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Influence of the Site-Specific Component of Kappa on the Magnitude-Dependency of Within-Event Aleatory Variabilities in Ground-Motion Models

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Abstract

The aleatory-variability component (standard deviation) of a ground-motion motion has a large influence on results of a probabilistic seismic hazard assessment. kappa, a measure of high-frequency attenuation, has site- and record-specific effects that have been suggested as reasons for observing heteroscedastic aleatory variability within earthquake ground motions. Specifically, kappa has been proposed as a reason why ground motions from small earthquakes are more variable than those from large earthquakes, which is modelled by magnitude-dependent within-event standard deviations in ground motion prediction equations (GMPEs). In this study, we use

ground motions simulated using the stochastic method to examine the influence of the site-specific component of kappa on aleatory variability of earthquake ground motions and examine the hypothesis that this could be a cause of the observed heteroscedasticity in this variability. We consider simulations with both fixed and continuous stress drop distributions and the site-specific component of kappa to demonstrate that variation in the stress drop parameter contributes minimally to magnitude-dependency, unlike the site-specific component of kappa, which causes significant magnitude-dependency. Variation in the site-specific component of kappa is, therefore, proposed to be at least partially responsible for the magnitude-dependency captured in the aleatory-variability components of some recent GMPEs. It is found, however, that the expected impact of the site-specific component of kappa on aleatory variability is much greater than modelled in these GMPEs, which suggests that there could be a mitigating effect that is not captured within the simulations (e.g. correlated inputs to the simulations).

Introduction

The uncertainty in ground-motion predictions is usually separated into epistemic uncertainty (due to a lack of knowledge), which in theory can be reduced, and aleatory variability (due to the randomness of the natural process), which is theoretically irreducible. A ground motion prediction equation (GMPE), more generally called a ground-motion model, is a simple representation of the physical processes associated with the generation and propagation of ground-motions (Douglas and Edwards, 2016). Observed earthquake ground motions often show considerable deviations from the predictions from these models, which is shown by wide residual distributions. Hence, the aleatory variability component of GMPEs, often modelled as a lognormal distribution of a standard deviation, σ, and zero mean, is a central part of GMPEs (Strasser et al., 2009). The value of σ greatly influences the predicted ground-motion, even more so at low annual frequencies of exceedance (AFE) that are of particular interest to earthquake engineering (Bommer and Abrahamson, 2006; Toro, 2006).

Conventionally, σ is split into between-event and within-event components. The between-event component (τ) captures the variability associated with event-specific factors (e.g. randomness in the earthquake source) that have not been accounted for in the GMPE. The within-event component (ϕ) models the variability associated with record-specific factors (e.g. randomness in the local site amplification for a given site class).

A commonly-used site parameter is the high-frequency attenuation operator, kappa (κ) (Anderson and Hough, 1984). This parameter describes the observed fall-off above the corner frequency (f_c) of the Fourier amplitude spectrum of the accelerogram recorded at a site. Anderson and Hough (1984) determined the decay of the Fourier amplitude spectrum to occur above f>~2 Hz, but subsequent studies (e.g. Anderson and Humphreys, 1991) suggested this decay occurs when $f>f_c$. Anderson and Hough (1984), observing that κ increases with source-to-site distance, proposed that κ is related to both the near-surface site conditions and the regional geological structure (i.e. κ is both site- and record-specific).

The site- and record-specific nature of κ results in this parameter contributing to ϕ within GMPEs. The influence of κ is not well understood and since it is a purely empirical parameter, a physical explanation is likely to be inherently problematic. Douglas and Jousset (2011) postulate that variations in κ_0 may be a reason for the magnitude-dependency of ϕ that is sometimes captured in GMPEs, particularly those covering a wide magnitude range (Ambraseys et al., 2005; Boore et al., 2014). However, Douglas and Jousset (2011) did not investigate this idea in detail. Therefore, this study examines the influence of the site-specific component of kappa (κ_0) upon ϕ (the path-dependent attenuation is modelled by the considered attenuation model – see Table 1), with an emphasis on its potential to explain the magnitude-dependency (heteroscedasticity) of this variability within some recent GMPEs. This study begins with a brief review of recent studies examining the magnitude-dependency of ground-motion variability, followed by an analysis examining: (1) the influence of κ_0 upon ϕ within simulation and (2) how well these simulated results match the ϕ models in some recent GMPEs.

Studies on the Magnitude-Dependency of Ground-Motion Variability

The magnitude-dependency of σ for peak ground acceleration (PGA) was first examined in-depth by Youngs et al. (1995), with the magnitude-dependency of τ being found to be stronger than the magnitude-dependency of ϕ. Youngs et al. (1995) confirmed that non-linear site effects contribute to the magnitude-dependency of σ, as proposed first by Chin and Aki (1991). Youngs et al. (1995) proposed that the magnitude-dependency of σ could also be due to: (1) the magnitude-dependent variability of the stress drop parameter ($\Delta\sigma$), (2) metadata errors for small magnitude earthquakes and (3) the duration of ground-motion being shorter for small events than for larger earthquakes.

