Revision of Boore (2018) Ground-Motion Predictions for the Central and Eastern North America: Path and Bias Adjustments and Extension to $200 \text{ m/s} \leq V_{S30} \leq 3000 \text{ m/s}$

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ABSTRACT

The three sets of ground-motion predictions (GMPs) of Boore (2018; hereafter B18) are compared to a much larger dataset than was used in deriving the predictions. The B18 GMPs work well for response spectra at periods between about 0.05 s and 2.0 s after an adjustment accounting for a path bias at distances beyond the maximum of 200 km that was used to derive the stress parameters on which the simulations in B18 are based. An additional offset adjustment is needed in the B18 predictions for short and long periods. The adjustment at short periods is most likely necessary because the $\kappa_0$ of 0.006 s stipulated by the NGA-East project to be used in deriving the GMPs is inconsistent with the observations on rock sites, which are more consistent with $\kappa_0$ near 0.0085 s. The explanation for the offset adjustment at long periods is not clear, but it could be a combination of limitations of the point-source stochastic model for longer period motions, as well as a decreasing number of observations at longer periods available to constrain the simulations on which the predictions are based.

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The predictions of B18, conditioned for very hard rock sites ($V_{s30}$ of 2000 m/s and 3000 m/s), have here been extended down to $V_{s30}$ values as low as 200 m/s. I find, as have others, that for a given $V_{s30}$ there is generally less site amplification for central and eastern North America (CENA) than for the active crustal region dataset used for the Boore, Stewart et al. (2014) (hereafter BSSA14) ground-motion prediction equations. This might have an impact on conclusions of several previous studies of CENA GMPs that used the site amplifications in BSSA14 in comparing data and predictions.

INTRODUCTION

As part of the NGA-East project (Goulet et al., 2018), I developed six sets of ground-motion predictions (GMPs), as described in Boore (2015a). The predictions are based on stochastic method simulations (Boore, 2003) with prescribed geometrical spreading models and a single $\kappa_0$ value of 0.006 s. The predictions are in the form of tables of predicted motions for a wide range of periods, magnitudes, and distances (hence I will sometimes refer to these as “ground-motion prediction tables” (GMPTs) rather than “ground-motion prediction equations” (GMPEs)). That work was revised in Boore (2018) (hereafter B18), who proposed three sets of predictions for use in central and eastern North America (CENA). The three sets had different path functions. Two of the sets were quite similar, with geometrical spreading of $1/R$ within 10 km, $1/R^{1.3}$ from 10 to 50 km, and $1/\sqrt{R}$ beyond 50 km (AB14mod1 and AB14mod2); the other set has $1/R$ spreading at all distances (BCA10D). Only BCA10D was used in Boore (2015a); the other two models are revisions of models used in Boore (2015a). As discussed in Boore (2012), the stress parameters used in the simulations on which the GMPs are based were determined by inverting data from nine of the best recorded earthquakes in CENA, recorded on hard-rock sites. The inversions used response spectra at 0.1 s and 0.2 s from recordings within 200 km. Aside from the path function and the associated stress parameter, all other parameters in the simulations were the same for all sets of GMPs.
The B18 paper did not look at residuals from the larger NGA-East dataset, and in fact, did not use any version of the NGA-East dataset. The data used in B18 had been compiled from earlier publications, before the NGA-East dataset was developed. In this article I used mixed-effects analysis of the residuals between NGA-East observations and B18 predictions to evaluate the B18 GMPs and to propose adjustments to those predictions. With one exception, all of the results illustrated by the figures in this article are for the AB14mod1 path function, as the figures for the other two path functions are similar in appearance to those for AB14mod1.

I first study hard-rock sites ($V_{s30}$ between 1000 m/s and 2050 m/s), finding that the B18 predictions are in reasonable agreement with the larger dataset for periods near those used in determining the stress parameters, with adjustments needed to the path models at larger distances and offset adjustments for short and long periods. When the path adjustments and hard-rock offset adjustments are made, I find significant $V_{s30}$-dependent biases when within-event residuals are computed using a dataset that includes observations with $V_{s30}$ as low as 200 m/s, with no site response adjustment. With the assumption that these biases are primarily due to site response, I compute a simple site response model of the form $A \propto (V_{s30}/2000)^c$, where $c$ is period dependent. In keeping with other studies, the site amplification $A$ is significantly less than that for western North America (as given in BSSA14) for low values of $V_{s30}$ (less than about 500 m/s to about 800 m/s, depending on period). The products of this study are revised B18 GMPTs, provided in an electronic supplement, a generic site amplification model for CENA, the conversion of as-recorded geometric mean GMIMs to RotD50 for CENA, and the finding that the hard-rock observations are more consistent with $k_0$ of 0.0085 s than the value of 0.006 s used in B18 and the NGA-East project.

