Toward an Understanding of κ_0 for a Generic Deep Firm-Rock (NEHRP B-C) Site Profile in Eastern North America

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Introduction

The U.S. Geological Survey (USGS) National Seismic Hazard Mapping Project (NSHMP) defines the reference site conditions used in the development of the national seismic hazard maps as the boundary between National Earthquake Hazard Reduction Program (NEHRP) site classes B and C (Frankel *et al*., 1996, 2002; NSHMP, 2007). The NSHMP refers to this site condition as firm rock or NEHRP B-C. It represents a site profile with a time-averaged shear-wave velocity in the top 30 m (V_{S30}) of 760 m/sec. The Building Seismic Safety Council uses the NSHMP seismic hazard maps as the basis for developing seismic design maps for the NEHRP *Recommended Provisions* (e.g., BSSC, 2004), which are subsequently adopted for use in engineering practice by the ASCE seismic design standards (ASCE, 2006) and the International Building Code (ICC, 2006).

Most of the contemporary ground motion models used to estimate peak ground motion parameters and response spectral ordinates in eastern North America (ENA), including those used in the 2007 update to the national seismic hazard maps (NSHMP, 2007), have been developed either for hard-rock site conditions (Atkinson and Boore, 1995, 1997; Toro *et al*., 1997; Somerville *et al*., 2001; Toro, 2002; Campbell, 2003, 2004; Silva *et al*., 2003; EPRI, 2004; Tavakoli and Pezeshk, 2005), and subsequently adjusted to firm-rock site conditions by the NSHMP, or for firm-rock site conditions (Atkinson and Boore, 2006; Campbell, 2007, 2008), in which case no adjustment is necessary. In all of these cases, the period-dependent amplification factors that are used to characterize NEHRP B-C site conditions are calculated using the quarter-wavelength method (e.g., Boore, 2003) based on a hypothetical firm-rock site profile (shear-wave velocity and density) developed by Frankel *et al*. (1996). The only difference is that the NSHMP uses a site spectral decay parameter (κ_0) of 0.01 sec to adjust the hard-rock ground motions to firm-rock site conditions; whereas, Atkinson and Boore (2006) and Campbell (2007, 2008) used a larger value of 0.02 sec to develop their models. Figure 1 demonstrates the significant effect that the value of κ_0 can have on the site amplification characteristics of the Fourier amplitude spectrum.

Background

Cormier (1982) suggested that seismic attenuation could be defined from the rate of high-frequency decay above the corner frequency of the displacement source spectrum. The decay was assumed to be proportional to the decay due to the source spectrum, f^{-n}, times an exponential decay factor, $e^{-\pi t^* f}$, where t^* represents the path-integrated effect of the quality factor Q

$$t^* = \int_{\text{path}} \frac{dr}{Q(r)\beta(r)} \tag{1}$$

Experimental measures of t^* lump scattering losses together with intrinsic anelasticity and combine frequency-dependent attenuation mechanisms together with frequency-independent attenuation mechanisms.

After studying the high-frequency decay of accelerograms recorded in California, Anderson and Hough (1984) suggested that the shape of the acceleration spectrum at high frequencies could be described by the equation

$$A(f) = A_0 e^{-\pi\kappa f}, \qquad f > f_E \tag{2}$$

where A_0 depends on factors such as source properties and propagation distance, κ is a spectral decay parameter, and f_E is a frequency beyond which the fall-off of the spectrum is approximately linear on a plot of $\ln A(f)$ versus f. Anderson and Hough noted that if $Q(r)$ and thus t^* is independent of frequency the effect of attenuation on a Brune (1970, 1971) source displacement spectrum, for which the high-frequency decay is proportional to f^{-2}, will yield the spectral shape given by both Cormier (1982) and Equation (2). These authors further found that κ is dependent on distance with a nonzero intercept that they interpreted to be attenuation due to propagation of shear waves through the subsurface geological structure and a slope that they interpreted to be the incremental attenuation due to horizontal propagation of shear waves through the crust. They also showed that for $Q = \infty$ or $Q \propto f$ the spectral decay is flat (i.e., $\kappa = 0$) and that for $Q = Q_0$ or $Q \propto f^{0.5}$ the spectral decay is linear (i.e., $\kappa > 0$), with the fractional frequency dependence for Q leading to a smaller value of κ than the model in which Q is assumed to be constant.

Hough *et al*. (1988) and Hough and Anderson (1988) performed a thorough study of κ using recordings of small earthquakes from the Anza, California, strong motion array. Hough and Anderson (1988) proposed a general model for κ

$$\kappa(r) = \int_{\text{path}} \frac{dr}{Q_i(z)\beta(z)} \tag{3}$$

from which they inferred the Q structure at Anza from a velocity model for the region. They noted that their proposed model was the same as equation (1) for t^* except that it used the frequency independent component of Q (Q_i) in place of the total Q. Hough *et al*. (1988) concluded from the similarity of the distance-dependence of $\kappa(r)$ in the Anza and Imperial Valley regions, areas in which the intercepts were very different presumably due to the vastly different subsurface geology, supported the earlier assumption by Anderson and Hough (1984) that the intercept of $\kappa(r)$ represented the attenuation of seismic waves beneath the site and that the distance-dependence of $\kappa(r)$ represented attenuation due to horizontal propagation of seismic waves in the crust.

