wave incidence. The shallow layer represents the Coastal Plain sedimentary sequence, with Vs = 700 m/s, and density 2,000 kg/m^3. The deeper layer represents weathered rock, with Vs = 2,500 m/s and density 2,500 kg/m3. The quality factors for the sediments and weathered rock layers are 32 and 600, respectively. The value of 32 is based on estimates derived from micro-earthquakes in the Middleton Place seismic zone (Chapman et al., 2003). The half-space, representing unweathered Mesozoic and Paleozoic sedimentary, metamorphic and igneous rock has velocity 3,500 m/s and assumed density of 2,600 kg/m^3. The transfer functions were computed for each of 1247 sites involved in the analysis using the ¼ wavelength approximation of Boore and Joyner, 1991. Figure 7 shows the moduli of the transfer functions for specific cases where the sediment thickness is 1 km, 500 m, 100 m and 10 m. Figure 7 also shows the transfer function used for sites outside the Coastal Plain, in which case the shallow sedimentary layer was omitted from the model.

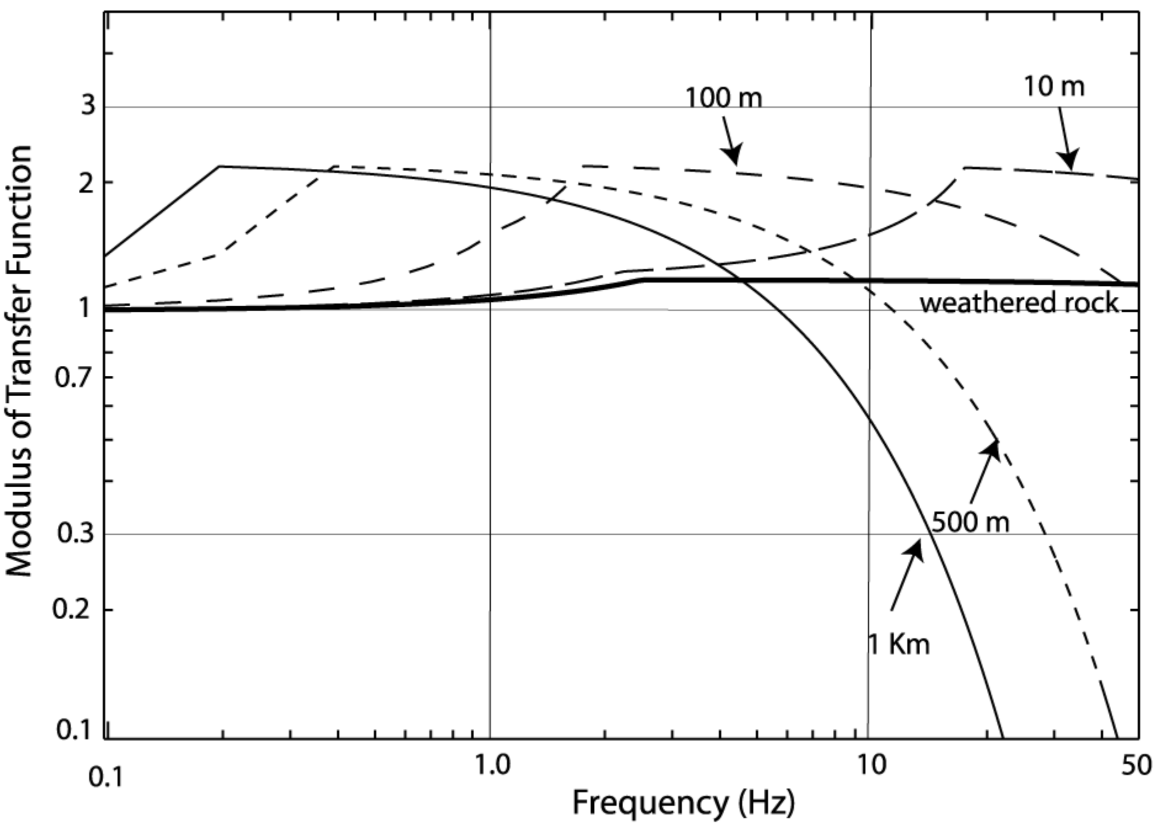

Figure 7. The modulus of the transfer function for vertically incident SH wave motion at sites in South Carolina, defined with respect to outcrop motions of hard rock basement. The examples show results for sites in the Coastal Plain with sediment thickness of 1 km, 500 m, 100 m and 10 m, as well as for sites outside the Coastal Plain (weathered rock).