DATA
As discussed in the Data and Resources section, I used a combination of a publicly available NGA-East flatfile, with updated $V_{s30}$ values from Parker et al. (2017). I used a subset of this combined database in the analysis, as follows: 1) no potentially induced earthquakes (PIE); 2) no data from the Mississippi Embayment/Gulf Coast region (as defined in Section C.2 of Appendix C in Goulet et al., 2014); 3) response spectra were only used for periods greater and less than the minimum and maximum usable periods specified in the flatfile, respectively; and 4) motions potentially influenced by microseisms were excluded. PIE events were excluded for a number of reasons, the main one being that I intend my GMPs to be applicable to tectonic earthquakes. Mississippi Embayment/Gulf Coast region stations were excluded because of the likely different site response for a given $V_{s30}$ (Hollenback et al., 2015). The magnitude-distance distribution of the subset for peak acceleration is shown in Figure 1. Because of the sparse data at distances less than 25 km, I only use data recorded at distances greater than or equal to 25 km in my analysis. The upper limit of 1200 km is imposed by the limit of the simulations used to create the B18 GMPs. Also shown in Figure 1 is the magnitude-distance distribution of the data used by B18 to invert for the stress parameters used in the simulations. It is clear that many more data are available in the NGA-East dataset. Seeing how well the B18 GMPs agree with the larger dataset was the main motivation for this article. In addition to the larger number of data now available, the ground-motion intensity measures (GMIMs) for the same site in the NGA-East database and the data used by B18 might not be the same because of differences in record processing and because some data used by B18 were converted from vertical component GMIMs.

A map of stations used in this article is given in Figure 2. This shows that most of the data used by B18 came from stations in the northeastern United States and southeastern Canada. There are, however, some recordings on rock (1000 m/s ≤ $V_{s30}$ ≤ 2050 m/s) to the west of most of the rock recordings. Most of the soil-station recordings (200 m/s ≤ $V_{s30}$ < 1000 m/s) are from the western portion of CENA.

The number of records available for analysis after applying the selection criteria are shown in Figure 3 as a function of period. Not surprisingly, there is a significant decrease in the number
of available records at short and long periods. The decrease at short periods starting at \( T = 0.06 \) s is primarily due to the relative low sample rate of many records. More than half of the records in the subset used in this article are from recordings with Nyquist frequencies of 20 Hz or less, many of these from the EarthScope Transportable USArray (TA) and the US National Seismic Network. There are so few records for \( T = 0.02 \) s that the analysis started at \( T = 0.025 \) s. The decrease in numbers of records at long periods is primarily due to the limitations imposed by long-period noise.

The horizontal component data used by B18 in deriving the stress parameters are equivalent to geometric means, while the NGA-East GMIMs are RotD50 (Boore, 2010; Goulet et al., 2014). For consistency, I convert the NGA-East observations to geometric means before computing the residuals used in the analysis. The conversion is shown in Figure 4; it is magnitude and distance independent, and is based on the database accumulated by T. Kishida for use in the analysis reported in Boore and Kishida (2017). As the focus in that article was on the NGA-West2 GMPEs (in particular, RotD50/GMRotI50, the numerator being used in NGA-West2 and the denominator in NGA-West1), the RotD50/GM_AR ratios for CENA were not included in the Boore and Kishida (2017) article or its electronic supplement.

**METHOD (RESIDUAL ANALYSIS)**

The analysis is based on mixed-effects regression of residuals calculated as the difference between observed GMIMs and the B18 GMPs. The GMIMs are peak velocity (PGV), peak acceleration (PGA), and 5%-damped pseudo-acceleration response spectra (PSA). For brevity, PSA at a given period is often referred to in this article by its period (e.g., \( T = 0.2 \) s” rather than “PSA(T=0.2 s)”). Both the observations and the B18 predicted GMIMs were adjusted for period-dependent site amplification (\( A \)), path (\( P \)), and offset (\( O \)) at various steps of the analysis. The total residual is defined in general as

\[
R_y(T) \equiv \left[ \ln Y_y(T) - A(T) \right] - \ln B18(M, R_{RUP}; T) + P(R_{RUP}; T) + O(T)
\]  

(1)
where $Y_{ij}$ is the observed GMIM for event $i$ at station $j$. $M$, $V_{S30}$, $R_{RUP}$ are values of moment magnitude, time-averaged shear-wave velocity to 30 m, and rupture distance, respectively. $T$ is the period of the GMIM under consideration. $A(V_{S30}, V_{REF}; T)$ is the site amplification for a site with an average shear-wave velocity of $V_{S30}$ relative to a site with an average velocity of $V_{REF}$. In this article $V_{REF} = 2000$ m/s; the B18 GMPs were for $V_{S30}$ equal to 2000 m/s and 3000 m/s—I chose 2000 m/s in this article because it is closer to the $V_{S30}$ values available for rock sites in the database. $P$ and $O$ are path and offset adjustments; they were applied to the B18 GMIMs at various steps of the analysis, as described below.