Anderson (1991) formalized the $\kappa(r)$ observations of the previous investigators by proposing a mathematical formulation of the observed behavior of κ that regards this parameter to be a function of distance, R, and a categorical site variable, S,

$$\kappa(R,S) = \kappa_0(S) + \tilde{\kappa}(R) \tag{4}$$

The site variable $\kappa_0(S)$ has been subsequently shortened to κ_0 and together with its corresponding spectral decay factor, $e^{-\pi\kappa_0 f}$, and a site amplification factor based on the quarter wave-length method has become the primary model for incorporating site amplification effects in stochastic ground motion simulation (e.g., Boore, 2003). In fact, all of the ground motion relations used in the 2007 update to the national seismic hazard maps (NSHMP, 2007) used this approach to incorporate site amplification in their ground motion estimates, whether or not these estimates represented hard-rock or firm-rock site conditions.

The site factors used to correct from hard-rock to firm-rock ground motions by the NSHMP and several other investigators were developed from the quarter-wavelength method assuming $\kappa_0 = 0.01$ sec (Frankel *et al*., 1996). NSHMP (2007) attributes this κ_0 to "ground shaking studies by J. Fletcher of the USGS observed in a borehole characterized by bedrock underlying a stiff soil condition with shear-wave velocity similar to that defining NEHRP B-C site conditions." Frankel *et al*. (1996) reference a specific study by Fletcher (1995) for this estimate, but this study does not give any specific information regarding the lithology or shear-wave velocities of the borehole sediments. Atkinson and Boore (2006), and later Campbell (2007), used the same velocity and density profile to represent generic NEHRP B-C site conditions in the development of their ground motion models, but assumed $\kappa_0 = 0.02$ without explaining why they selected that particular value. Frankel (personal comm., 2007) concludes that the limited data on κ_0 for NEHRP B-C sites in ENA cannot rule out values of either 0.01 or 0.02.

Since there is insufficient documentation to validate either of these estimates for κ_0 as representative of a typical firm-rock site in ENA, I performed a literature search and supporting calculations to determine which, if either, of these candidate values might be more appropriate. The value of κ_0 for a given geological structure beneath a site is composed of that due to the sedimentary deposits and that due to the hard rock that underlies these deposits. Therefore, it is useful to first review the basis for the κ_0 values that have been proposed for ENA hard rock before exploring those that might be more appropriate for firm rock.

Generic Hard-Rock Site Profile in ENA

Silva and Darragh (1995) used template fits of response spectral shapes that were derived from stochastic ground motion simulations to determine κ_0 for 16 strong motion recordings located on hard rock in ENA. They found a median κ_0 of 0.007 sec with individual estimates that ranged between 0.004 and 0.016 sec for sites described geologically as granitic plutons, carbonates, and Precambrian rock of the Canadian Shield. An earlier version of this study was used by EPRI (1993) and by Toro *et al*. (1997) to select a median hard-rock κ_0 of 0.006 sec to use in the development of a commonly used ground motion model for ENA. These median values are somewhat higher than the upper-bound estimate of 0.004 sec inferred for the Canadian Shield by Atkinson (1996) over the frequency band 4 to 30 Hz from small earthquakes recorded by the Eastern Canadian Telemetered Network (ECTN). Based in part on the Atkinson study, Beresnev and Atkinson (1999) adopted a κ_0 of 0.002 sec in the development of a stochastic finite-source ground motion model for ENA. Close inspection of Atkinson's (1996) Figure 7 suggests that κ_0 could be as high as 0.007 sec over the frequency band 12 to 22 Hz for which the observed spectral decay appears to be less impacted by possible low-frequency source and site effects or by high-frequency noise. It is also possible that the Canadian Shield ECTN sites, which are sited directly on glacially scoured hard rock (Beresnev and Atkinson, 1997), are underlain by higher quality rock than the average hard-rock site used by Silva and Darragh (1995). Rock quality can have a significant impact on the value of κ_0 (e.g., Anderson and Hough, 1984; Anderson, 1986, 1991; Anderson *et al*., 1996). A specific example for ENA is given by Atkinson (1996), who found much larger values of κ_0 ranging between 0.02 and 0.04 sec for ECTN sites in the Charlevoix and Sudbury areas of southeastern Canada that are reportedly on fractured Precambrian rock within an ancient meteor impact crater. Silva and Darragh (1995) found a similar κ_0 of 0.025 sec from strong motion recordings obtained on "sheared" hard rock during the 1988 Nahanni earthquake sequence.