The functions shown in Figure 7 represent the ratio of the Fourier amplitude spectrum of SH motion on the ground surface divided by the amplitude spectrum of motion that would be recorded on an outcrop of the basement half-space. A large number of stochastic time series simulations using the 2 layer model over the full range of sediment thickness show that these amplitude spectra accurately approximate the amplification ratio (surface amplitude divided by basement outcrop amplitude) of PSA oscillator response for 5% critical damping, in the restricted range 0.5 to 13 Hz of interest in this study. The amplification ratio for peak ground acceleration cannot be easily inferred from the Fourier amplitude spectrum of the SH ground motion transfer function. The PGA amplification ratios for different sedimentary layer thicknesses where developed directly from the suite of stochastic time series simulations. Figure 8 shows the resulting model for the amplification ratios of PGA.

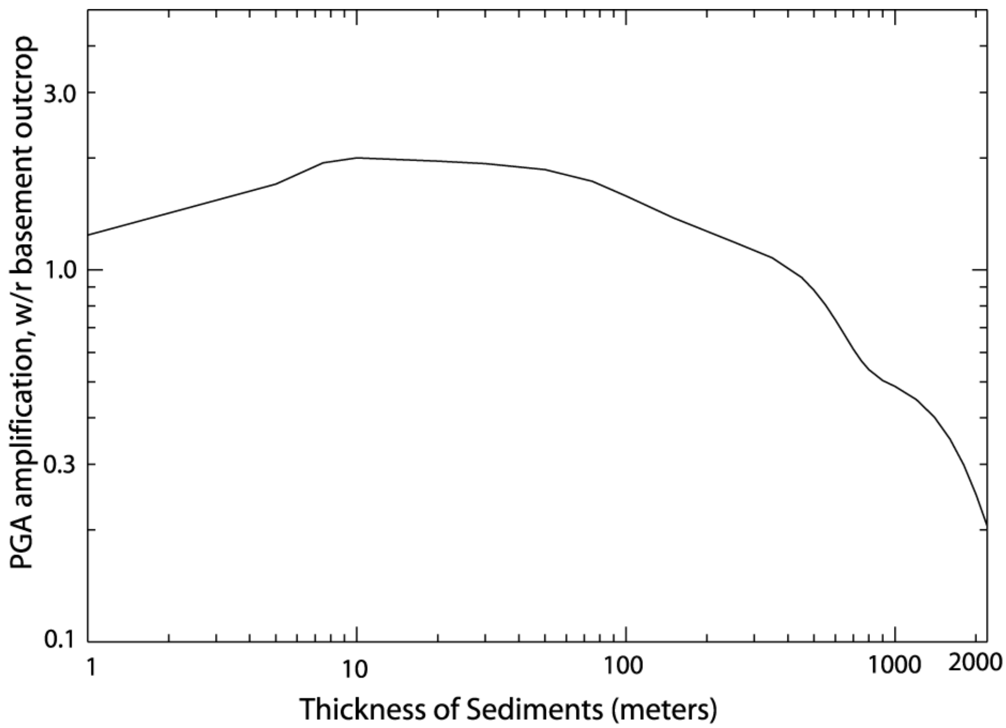

Figure 8. Ground surface/basement outcrop amplification ratios for peak horizontal ground acceleration versus thickness of sediments, based on stochastic simulations using the 2 layer over half-space model for Coastal Plain velocity structure. The asymptotic value for zero sediment thickness is 1.18, and represents the PGA amplification ratio for sites outside the Coastal Plain.