The analysis relied on a mixed-effects regression to partition the total residuals, proceeding in a series of steps, as described in subsequent sections. The mixed-effects regression used this function:

$$R_{ij} = B + \eta_i + \epsilon_{ij}$$

where period is implied. $\eta_i$ and $\epsilon_{ij}$ are the between-event residuals, accounting for differences between events, and within-event residuals, representing differences between paths and sites, respectively (Al Atik et al. 2010); they have a mean of 0.0. The remaining bias is given by $B$. A word on possibly confusing terminology: “residuals” is used both for the quantity computed by equation (1) and by the quantities $\eta$ and $\epsilon$ returned by the mixed-effects function. I have tried to use the modifiers “between-event” and “within-event” when referring to the latter residuals.

The analysis of the performance of the three sets of the B18 GMPs as compared to the NGA-East dataset, and the subsequent determination of adjustments, were carried out in an iterative manner. For each set of GMPs, the following steps were taken. More details and explicit results are given in subsequent sections.
1. Total residuals, \( R_{ij} \), were computed using the NGA-East GMIMs from sites with 
\[ 1000 \text{ m/s} \leq V_{S30} \leq 2050 \text{ m/s} \] and the B18 GMP (Equation (1)). No adjustments were taken 
in this step, in other words \( A, P, \) and \( O = 0 \).

2. The total residuals were partitioned (Equation (2)) and analyzed as a function of various 
metadata. The overall model bias, \( B \), was computed as a function of period in this step. A 
path term \( P \) was derived to remove trends in the within-event residuals. The model bias 
was used for the first of two offsets (termed \( O_1 \)) to be applied to adjustments of the B18 
GMPs.

3. Total residuals, \( R_{ij} \), were computed (Equation (1)) using the NGA-East GMIMs from 
sites with \( V_{S30} \geq 200 \text{ m/s} \) and the B18 GMPs with adjustments \( P \), from step (2), and 
\( O = O_1 \) but with no site adjustment applied to the observations ( \( A = 0 \) ).

4. As in step (2), the total residuals were analyzed using mixed-effects analysis. Adding the 
resulting bias \( B \) to the within-event residuals showed a consistent trend with \( V_{S30} \), 
intersecting the zero line for \( V_{S30} \) near 2000 m/s. The trends were fit using a simple 
function to derive a site amplification model \( A(V_{S30}, V_{REF}; T) \).

5. Total residuals, \( R_{ij} \), were computed (Equation (1)) using the NGA-East GMIMs from 
sites with \( V_{S30} \geq 200 \text{ m/s} \) and the B18 GMP with adjustments \( P \) from step (2), \( O = O_1 \) 
from step (3), and \( A \) from step (4).

6. The mixed effects analysis of the residuals computed in step (5) found a small remaining 
bias for longer periods. This bias was added to \( O_1 \) to produce a second bias \( O_2 \) for use in 
adjusting the B18 GMPs. An application for this second bias would be in adjusting the 
B18 GMPs if those models were to be used for soil and rock sites.

RESULTS: SITES WITH \( V_{S30} \geq 1000 \text{ m/s} \)
The first step of the analysis used residuals from rock sites ($1000 \text{ m/s} \leq V_{S30} \leq 2050 \text{ m/s}$), with no site, path, or offset adjustments, and therefore the results represent the best view of how well the B18 GMPs agree with the larger dataset being used in this article. The between- and within-event residuals are shown in Figure 5 and 6 for periods of 0.2 s and 2.0 s, as a function of $M$, depth, $R_{RUP}$, and $V_{S30}$. The antilog of the between- and within-event residuals are shown to avoid any possible confusion about what type of logarithm was used. The B18 GMPs provide a good fit to the larger dataset, particularly for the $T=0.2$ s response spectra. For $T=2.0$ s, there seems to be an overall difference in the magnitude dependence of the between-event residuals for data from events used by B18 and the rest of the events. But it is also true that the non-B18 events are smaller magnitude than the B18 events in general, which raises the possibility of consistent differences in instrument response, the determination of moment magnitudes, or the removal of long-period noise. Any differences in the relative motions for the two sets of events is probably not due to differences in the stress parameters, as this should not affect longer periods as much as shorter periods. As the intent of this article is to derive adjustments to the B18 GMIMs that will apply to the overall dataset, I have not attempted to make changes to the magnitude scaling of the B18 GMPs. The analysis in this article depends primarily on the within-event residuals, for which the between-event residuals have been removed.

I made changes to account for the obvious trend of the within-event residuals with distance for the longer period response spectra; this trend is seen in the lower left graph in Figure 6 (recall that the overall bias $B$ has been removed from the residuals being plotted). The residuals grow with distance, implying that the attenuation in the B18 GMPs is too rapid. After exploring various functions, I fit the following equation to the within-event residuals $\epsilon$:

$$P_{FIT} = i + bR_{RUP}$$  \hspace{1cm} (3)$$

where $i$ and $b$ are functions of period. The resulting equation, without the intercept term $i$, is used as the path adjustment $P(R_{RUP}; T)$ in equation (1). The effect of the intercept was folded into the overall bias $B$ in the residual analyses that used $P(R_{RUP}; T)$ for the path adjustment.