Chapman *et al.* (2003) analyzed 25 recordings which were located approximately 10 km from a swarm of very shallow (0.1–2.4 km deep) microearthquakes at Monticello Reservoir, South Carolina, and found a median κ of 0.018 sec. The earthquakes and recording site are located within the Charlotte Belt metamorphic rocks of the Piedmont Province, which are described geologically as Paleozoic metamorphic and igneous rock. The relatively high value of κ contains both a travel-path component and a site component and might reflect in part a travel path that lies predominantly within the relatively more fractured rock that composes the upper kilometer of the crust in the Monticello Reservoir area, where, for example, Moos and Zoback (1983) have found shear-wave velocities of approximately 2500 m/sec at a depth of 40 m in two boreholes drilled within small plutons of granitic to granodioritic composition. Atkinson and Boore (2006) made a careful examination of the ENA spectral data presented by Atkinson (2004) and found that these data were consistent with a median κ_0 of 0.005 sec with individual estimates that ranged between 0 and 0.01 sec. These data were recorded by the short-period ECTN and the broadband Canadian National Seismographic Network (CNSN) and U.S. National Seismic Network (USNSN) on sites reported to have surface shear-wave velocities greater than 2000 m/sec.

It is useful to look at what might be considered localized southern California analogy to an ENA hard-rock environment. The Anza strong motion array contains several sites that are located within the Southern California Batholith, a region of relatively massive granitic rock. Two of these sites, PFO (Piñon Flat Observatory) and KNW (Keenwild), are located on granitic plutons with shear-wave velocities in excess of 1600 and 2600 m/sec at depths of 20 and 50 m below the sites, respectively (Fletcher *et al*., 1990). Lower velocities were found in the more highly weathered rock above 20 m. Anderson (1991) reports $\kappa_0 = 0.002$ sec for KNW and 0.004 sec for PNO. Silva and Darragh (1995) found $\kappa_0 = 0.006$ sec for these two sites. I calculated an average κ_0 of 0.007 sec for the six hardest sites in the array based on data in Anderson (1991). These values are similar to those found for hard-rock sites in ENA. Hough and Anderson (1988) inverted the $\kappa(r)$ observations of Hough *et al*. (1988) for the Q_i structure at Anza and found that these observations could be explained by a three-layer model where $Q_i = 600$ from 0–5 km where β increases from 1.6 to 3.6 km/sec, $Q_i = 2500$ from 5–12 km where $\beta = 3.6$ km/sec, and $Q_i = 1000$ from 12–14 km where $\beta = 3.6$ km/sec. Assuming an average shear-wave velocity of 2.2 km/sec over the top 5 km (the geometric average of the top and bottom velocities), equation (3) yields $\kappa_0 = 0.004$ sec, which is similar to that found for KNW and PFO, the hardest sites at Anza, and to the median estimate of 0.005 sec found by Atkinson and Boore (2006) for hard-rock sites in ENA.

For the estimates of κ_0 for the entire geological profile presented in the next section, I will use a median hard-rock value of 0.005 sec. This value is consistent with the estimate of Atkinson and Boore (2006) and falls in the middle of the hard-rock estimates presented above. In order to add this hard-rock κ_0 to the value obtained for the overlying sediments, I assume that it corresponds to a depth much larger than that of the sediments. Anderson and Hough (1988) took this depth to be 5 km, which they based on the results of their inferred Q_i structure at Anza and the results of laboratory experiments that indicated Q_i increases with hydrostatic pressure up to a value that corresponds to the pressure at depth of around 5 km, after which it becomes independent of pressure. If a similar depth is assumed for ENA, it is not necessary to adjust the hard-rock value of κ_0 before adding it to that of the sediments in order to derive a value for the entire geological structure (sediment deposits plus hard rock) beneath the site, since sediment depths in ENA are typically less than 1000 m in thickness (Table 1).

Generic Deep Firm-Rock Site Profile in ENA

There are very few direct measurements of κ_0 for firm-rock sites in ENA. Silva and Darragh (1995) analyzed three ENA strong motion recordings reported to be on sandstone and claystone (referred to as ENA soft rock but considered by these authors to represent NEHRP B-C site conditions) and found a median κ_0 of 0.017 sec with individual estimates that ranged between 0.015 and 0.018 sec. Partly based on these measurements and a relationship between κ_0 and V_{S30} developed from western United States data, Silva *et al.* (1999) used stochastic ground motion simulations and generic site profiles appropriate for ENA to conclude that, although $\kappa_0 = 0.01$ sec might be an appropriate value for a relatively shallow (≤ 91 m) generic NEHRP B-C site profile in ENA, a more realistic value for a deeper site profile, typical of sandstones of the Gulf Coast region and mudstones, claystones and siltstones of South Carolina and the Denver Basin of Colorado, would be 0.02 sec.