3.0 Hazard Calculations

Figure 9 illustrates a path through the logic-tree developed to incorporate knowledge-based uncertainty on the locations and magnitudes of characteristic earthquakes in coastal South Carolina, ground motion prediction and the activity rates of non-characteristic events in South Carolina and vicinity. Each branch in the logic tree has an associated probability, reflecting a subjective degree of belief in a particular model element. The probabilities of each branch sum to 1 at each node, reflecting an important fundamental assumption of this analysis. It is assumed that the alternative branches form a mutually exclusive and *collectively exhaustive* set of parameter states. It is important to recognize that the latter requirement may be impossible to achieve without complete knowledge of the process being modeled.

The hazard calculation involves 1247 realizations of the hazard model for sites located on a 0.025 x 0.025 degree grid of latitude and longitude. Mean hazard for each site is calculated for 4 probability levels: 2%, 5%, 7% and 10% probability of exceedance for a 50 year exposure period. These calculations are performed for pseudo-acceleration response spectral ordinates (PSA) at frequencies 0.5, 1.0, 2.0, 3.3, 5.0, 6.67, and 13.0 Hz, for a damping ratio of 0.05. The calculations also are performed for peak horizontal ground acceleration (PGA). The results are presented for geologically realistic site conditions, as well as for hypothetical hard-rock basement outcrop.

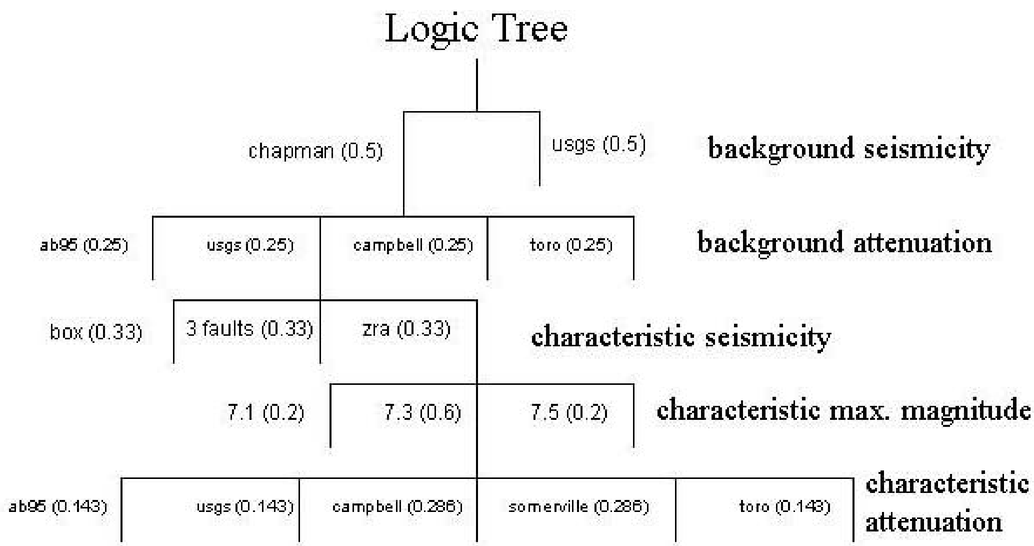

Figure 9. Logic tree used for hazard calculation. Numbers in parentheses indicate weights (probabilities) of each alternative hypothesis. The background seismicity hypotheses referred to by "chapman" and "usgs" are shown in Figures 1 and 2, respectively. Sources for the "box", "3-faults" and "ZRA" characteristic seismicity alternatives are shown in Figure 5. The 5 alternative "attenuation models" are discussed in the text in section 2.2.1.

3.1 Deaggreations

Total seismic hazard at a given site represents a double integration over the random variables magnitude and source to site distance. The distance and magnitude determine to a large extent the character of ground motion in terms of spectral content and duration. Examination of the contributions to this integration in distance and magnitude space can provide some insight into the nature of the hazard (Chapman, 1995; McGuire, 1995). This gives a quantitative basis for making decisions concerning the types of earthquake time series that are most consistent with a given probability of exceedance at a given site. For example, the earthquakes that contribute the most to the probability of exceeding PGA values corresponding to 2% probability of exceedance in 50 years for a site near Summerville, SC are certainly not the same events (in terms of both distance and magnitude) that would contribute the most to hazard near Spartanburg.