Graphs of the antilog of the within-event residuals as a function of distance, without and with the...
path adjustment, are shown in Figure 7 for a period of 2.0 s. When the path adjustment has been included the overall trend has been removed, and the antilog of the bias $B$ has been reduced from 1.56 to 1.09.

The antilog of the bias $B$ from the mixed-effect analyses of hard-rock residuals computed with different adjustments to the observed GMIMs and the B18 GMIMs are shown in Figure 8 for all periods. The squares with horizontal lines show the bias with no adjustments to the residuals being analyzed, so as mentioned before, the results give the best representation of how well the original B18 GMPs agree with the larger dataset being considered in this article. The bias is relatively small (less than a factor of 1.1) for periods near those used in the determination of the stress parameters (0.1 s and 0.2 s). In view of the larger number of data used in the analysis, recorded at much greater distances than considered in B18, this is a reassuring result, in that the use of the larger dataset did not reveal any significant problems in the models used in B18 at periods near 0.2 s. On the other hand, the analysis revealed significant biases elsewhere, particularly at longer periods. The circles with vertical lines show the bias when the path adjustment is made to the B18 predictions. This results in a significantly smaller bias at longer periods, but also produces a larger negative bias at shorter periods than when no path adjustment is made. The bias from the run with the path-adjustment only is used to define one of the two sets of $O(T)$ used in this article to modify the B18 GMIMs; I call it $O_1$ to distinguish it from the second $O(T)$ discussed later. When applied to the B18 GMIMs, this $O(T)$ adjustment results in the bias $B$ given by the small squares in Figure 8. This is a consistency check, as there should be no bias in this case since the $O(T)$ is equal to the path-only bias $B$. The small squares are only shown for comparison to the symbols given by small squares with black square insets. Those symbols show the bias $B$ when a second set of $O(T)$ is applied; this second set ($O_2$) is shown by the large squares in Figure 8. This second set of $O(T)$ was derived after adjusting for the site amplification, the subject of the next section. As discussed there, a limitation to the simple site amplification model at longer periods is mapped into a bias for rock residuals, as shown by the small square/black inset symbols in Figure 8.
After the analyses for the rock sites discussed above, I did a residual analysis in which the data were expanded to include $V_{530}$ as low as 200 m/s. The B18 GMIMs were adjusted for the path and the offset term $O$, given by the circles with vertical lines in Figure 8. Not surprisingly, the resulting bias $B$ was quite large, because no site adjustment was made. Plots of the antilog (within-event residuals) vs $V_{530}$ are shown in Figure 9. The antilogs of the residuals have been multiplied by a scale factor given by the antilog of the bias $B$ from the mixed effects analysis; this was done in order to uncenter the within-event residuals. Also shown in Figure 9 are antilogs of bin averages of the uncentered within-event residuals ($\varepsilon + B$). The resulting graphs for all periods (only 0.2, 2.0, and 4.0 s are shown in Figure 9) showed clear trends of increasing residuals with decreasing $V_{530}$. Although there is a large amount of scatter for the individual observations, the bin averages are generally well determined. They suggest a linear trend over the range of $V_{530}$, without the flattening at low and high $V_{530}$ found by some others (e.g., Stewart et al., 20xx), but the data used in this article are sparse for low velocities, and at high velocities are dominated by observations at stations assigned $V_{530} = 2000$ m/s; most of the assignments are based on proxies and not measurements. Note also the consistently low residuals for $V_{530}$ near 1400 m/s. These also appear in figures in Parker et al. (2019) and Stewart et al. (20xx), without comment. I have no explanation for these low residuals. I can say that they are not from stations in a single, small geographic region. Having no reason to discard them, they were retained in the analysis. Plots for all periods show that the bin averages of the uncentered within-event residuals are close to 0 (antilogs equal to 1) for periods less than about 3.0 s. I assumed that the trends in the residuals shown in Figure 9 (and similar figures for the other periods not shown here) were entirely due to site response, and I fit the adjusted within-event residuals ($\varepsilon + B$) to the following simple equation:

$$\ln A_{fit} = a + c \ln \left( \frac{V_{530}}{2000} \right)$$

(4)
As shown in Figure 9, the fit to both the individual observations and the bin averages are very similar. The regression coefficients $a$ and $c$ are plotted vs. period in Figure 10. The intercept term $a$ is small for periods less than 3.0 s. This is shown in the individual graphs in Figure 9 by the values of $A_{FIT}$ evaluated at $V_{s30} = 2000$ m/s (which is the same as the antilog of the intercept $a$). I have no explanation for the increase in the intercept for periods of 3.0 s and beyond, but as shown in Figure 3, the number of available observations falls off rapidly at these periods. The slope coefficient $c$ is very similar for the three B18 models. Also shown in Figure 10 are values of $c$ when a linear dependence of $R_{RUP}$ is added to equation (4). This was done to account for possible regional differences in the path term between the two datasets being analyzed here (rock and soil plus rock). There is little difference in $c$ without and with the added term, so the results in the rest of this article use $c$ from equation (4) without the added term. In view of the small value of the intercept $a$ for most periods and the similarity of the slope $c$ for the three models, I propose the following model for linear site amplification in CENA:

$$A(V_{s30})/A(V_{REF}) = (V_{s30}/V_{REF})^{c}$$

(5)

for $200$ m/s $\leq V_{s30} \leq 3000$ m/s. The reference velocity is taken as $V_{REF} = 2000$ m/s and the exponent $c$ is given in Table 1. The values of $c$ to be used for $V_{s30} < 2000$ m/s are the smoothed averages shown in Figure 10, while the values to be used for velocities between 2000 and 3000 m/s came from the average of ratios of simulations for the three B18 attenuation models for 2000 m/s and 3000 m/s, evaluated at $M = 5.5$ and $R_{RUP} = 50$ km (the ratios are insensitive to $M$ and $R_{RUP}$ for $M$ greater than about 4; see Boore, 2015b).

As shown in the next section, ignoring the intercept term $a$ in the site amplification model will lead to a noticeable bias for periods longer than 3.0 s in the mixed-effects analysis of residuals when the observations have been adjusted to the reference velocity of 2000 m/s using the site amplification model given by equation (5).
A number of recent articles have derived site amplification models for CENA. Those models all use an amplification proportional to \( \left( \frac{V_{30}}{V_{\text{REF}}} \right)^c \) for a range of \( V_{30} \), but because the limits of that range are not all the same, a plot of the exponents \( c \) is not a good way of comparing the models. Instead, I show in Figure 11 the amplifications for each model as a function of \( V_{30} \) for periods of 0.2 s and 2.0 s. The site amplifications for my model are quite similar to those of most of the other CENA models, particularly for shorter periods. The amplifications of Graizer (2017) are closest to my model. All of the CENA-specific amplifications are consistent in predicting smaller amplifications at \( V_{30} \) less than about 500 m/s to 800 m/s (depending on model and period) than for the model used in BSSA14 for active crustal regions. As noted by others, this may be because sites in CENA are generally underlain by rocks whose velocities increase more rapidly with depth than in active crustal regions (e.g., Boore, 2016), and thus for a given \( V_{30} \), the effective velocity controlling the amplification is higher in CENA than elsewhere, leading to a lower amplification from seismic impedance considerations (e.g., Boore, 2013).

Several GMPMs for CENA used the site amplification model in BSSA14 in their derivations (Hassani and Atkinson, 2015; Yenier and Atkinson, 2015; Pezeshk et al., 2018). It is beyond the scope of this article to assess the impact of using an inappropriate site amplification model in those studies; the impact depends on the way that the amplification was used and how the GMPs were adjusted to account for any biases that resulted from using the amplification model.

RESULTS: SITES WITH \( V_{30} \geq 200 \text{ m/s} \)

Having developed the site amplification model, I did a mixed-effect analysis of residuals using observations with \( V_{30} \) between 200 m/s and 2050 m/s. The residuals used in the analysis were computed by adjusting the observations for site amplification using equation (5) and adjusting the B18 GMPs for path and for the offset \( O_1 \). The antilog of the resulting bias \( B \) is shown by
the squares in Figure 12. There is an abrupt increase in $B$ for periods of 3 s and longer (this
increase could occur at a period between 2 and 3 s, as I did not include those periods in my
analysis). The increase is a reflection of ignoring the intercept term $a$ in the site amplification
model. I added this bias to the bias from the hard-rock run to produce a second offset $O(T)$ to be
removed from the B18 GMPs in computing the residuals used in the mixed-effect analysis
(equation (1)). This second offset (called $O_2$ to distinguish it from the first offset obtained from
the analysis with $V_{S30} \geq 1000$ m/s) is shown by the large squares in Figure 8. Using this offset, I
ran mixed-effect analyses for the two ranges of $V_{S30}$: between 200 m/s and 2050 m/s, and
between 1000 m/s and 2050 m/s. The antilog of the bias from the first range is shown by the
square/black inset symbols in Figure 12. There is essentially no bias remaining; the small scatter
in $B$ is because the average site amplification model was used rather than the one for
AB14mod1. On the other hand, there is now a bias for the hard rock residual analysis (Figure 8,
square/black inset symbols). I have not been able to find adjustments that removes the bias for
all subsets of $V_{S30}$ and period, but I am willing to tolerate adjustments that only produces biases
at longer periods, as response spectra at these periods are of less engineering importance than the
shorter period GMIMs, and the fewer data available for the longer periods means that the bias
results are less certain. The adjustments in this article work well for the bulk of the data.