All other values of κ_0 for firm-rock site conditions must be estimated or inferred from direct measurements and/or velocity and Q profiles for softer sedimentary deposits. In the latter case, I calculated κ_0 from the relationship (modified from Hough and Anderson, 1988, and Chapman *et al.*, 2003)

$$\kappa_0 = \int_0^z \frac{dz}{Q(z)\beta(z)} \tag{5}$$

where $Q(z)$ and $\beta(z)$ are the quality factor and the shear-wave velocity for an arbitrary depth, z, within the site profile. This relationship is consistent with equation (3) except that it isolates the contribution due to the sediments. By stripping away the softer sediments, I can use equation (5) to estimate κ_0 for that part of the profile that lies below the $V_{S30} = 760$ m/sec (NEHRP B-C) velocity horizon. Table 1 presents a summary of the κ_0 estimates that were derived in this manner. Also included in this table are the values of κ_0 calculated for the original sedimentary profile, the depths of the original and firm-rock sedimentary profiles, and an estimate of the values of κ_0 that would correspond to a hypothetical reference 1000-m firm-rock sedimentary profile. This latter value was calculated by proportionally increasing the thickness of each layer until the total thickness equaled 1000 m. It is intended to provide a standard value that can be compared among sites of varying sedimentary thicknesses. These values can be standardized to any arbitrary depth by multiplying the κ_0 of the sediments listed in the table by the ratio $d/1000$, where d is the new depth, and adding to this value the hard-rock κ_0 of 0.005 sec.

I demonstrate and validate the proposed method for estimating κ_0 described above using a sedimentary profile for the Memphis, Tennessee, area developed from data provided by Gomberg *et al*. (2003) and Cramer *et al*. (2004). These investigators used *in-situ* geophysical measurements to estimate β for various geologic units that underlie the city of Memphis and Shelby County. They used these estimates to construct a grid of sedimentary profiles to use in the development a site-specific seismic hazard map for the region. Q values were estimated to be a function of shear-wave velocity and depth based on the assessments of Boore and Joyner (1991) and Cramer *et al*. (2004). Using a 960-m deep site profile typical of downtown Memphis (Table 2), I calculated $\kappa_0 = 0.057$ sec from equation (5) for the entire sedimentary column, which, when combined with the incremental κ_0 of 0.005 sec attributable to the hard rock below the sediments, yields a total value of 0.062 sec. This value is consistent with the $\kappa_0 = 0.063$ sec calculated by Herrmann and Akinci (1999) from recordings in the Memphis area. As indicated in Table 1, this estimate is similar to values found for other sedimentary profiles in the Mississippi Embayment using a variety of direct and indirect methods. Using this same method, I calculated $\kappa_0 = 0.014$ sec for the 564-m section of the sedimentary column that underlies the $V_{S30} = 760$ m/sec velocity horizon, which when added to the hard-rock value of 0.005 sec gives a total firm-rock κ_0 of 0.019 sec for the entire geological profile. This latter value is consistent with the values calculated by Silva and Darragh (1995) from recordings on ENA soft rock. An estimate of κ_0 for a hypothetical 1000-m firm-rock sedimentary profile was calculated by multiplying 0.014 by the ratio 1000/564, yielding 0.024 sec, which after adding 0.005 results in a total κ_0 of 0.0029 sec. All of the estimates identified in Table 1 as "calculated" have been estimated in this manner.

Boore and Joyner (1991) developed a generic 650-m deep-soil profile for the Mississippi Embayment for which they calculated $\kappa_0 = 0.03$ sec based on a velocity profile developed from shear-wave velocity measurements for ENA deep-soil sites (Bernreuter *et al*., 1985) and Q values consistent with those inferred by Andrews from recordings in the Mississippi Embayment (M. Andrews, written comm., 1990). This corresponds to a total κ_0 of 0.035 sec for the entire geological profile. I calculated $\kappa_0 = 0.015$ sec for the 550 m of the sedimentary column that falls below the $V_{S30} = 760$ m/sec velocity horizon, which yields a total firm-rock κ_0 of 0.02 sec for the entire geological profile. Extrapolating these estimates to the hypothetical 1000-m reference profile results in a sedimentary and total geological κ_0 of 0.031 and 0.036 sec, respectively.

Wen and Wu (2001) developed generic velocity profiles for the cities of Memphis (Tennessee), Carbondale (Illinois), and St. Louis (Missouri) for which they estimated depths to hard rock ($\beta > 2000$ m/sec) of 1000, 165 and 16 m, respectively. Wen and Wu report total κ_0 values of 0.063, 0.043 and 0.0076 sec for the Memphis, Carbondale and St. Louis profiles, respectively, which they attribute to ground motion measurements made by Herrmann and Akinci (1999). Carbondale and St. Louis have relatively low shear-wave velocities of 310 m/sec or less above these depths, making them very shallow soil sites unsuitable for estimating κ_0 for a deep firm-rock site. Subtracting off the hard-rock contribution yields a κ_0 of 0.058 sec for the Memphis sedimentary column. Using the velocity profile of Wen and Wu and Q values typical of similar deposits in Memphis (Cramer *et al.*, 2004) and the Mississippi Embayment (Boore and Joyner, 1991), I calculated $\kappa_0 = 0.018$ sec for the 600-m thickness of the Wen and Wu Memphis profile that falls below the $V_{S30} = 760$ m/sec velocity horizon, resulting in a total firm-rock value of 0.023 sec for the entire geological profile. The corresponding values of κ_0 for the hypothetical 1000-m reference and total geological profiles are 0.030 sec and 0.035 sec, respectively.