We have deaggregated the hazard calculations for 2% probability of exceedance in 50 years, for 1Hz PSA and PGA, at 18 cities and town across South Carolina. The locations where chosen to represent a sufficient density of sites such that it will be possible, from the deaggreations, to infer the most important magnitude-distance scenarios for any site in the state. This can be used for making decisions regarding the duration and frequency content for scenario earthquakes to be used in dynamic analyses, consistent with 2% probability of exceedance for 50 year exposure. The locations for the deaggreations are shown in Figure 10.

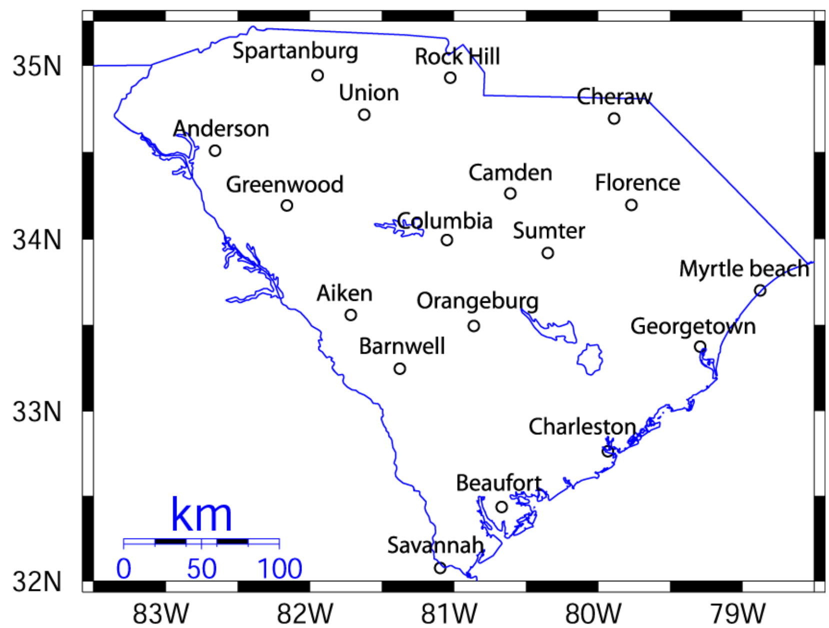

Figure 10. Cites and towns for which seismic hazard has been deaggregated for 2% probability of exceedance in 50 years, for PGA and 1 Hz PSA.

4.0 Results

4.1 Hazard Maps

Appendices A1, A2, A3 and A4 are figures showing the mapped seismic hazard results for 2%, 5% 7% and 10% probabilities of exceedance for 50 year exposure. For each hazard level, there is a map showing results for geologically realistic site conditions, taking into account sediment thickness and/or near surface weathering, and a map showing the results for surface motion on a hypothetical outcrop of hard-rock basement. In addition to the hardcopies, the maps shown in appendices A1 through A4 are provided in electronic from on an accompanying CD.

4.2 Deaggregations

Appendix B shows the results of the deaggreation analysis for 2% probability of exceedance in 50 years. For each of the 18 sites shown in Figure 10, we plot the joint moment magnitude-distance density, as well as the marginal densities for magnitude and distance. The densities have been normalized to a maximum value of unity for convenience of plotting.

Examination of the plots in Appendix B shows the complexity of seismic hazard across South Carolina at this probability of exceedance. Some degree of categorization can be made by considering three zones. The northwestern zone is represented by Anderson, Spartanburg, Greenwood , Union and Rock Hill. The central zone is Aiken, Columbia, Camden, Cheraw, Barnwell, Orangeburg, Sumter and Florence. The southeastern, or coastal zone is Savannah, Beaufort, Charleston, Georgetown and Myrtle Beach.