The antilog of the between- and within-event residuals for the mixed-effects analysis of residuals
for which $V_{S30}$ was between 200 m/s and 2050 m/s are shown in Figures 13 and 14 for periods of
0.2 s and 2.0 s. These plots are in the same format as Figures 5 and 6, and the overall trends and
biases are similar to those in the earlier figures. Aside from some separation of event terms for
B18 and xB18 events for $T=2.0$ s (similar to that shown in Figure 6), the adjustments to the B18
GMPs seem to work well when applied to the large NGA-East dataset.

I have also shown separate bin averages for the B18 and xB18 events in the graph of
antilog(within-event residual) vs. $R_{rup}$ in Figures 13 and 14. I did this to assess possible
regional differences in attenuation, as most of the B18 events occur in the northeastern United
States and southeastern Canada (Figure 2). Separate bin averages are not shown for the graph of
residuals vs. $V_{s30}$ because there are few B18 events recorded at stations with $V_{s30}$ less than 1000 m/s. Although there is considerable scatter, particularly for shorter distances, there is not an obvious regional dependence in the attenuation of the ground motions, a conclusion also made by Hassani and Atkinson (2015).

**OVERALL UNCERTAINTY $\sigma$**

It is obvious from looking at the figures in this article that there is a large amount of scatter in the observations, and that the adjustments to the B18 GMPs will not produce a significant reduction in this scatter. This is shown in Figure 15. The rock data have a noticeably smaller scatter than do the soil-plus-rock data, and the path adjustment, derived for the rock data, produces only a small reduction in the scatter, and that for periods on either side of the 0.1 s to 0.4 s range for both the rock and the soil-plus-rock data. The soil-plus-rock data show a modest reduction in scatter for all periods when the site amplification function is applied. This small reduction is not surprising, as the site amplification is intended to capture the amplification for an average site. Clearly any individual site can have an amplification far from the average because of local site conditions that can lead to resonances, topographic effects, etc. Finally, applying an offset adjustment has no effect on the scatter, as measured by the overall standard deviation $\sigma$. This is expected, as the offset is constant for a given period and is independent of the predictor variables $M$, $R_{rup}$, and $V_{s30}$; its effect is removed as part of the mean when computing $\sigma$.

**POSSIBLE EXPLANATION OF THE BIAS AT SHORT PERIODS**

A simple explanation for the bias at short periods is that the $\kappa_0$ stipulated for use in the NGA-East project ($\kappa_0 = 0.006$ s; Hashash et al. 2014) is smaller on average than that for the stations providing the data used in the residual analyses. To test this, I repeated the B18 SMSIM
simulations (Boore, 2005) for several representative magnitudes and distances, varying only $\kappa_0$.

I did the simulations for a suite of $\kappa_0$ (from 0.006 s to 0.020 s). I compared the ratio of the simulated PSA for a given $\kappa_0$ and for $\kappa_0 = 0.006$ s with the observed bias. Out of the suite of $\kappa_0$ the best subjective fit to the observed bias was for $\kappa_0 = 0.0085$ s. Figure 16 shows the comparison. I think the results are a strong indication that a larger $\kappa_0$ than used by B18 should be have been used in the simulations. Rather than redoing the original B18 simulations, however, I have provided tables of motions in the electronic supplement in which the B18 results are adjusted for path and offset. Even if I reran the simulations with a larger $\kappa_0$ to remove the bias at short periods, I would still need to remove the path effect and the offset at longer periods from the ground-motion intensity measures, as I have not tried to modify the original path models to remove the path effect, and I have no idea how to modify the simulations to remove the long-period biases.

SUMMARY AND CONCLUSIONS

I find that the B18 GMPs are in reasonable agreement with the larger NGA-East dataset (Goulet et al. 2014) for hard-rock sites ($V_{330}$ between 1000 m/s and 2050 m/s), with adjustments needed to the path model at larger distances and a period-dependent offset adjustment at short and long periods. For most periods of engineering interest (from about 0.05 s to 2.0 s) the offset adjustment is small, even though the stress parameters used to derive the B18 GMPs were determined from a much more limited dataset than used in this article (periods of 0.1 s and 0.2 s and distances less than 200 km, with fewer observations for these periods and distances than in the NGA-East flatfile). I think the short-period bias adjustment exists because the $\kappa_0 = 0.006$ s specified in the NGA-East project is smaller than the $\kappa_0$ at the observation sites; $\kappa_0 = 0.0085$ s provides a better fit between observations and simulations. I am not sure what produces the longer period bias, but a number of comparisons in previous studies have found the point-source stochastic model (and even finite-fault simulations [Dreger et al., 2015]) has a bias at longer
periods (e.g., Figure 6 in Boore, Di Alessandro, *et al.*, 2014). This possible limitation may be partially related to the presence of surface waves and higher modes in the observations whose excitation is not explicitly accounted for in the stochastic model, which is based on the source excitation and propagation of body waves.