Park and Hashash (2004) used ground motions recorded in the Mississippi Embayment for the 2001 Enola, Arkansas, earthquake, together with a generic 1000-m deep Mississippi Embayment shear-wave velocity profile developed by Romero and Rix (2001), to back-calculate a small strain damping profile for the region, from which they calculated $\kappa_0 = 0.053$ sec for the sedimentary column above Paleozoic bedrock. This estimate yields a total κ_0 of 0.058 sec for the entire geological profile. Using these same profiles, I calculated a firm-rock κ_0 of 0.009 sec for the 473-m thickness of the Romero and Rix sedimentary column that falls below the $V_{S30} = 760$ m/sec velocity horizon and a total firm-rock κ_0 of 0.014 sec for the entire geological profile. The corresponding values of κ_0 for the hypothetical 1000-m reference and total geological profiles are 0.019 sec and 0.024 sec, respectively.

Using recordings from microearthquakes in the Summerville-Middleton Place seismic zone, Chapman *et al*. (2003) estimated κ_0 to be 0.049 sec for a 775-m sedimentary column in the Atlantic Coastal Plain near Charleston, South Carolina. Later, Chapman *et al*. (2006) compiled a detailed 830-m deep velocity profile for a nearby site in downtown Charleston based on velocity measurements and geophysical investigations conducted by several researchers. Using this latter velocity profile and Q values that are consistent with the κ_0 determined by Chapman *et al*. (2003) and with similar sedimentary deposits in Memphis (Cramer *et al.*, 2004) and the Mississippi Embayment (Boore and Joyner, 1991), I calculated κ_0 values of 0.060 sec for the Charleston sedimentary column and 0.008 sec for the 327-m section of the column that falls below the $V_{S30} = 760$ m/sec velocity horizon, yielding total soil and firm-rock κ_0 values of 0.065 and 0.013 sec, respectively, for the entire geological profile. The corresponding values of κ_0 for the hypothetical 1000-m reference and total geological profiles are 0.024 sec and 0.029 sec, respectively. The model I used for the 830-m Charleston sedimentary profile results in a path-averaged Q ($\bar{Q}$) of 22, which is the same value that Chapman *et al*. (2003) calculated for the Summerville-Middleton Place seismic zone from the observed values of κ_0 and the one-way shear-wave travel time through the sediments, t_r, from the equation $\bar{Q} = t_r / \kappa_0$. The value of $\bar{Q}$ increases to 48 for the firm-rock section of the sedimentary column.

NSHMP Shallow Firm-Rock Profile in ENA

The hypothetical firm-rock site profile proposed by Frankel *et al.* (1996) for use in ENA by the NSHMP is much shallower and has a much steeper shear-wave velocity gradient in the upper 200 m than the generic deep firm-rock site profiles described above. The relatively steep velocity gradient was intended to be steeper than that for a typical WNA rock site. A less steep gradient was imposed below 200 m where velocities approached those corresponding to hard rock at depth. The velocities and densities were chosen with consideration given to the gross differences in the lithology and age of the rocks in ENA as compared to those in coastal California, where much of the borehole data comes from that can be used to constrain velocity-depth functions. The expectation was that ENA rocks should have higher velocity and density than rocks in coastal California at any given depth below the surface.

Frankel *et al*. (1996) attribute their estimate of $\kappa_0 = 0.01$ sec to studies of shear waves recorded at various levels in a borehole at the DOE Savannah River Site (SRS) in Aiken, Georgia (Fletcher, 1995). NSHMP (2007) characterizes this site as a stiff soil condition with shear-wave velocity similar to that defining NEHRP B-C site conditions. There are issues concerning both of these statements. First, shear-wave velocity measurements at SRS (Lee *et al*., 1997) indicate that the site is technically characterized as NEHRP D ($V_{S30} = 355$ m/sec). A shear-wave velocity of 760 m/sec is not attained until a depth of around 180 m. Second, Fletcher (1995) determined a total path t^* for four earthquakes ($\mathbf{M} \sim 1.8$ to 3.6) from recordings obtained at the surface and at a depth of 91 m within a ~ 300-m deep borehole. The earthquakes were located anywhere from 19 to 49 km from the site. The recording at 91-m depth is well above the NEHRP B-C velocity horizon, where the shear-wave velocity is ~ 500 m/sec (NEHRP C). There is a systematic increase in the value of t^* with increasing distance, which if interpreted as $\tilde{\kappa}(R)$, results in an intercept (κ_0) of 0.006 sec for both the surface and downhole recordings. The similarity of these two estimates and their discrepancy with the estimate of $t^* = 0.014$ sec found from the fall-off at high frequencies of the spectral ratio (surface/325 m downhole) of seismograms recorded from a blast that was part of a refraction study, lead Fletcher (1995) to dismiss these estimates as mostly “random error.”