The events that contribute the most to seismic hazard are referred to as "modal events". The modal events for the northwestern zone for PGA are very different from the modal events for 1 Hz PSA. Examination of the deaggreations shows that the major contribution to PGA hazard (or hazard for high-frequency oscillators) is due to the potential for $M<7.0$ shocks at small distances (less than approximately 50 km). On the other hand, the events that contribute the most to hazard for 1 Hz PSA are at distances in excess of approximately 160 km. The magnitudes of the events are greater than 7.0. Thus we can conclude that for the northwestern section of the state, the hazard at high frequencies is dominated by the non-characteristic seismicity, whereas the low frequency (e.g. 1 Hz) hazard is strongly influenced by the distant, characteristic seismicity.

The coastal region shows a very different deaggreation pattern. Non-characteristic seismicity is of very low rate in these areas, whereas the sites are close the inferred sources of the large magnitude ($M>7.0$) characteristic events. As a consequence, the seismic hazard at the coastal sites, for both high and low frequencies, is almost entirely determined by the characteristic earthquakes.

In the central region of the state, the situation is a continuum between the extremes represented by the northwestern and southeastern regions. There is much variation of hazard in this area. Generally, the low frequency hazard in dominated by the characteristic seismicity, although sites in the west-central part of the state (e.g. Aiken, Barnwell) show a significant contribution to hazard at 1 Hz from non-characteristic events. The situation with PGA and high frequency oscillator response is too complex to generalize. At Aiken, Barnwell, Orangeburg, Columbia and Camden, the non-characteristic seismicity contributes somewhat more to the total hazard than does the characteristic seismicity. The opposite holds for Cheraw, Florence and Sumter.

The plots included in Appendix B are also provided in electronic format on the accompanying CD.

4.3 Computer Files and Software

4.3.1 Spreadsheet

The EXCEL spreadsheet file **data.xls** written on the accompanying CD contains the hazard calculations for 1247 sites in South Carolina and adjacent parts of surrounding states. The columns contain values of latitude, longitude (in degrees), and 5% damped PSA response at 0.5, 1.0, 2.0, 3.3, 5.0, 6.7 and 13 Hz, and peak ground acceleration (PGA). The physical units of the acceleration columns is percentage g, (g = 981 cm/sec^2). There are 9 layers in the spreadsheet file. There are 2 layers for each of four probabilities of exceedance, containing results for geologically realistic site conditions, as well as for hard-rock basement outcrop. A ninth layer lists, for each of the 1247 locations, latitude, longitude, ground surface elevation (in meters), thickness of Coastal Plain sediments (meters), the elevation of the basement surface (in meters relative to sea level), and the amplification factor (ground surface/ basement outcrop) due to the presence of the sediments, for each of the 7 oscillator frequencies and PGA.

The naming of the layers in **data.xls** is as follows: **soil-2%, soil-5%, soil-7%,** and **soil-10%,** for results on geologically realistic site conditions for 2%, 5%, 7% and 10% probabilities of exceedance for 50 year exposure. Four layers named **rock-2%, rock-5%, rock-7%** and **rock-10%** contain results for hard-rock basement outcrop. The ninth layer, named **soil**, contains the amplification factors, ground surface and basement surface elevations, and sediment thickness.

4.3.2 Analysis Software

The folder named **programs** on the accompanying CD contains FORTRAN source code and PC Windows (98, 2000 and ME) executable code for the analysis program **scenario_pc**. Also contained in the folder are the necessary input files for execution of **scenario_pc**. All files in the folder **programs** must be copied to the same directory of the system hard drive for execution. **Scenario_pc** will accomplish the following tasks.

1) Interpolate the results contained in the spreadsheet **data.xls** to any geographic location in South Carolina.

2) Generate acceleration time history simulations and corresponding response spectra that are consistent with the results of hazard analysis. Several options are available that will cover a wide range of applications.

A help file with a user's manual for **scenario_pc** is contained in the **readme** file in the **programs** folder of the accompanying CD, and in Appendix C of this report.

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