After the path adjustments and hard-rock offset adjustments are made, I find significant $V_{s30}$-dependent biases when residuals are computed using a dataset that includes observations with $V_{s30}$ as low as 200 m/s. With the assumption that these biases are primarily due to site response, I formulate a simple site response model of the form $A(V_{s30})/A(V_{REF}) = (V_{s30}/V_{REF})^c$, where $c$ is period dependent. Because I am using the B18 GMPs for $V_{s30} = 2000$ m/s in computing the residuals used in the mixed-effects residual analysis, I chose $V_{REF} = 2000$ m/s, although any value could have been chosen. The site amplification model works well for periods less than about 3 s, but for longer periods some bias results when the mixed-effects analysis is applied to residuals computed using the site response model. The model bias is not too large (less than a factor of 1.3, the largest bias being for the maximum period of 10 s).

The overall impact on the B18 GMPs is relatively small, as shown in Figure 17, which compares the original and adjusted AB14mod1 and BCA10D GMPs. With the exception of longer periods and large distances, the biggest differences in Figure 17 are between models, and not between a given original and adjusted model. These differences are an expression of the epistemic uncertainty in the predicted ground-motions.

New to this article are period-dependent adjustments to convert RotD50 to as-recorded geometric means for recordings in CENA. These adjustments used the methodology and database in Boore and Kishida (2017); the adjustments were not included in their article, but are included here in the electronic supplement.

**DATA AND RESOURCES**
The ground-motion database used in this article was a combination of the NGA-East flatfile (described in Goulet et al., 2014, and available from https://peer.berkeley.edu/sites/default/files/nga-east_rot50_5pct_flatfile_public_20141118.xlsx, last accessed May, 2019) and a file from the electronic supplement of Parker et al. (2017); the combined file was prepared by G. A. Parker. Ground-motion simulations used the SMSIM software available from http://www.daveboore.com (last accessed June, 2019). Most of the analysis used scripts written in R (R Core Team, 2018), relying heavily on the mixed-effects analysis provided by the function lme in the nlme package (Pinheiro et al., 2018). The figures were prepared using CoPlot (www.cohort.com, last accessed June, 2019).

ACKNOWLEDGMENTS

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REFERENCES


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Table 1. Coefficients of site amplification for the smoothed average of the coefficients from the three sets of B18 GMPs for $V_{s30}$ less than and greater than the reference velocity of 2000 m/s.