The hypothetical NSHMP profile attains a shear-wave velocity in excess of 2000 m/sec, or what Atkinson and Boore (2006) classify as ENA hard rock, at a depth of 175 m; whereas, the Memphis, Mississippi Embayment, and Charleston firm-rock profiles reach this velocity at depths ranging between 327 and 600 m. The Carbondale profile of Wen and Wu (2001) has about the same depth to hard rock as the hypothetical NSHMP profile, but it is composed of much softer deposits in the upper 30 m with a correspondingly higher κ_0 (0.043 sec).

Without having a reasonable *in-situ* analog for the hypothetical NSHMP firm-rock profile, I decided to derive an independent estimate of κ_0 from the inferred values of Q and κ_0 that were measured or estimated from the site profiles discussed above. I assumed Q values of 25 and 50 for deposits with β ranging between 648–850 m/sec and 850–2250 m/sec, respectively, based largely on the studies of Boore and Joyner (1991) and Cramer *et al*. (2004). Using equation (5), I calculated $\kappa_0 = 0.004$ sec ($\bar{Q} = 41$) for the presumed 200-m thickness of the sedimentary part of the profile above the shear-wave velocity horizon corresponding to 2250 m/sec, where the velocity profile becomes less steep. The corresponding κ_0 is 0.009 sec for the total geological profile. The average value of Q for the upper 200 m of the NSHMP profile is larger than that for the Charleston firm-rock profile, consistent with its larger velocity gradient. The calculated $\kappa_0 = 0.009$ sec for the total NSHMP geological profile is generally consistent with the 0.01-sec value adopted by Frankel *et al*. (1996). I conclude that, although the κ_0 used by Frankel *et al*. (1996) and the NSHMP (2007) appears to be reasonable given the shallow nature of their hypothetical profile, the issue remains as to whether it is representative of a more generic, deeper firm-rock profile in ENA. That issue is addressed below and in the next section.

In order to demonstrate the importance of profile depth on the value of κ_0, it is interesting to extrapolate the results obtained above for the hypothetical NSHMP firm-rock sedimentary profile to a reference 1000-m depth. I performed this extrapolation using the same method as described in the previous section. The resulting value of κ_0 is 0.020 sec, yielding a total κ_0 of 0.025 sec for the entire geological profile. This later value is 2.5 times larger than the original value and is seen to fall at the lower end of the range of values found for the deeper sedimentary deposits in the Mississippi Embayment and Charleston areas.

Discussion

The estimates of κ_0 presented in this paper indicate that typical values for this spectral decay (attenuation) parameter for deep firm-rock sites in ENA range between 0.013 and 0.023 sec, with a median value of 0.019 sec and mean value of 0.018 sec. These estimates are based on measurements at deep soft-rock sites in ENA and calculations for firm-rock site profiles with depths ranging between 327 and 600 m in the Mississippi Embayment and the Charleston area of the Atlantic Coastal Plain. These estimates are consistent with the 0.02-sec value recommended by Silva *et al.* (1999) for a generic deep NEHRP B-C site profile in ENA. However, as Silva *et al*. (1999) and Wen and Wu (2001) have found, shallower profiles will generally lead to smaller values of κ_0. The importance of depth is demonstrated in Table 1, where estimates of κ_0 are found to increase systematically with the depth of the sedimentary column and where estimates of total κ_0 are found to range between 0.024 and 0.036 sec when extrapolated to a hypothetical reference 1000-m thick firm-rock profile. Silva *et al*. (1999) came to a similar conclusions based on 1-D site response analyses of typical site profiles in ENA. The importance of sediment depth suggests that perhaps it might be necessary to develop more than one firm-rock site profile for ENA when developing seismic hazard maps for a reference firm-rock site condition. This is likely to be the case for WNA as well, according to site response analyses of typical site profiles in WNA by Silva *et al*. (1999). However, adopting such a regional approach to defining reference soil conditions will likely require a similar regionalization of the NEHRP site coefficients.

Based on the same method used to estimate κ_0 for other firm-rock profiles, I confirmed that the $\kappa_0 = 0.01$ sec value adopted by Frankel *et al.* (1996) for estimating amplification factors used by NSHMP (2007) to adjust estimates of hard-rock ground motion to firm-rock site conditions is generally consistent with their relatively shallow firm-rock site profile. The NSHMP profile has a much stronger velocity gradient than the deep sedimentary profiles evaluated in this paper, attaining a shear-wave velocity of 2250 m/sec (consistent with the definition of hard rock by Atkinson and Boore, 2006) at a relatively shallow depth of 200 m. This relatively strong velocity gradient will result in somewhat higher amplification factors at high frequencies, which compounds the impact of the relatively low κ_0 value. It is interesting to note that if the 200-m NSHMP profile is extrapolated to the depth of 1000 m, the estimated value of κ_0 increases to 0.025 sec, similar to that found for several of the deeper profiles when extrapolated to this depth (Table 1).