<table>
<thead>
<tr>
<th>Period (s)</th>
<th>$c(V_{s30}&lt;2000)$</th>
<th>$c(V_{s30}\geq2000)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.000</td>
<td>-0.393</td>
<td>-0.334</td>
</tr>
<tr>
<td>0.000</td>
<td>-0.288</td>
<td>-0.557</td>
</tr>
<tr>
<td>0.010</td>
<td>-0.449</td>
<td>-0.564</td>
</tr>
<tr>
<td>0.020</td>
<td>-0.440</td>
<td>-0.586</td>
</tr>
<tr>
<td>0.025</td>
<td>-0.434</td>
<td>-0.589</td>
</tr>
<tr>
<td>0.030</td>
<td>-0.424</td>
<td>-0.591</td>
</tr>
<tr>
<td>0.040</td>
<td>-0.404</td>
<td>-0.593</td>
</tr>
<tr>
<td>0.050</td>
<td>-0.359</td>
<td>-0.592</td>
</tr>
<tr>
<td>0.075</td>
<td>-0.208</td>
<td>-0.587</td>
</tr>
<tr>
<td>0.100</td>
<td>-0.253</td>
<td>-0.578</td>
</tr>
<tr>
<td>0.150</td>
<td>-0.329</td>
<td>-0.551</td>
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<tr>
<td>0.200</td>
<td>-0.370</td>
<td>-0.521</td>
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<tr>
<td>0.250</td>
<td>-0.376</td>
<td>-0.489</td>
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<tr>
<td>0.300</td>
<td>-0.376</td>
<td>-0.458</td>
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<tr>
<td>0.400</td>
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<tr>
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<td>7.500</td>
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<td>-0.079</td>
</tr>
<tr>
<td>10.000</td>
<td>-0.198</td>
<td>-0.078</td>
</tr>
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Figure 1. Moment magnitude-rupture distance distribution of data for observations of peak acceleration. Dots: subset of NGA-East data considered for analysis; small and large circles: subset used in this article ($R_{RUP} \geq 25$ km) for two ranges of $V_{S30}$; squares: data used in Boore (2018).
Figure 2. Map of stations providing data used in this article. The plus symbols are for events used by Boore (2018; B18), but do not necessarily correspond to stations used in B18.
Figure 3. Number of records (Nrecs) as a function of period for two ranges of $V_{S30}$, after applying the various selection criteria used in this article. Periods of -1 and 0 correspond to peak ground velocity (PGV) and peak ground acceleration (PGA). Note the small number of data for $T=0.02$ s; for this reason, the analysis did not consider this period.
Figure 4. Ratio of RotD50 to the as-recorded geometric mean (GM_AR). Shown are the geometric mean of the ratio in various magnitude and distance bins, as well as the subjectively chosen values used in this article. The dataset did not include PIE events, records from the Mississippi Embayment/Gulf Coast regions, or periods dominated by microseisms.
Figure 5. Antilog of the between-event (η) and within-event (ε) residuals for T=0.2 s. As shown in the lower right graph, only observations from stations with 1000 m/s ≤ V_{S30} ≤ 2050 m/s were used in this stage of the analysis. The open squares in the top row of graphs are for the earthquakes used in B18, although the particular stations and ground-motion values might be different than used in B18, and the open circles are the other events used in the analysis. In all graphs the filled squares are bin averages with 95% confidence intervals. The antilog of the overall bias, B, is shown in the text box in the upper left graph. The overall bias B has been removed from the mixed-effects analysis residuals.
Figure 6. As in the previous figure, but for T=2.0 s. No path adjustment was made for this and the previous figure. See Figure 5 caption for explanation of symbols.
Figure 7. Within-event ($\varepsilon$) residuals for $T=2.0$ s as a function of $R_{RUP}$ without and with path adjustment $P$ (left and right panels, respectively).
Figure 8. With one exception, antilog of the bias ($B$) from various mixed-effects residual analyses, for rock sites ($1000 \text{ m/s} \leq V_{S30} \leq 2050 \text{ m/s}$). The 95% confidence intervals of the square/back insert symbols are shown by thin bars, but only for periods greater than 2 s to avoid overlap with the confidence intervals of the circles with vertical lines.
Figure 9. Within-event residuals for periods of 0.2, 2.0, and 4.0 s resulting from a mixed effects analysis using residuals in which the B18 GMPs were adjusted for the path trend and the offset $O_t$. The antilog of the mixed-effects within-event residuals has been multiplied by a scale factor (SF) equal to the antilog of $B$ found in the mixed-effects analysis. The thicker line is a regression fit to all of the residuals, while the thinner line is the fit to the bin averages shown by squares (with 95% confidence intervals). $A_{RF}(2000)$ is the value of the thicker regression line at $V_{530} = 2000$ m/s.
Figure 10. The regression coefficients in equation (4) as a function of period. The coefficient $a$ is only shown for the AB14mod1 GMPs, while $c$ is for the three sets of GMPs (and for AB14mod1, for an analysis in which a linear term in $R_{rup}$ is added to equation (4)). The 95% confidence intervals are only shown for the results from the AB14mod1 analysis; the intervals for the other models are very similar. Also shown is the average exponent used to adjust for the site in the residual analyses discussed in this article.
Figure 11. Site amplifications in central and eastern North America as a function of $V_{s30}$ for two periods (0.2 s and 2.0 s) from a number of studies. The acronyms refer to these papers: G-16v2: Graizer (2017); HA18: Hassani and Atkinson (2018); Sea19: Stewart et al. (20xx); ZR19: Zalachoris and Rathje (20xx); B18revision: this article. Also shown for comparison are the amplifications for active crustal regions used by Boore et al. (2014; BSSA14).
Figure 12. Bias from two residual analysis runs, where the observations used to compute the residuals being analyzed were adjusted to $V_{s30} = 2000$ m/s using the average site amplification given by equation (5), with coefficients given in Table 1, for stations with $200 \text{ m/s} \leq V_{s30} \leq 2050$ m/s. The B18 predictions used in computing the residuals being analyzed were adjusted for the path and for two bias adjustments, as indicated in the legend.
Figure 13. antilog of the between-event ($\eta$) and within-event ($\varepsilon$) residuals for $T=0.2$ s. The residuals used in the mixed-effects analysis were computed by adjusting the observations to $V_{S30} = 2000$ m/s using equation (5) and the coefficients in Table 1 and adjusting the B18 predictions for path and the offset $O_2$ (shown by the large squares in Figure 8). As shown in the lower right graph, observations from stations with $200$ m/s $\leq V_{S30} \leq 2050$ m/s were used in the analysis. See Figure 5 caption for explanation of symbols.
Figure 14. As in the previous figure, but for T=2.0 s. See Figure 5 caption for explanation of symbols.
Figure 15. Total uncertainty $\sigma$ for various runs, for the AB14mod1 model.
Figure 16. Ratio of response spectra for various magnitudes and distances, computed for the AB14mod1 model, keeping all stochastic-model parameters the same except for $\kappa_0$, compared with the bias from the rock mixed-effects analysis when the only adjustment to the B18 predictions is for the path trend. To avoid a clutter of symbols, lines were used to connect the periods of -1 s and 0 s in the left graph; only the endpoints are meaningful.
Figure 17. Comparison of GMIM from the B18 GMPs (converted to RotD50) and from adjustments for path and offset $O_2$. The results for the AB14mod2 model are not shown because they are very similar to those for the AB14mod1 model.