The issue remains as to whether the relatively shallow firm-rock site profile used by NSHMP (2007) is appropriate for defining generic firm-rock site conditions in ENA when ground motions based on these site conditions are used in conjunction with the site coefficients adopted in the NEHRP *Recommended Provisions* (BSSC, 2004) and the seismic design codes used in engineering practice (e.g., ASCE, 2006; ICC, 2006). The same issue applies to other empirically based site factors that have recently been recommended for use in ENA (e.g., Atkinson and Boore, 2006; Campbell, 2007, 2008). The NEHRP site coefficients were developed for a typical deep site profile in WNA (Borcherdt, 1994; Dobry *et al.*, 2000). According to Boore and Joyner (1997), such a profile has a depth of about 325 m to the 2000 m/sec velocity horizon and 1750 m to the 2800 m/sec velocity horizon, values much larger than the 175-m and 455-m depths to these velocity horizons in the hypothetical ENA firm-rock site profile used by the NSHMP. Therefore, in order to be consistent with the use of a deep WNA site profile to develop the NEHRP site coefficients, it would seem appropriate also to use a relatively deep site profile to represent generic firm-rock site conditions in ENA. Furthermore, a spectral decay parameter consistent with a site profile that is deeper than the hypothetical NSHMP firm-rock sedimentary profile would seem to be appropriate for sites located in the Mississippi Embayment, the Atlantic Coastal Plain, the Gulf Coast region, and the Denver Basin.

Because of the importance of profile depth, values of κ_0 as well as the NEHRP site coefficients should be revised for regions in both WNA and ENA where relatively shallow or very deep firm-rock site conditions exist (e.g., Silva *et al*., 1999). Until this is done, I suggest that it is more reasonable to use $\kappa_0 = 0.02$ sec rather than $\kappa_0 = 0.01$ sec for purposes of estimating the ground motion on a generic NEHRP B-C site in ENA based on the relatively shallow hypothetical firm-rock site profile defined by Frankel *et al.* (1996). That should not be interpreted to imply that a smaller value of κ_0 is not appropriate for relatively shallow firm-rock profiles in ENA, only that the use of the larger value is more consistent with (1) the use of ground motion models in WNA that are representative of a relative deep generic-rock site profile (Boore and Joyner, 1997; NSHMP, 2007) and (2) the use of NEHRP site coefficients that are based on relatively deep site profiles in WNA (Borcherdt, 1994; Silva *et al*., 1999; Dobry *et al*., 2000).

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Table 1

Estimates of κ_0 for Deep Firm-Rock (NEHRP B-C) Sites in ENA

					κ_0 (sec)					
Profile		Depth (m)			Original		Firm Rock		Firm Rock (1000 m)	
Description	Reference	Total	Firm Rock	Method[a]	Sediments	Geologic[b]	Sediments	Geologic[b]	Sediments	Geologic[b]
ENA soft rock	Silva & Darragh (1995)	—	—	1	—	—	—	0.017	—	—
Miss. Embayment	Boore & Joyner (1991)	650	550	2	0.030	0.035	0.015	0.020	0.031	0.036
ENA NEHRP B-C	Silva *et al*. (1999)	—	—	2	—	—	—	0.020	—	—
St. Louis, MO	Herrmann & Akinci (1999)	16	—	1	—	0.008				
Carbondale, IL	Herrmann & Akinci (1999)	165	—	1	—	0.043				
Memphis, TN	Herrmann & Akinci (1999)	1000	—	1	—	0.063	—	—	—	—
Memphis, TN	Wen & Wu (2001)	1000	600	1,2	0.058	0.063	0.018	0.023	0.030	0.035
Memphis, TN	Cramer *et al*. (2004)	960	564	2	0.057	0.062	0.014	0.019	0.024	0.029
Miss. Embayment	Park & Hashash (2004)	1000	473	1,3	0.053	0.058	0.009	0.014	0.019	0.024
Charleston, SC	Chapman *et al*. (2004)	830	327	1,2	0.060	0.065	0.008	0.013	0.024	0.029
NSHMP firm rock	Frankel *et al*. (1996)	—	200	2	—	—	0.004	0.009	0.020	0.025

[a] Method used to estimate κ_0: 1, measured from high-frequency slope of recorded spectra; 2, calculated from equation (5); 3, inverted from recordings.

[b] Includes an additional value of 0.005 sec that to represent the contribution from the hard-rock part of the geological profile that underlies the sedimentary column.

Table 2

Representative Site Profile for Downtown Memphis, Tennessee

Unit/Formation (Age)	Description	Depth (m)	Thickness (m)	β (m/sec)	Q	κ_0 (msec)
Loess (Pleistocene)	Eolian, unconsolidated, poorly stratified glacial silts and fine sands	0	12	191	10	6.28
Lafayette Formation (Pleistocene & Pliocene	Weakly to strongly indurated clay, silt, sand, gravel, and cobbles, locally iron oxide cemented	12	12	268	15	2.99
Upper Claiborne Group (Eocene)	Dense clays, silts, and fine sands with organic fragments	24	56	360	20	7.78
Memphis Sand (Eocene)	Fine to coarse sands interbedded with thin layers of silt and clay	80	240	550	20	21.82
Flour Island Formation (Paleocene)	Dense clays, with fine-grained sands and lignite	320	80	675	25	4.74
Fort Pillow Sand (Paleocene)	Well-sorted sands with minor silt, clay, and lignite horizons	400	70	775	25	3.61
Old Breastworks Fm. (Paleocene)	Dense clays and silts, with some sands and organic layers	470	240	850	50	5.65
Sedimentary rock (Cretaceous)	Undifferentiated sediments	710	250	1175	50	4.26
Bedrock (Paleozoic)	Limestone	960	—	3400	500	—

The values for Q were taken from data provided by Boore and Joyner (1991) and Cramer *et al* (2004); all other data were taken from Gomberg *et al*. (1993) and Cramer *et al* (2004). The values of κ_0 listed in the last column were calculated from equation (5) and have a total value of 57.13 msec (0.057 sec).

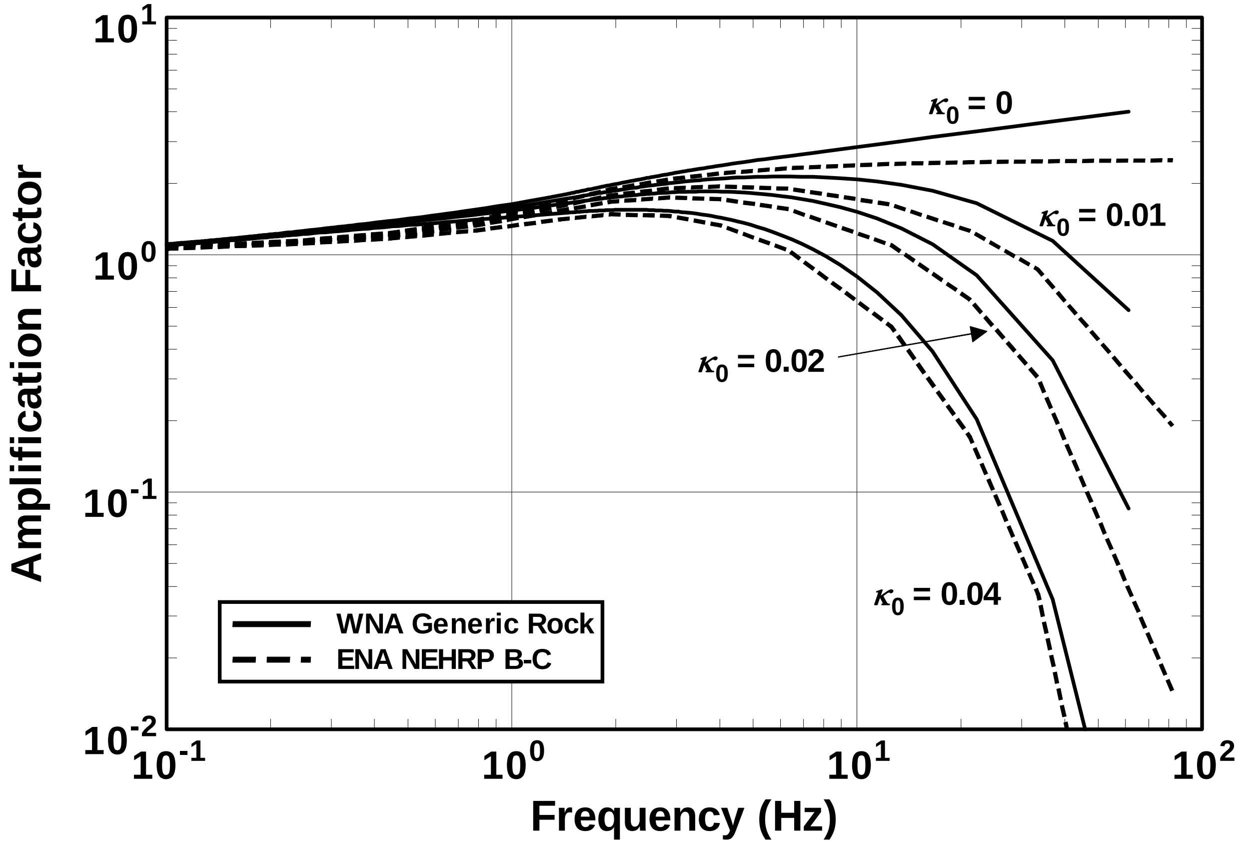

Figure 1. Site amplification factors of Fourier amplitude spectra for the WNA generic-rock profile of Boore and Joyner (1997) and the hypothetical ENA NEHRP B-C site profile of Frankel *et al*. (1996), calculated using the quarter-wavelength method (Boore, 2003). The different curves show the effect of the site spectral decay parameter, κ_0.