Ambraseys et al. (2005) found a statistically-significant magnitude-dependency in σ for short-period (<1s) spectral acceleration (SA) but that this statistical significance did not hold for long-period (>1s) SAs. They noted that the lack of statistically significance could be attributed to the cut-offs used to filter the strong-motion records, which resulted in fewer long-period than short-period SAs, rather than a true effect. Ambraseys et al. (2005), in contrast to Youngs et al. (1995), assumed that the magnitude-dependency of σ was partitioned equally between τ and ϕ (rather than being predominantly associated with τ) because of the complex mapping of the magnitude-dependency upon both components. The magnitude-dependency could be due to site or propagation path variability (thus manifesting in ϕ), due to the regression method used to derive the GMPE (thus manifesting in τ) or due to metadata issues associated with estimation of source-to-site distances and magnitudes (thus manifesting in ϕ and potentially τ depending on the spatial distribution of sites relative to the earthquake source).

Bommer et al. (2007) demonstrated that reduction of the lower magnitude limit of the strong-motion data used to derive a GMPE (from moment magnitude 5 to 3) significantly increases τ but minimally increases ϕ (see their Figure 12). This lends support to Youngs et al. (1995)'s observation that the magnitude-dependency of τ is stronger than the magnitude-dependency of ϕ. Bommer et al. (2007) demonstrated that the expanded magnitude range increases ϕ slightly more for short-period ground motions than ϕ for long-period ground-motions. Expansion of the magnitude range likely increases ϕ for a given magnitude because of the inclusion of more sites and additional records from each site. The increased site variability affects the shorter periods more, so the responsible mechanism must cause greater variability at these periods than at longer periods. This is suggestive of variation in κ_0 among sites potentially being a responsible mechanism for the observed heteroscedasticity.

Bommer et al. (2007) also noted that the increased variability resulting from an increased magnitude range could be due to the incorporation of data from different regions because: (1) different instrument types are often used in different regions and (2) ground motions generated by smaller earthquakes are more sensitive to differences in regional attenuation (due to differing crustal structures and Q). Sensitivity analyses reported by Bommer et al. (2007) indicated, however, that the median predictions and associated variabilities were not significantly influenced by the inclusion/exclusion of different regional datasets. In contrast, Chiou et al. (2010)

demonstrated that, by accounting for regional differences in Californian ground motions, the magnitude-dependency of τ is decreased.

Douglas and Jousset (2011) demonstrated using stochastic simulations that variations in κ_0 affect PGA more for small magnitude earthquakes than for large magnitude earthquakes, and proposed that this may explain the magnitude-dependency of σ within some GMPEs. This observation was the trigger for the current study, which examines this potential explanation in more detail.

Through consideration of a standard Brune (1970; 1971) source spectrum model, Kotha et al. (2017) expanded upon the physical explanation for the influence of $\Delta\sigma$ on the magnitude-dependency of τ provided by Youngs et al. (1995). For a given moment magnitude (M_w), an increase in $\Delta\sigma$ lowers the corner frequency (f_c), and increases ground-motion amplitudes for $f > f_c$ whilst ground-motion amplitudes for $f < f_c$ remain unmodified. If one considers a primary frequency f_1 and a secondary frequency f_2, when $(f_1, f_2) < f_c$ neither f_1 or f_2 is affected by variability in $\Delta\sigma$, so their correlations are strong. When $(f_1, f_2) > f_c$, ground-motion amplitudes increase monotonically with variation in $\Delta\sigma$, so their correlations are also strong. Therefore, Kotha et al. (2017) state that for large magnitude earthquakes with a low f_c, stronger correlations would be expected over a wide range of $(f_1, f_2) > f_c$ than would be observed for small magnitude earthquakes. This is observed in the correlation coefficients computed by Kotha et al. (2017) over the range of considered values for f_2 (with a fixed f_1) for large and small earthquakes (see their Fig. 3), supporting this expanded physical explanation for the influence of $\Delta\sigma$ on the magnitude-dependency of τ.

It should be noted that heteroscedasticity has been observed in the ground-motion residuals of several GMPEs but the final aleatory-variability models recommended for these GMPEs are homoscedastic. For example, Kotha et al. (2020) observed heteroscedasticity of τ with respect to magnitude, but due to the limited number of large earthquakes compared to many small to moderate earthquakes within their dataset, they decided that this observation was not convincing enough to be incorporated into their final model. However, GMPEs have been developed which successfully account for some of the effects contributing to the heteroscedasticity of σ. Kotha et al. (2019) accounted for the influence of earthquake size on ϕ due to azimuthal variation of ground-motions (small earthquakes have simpler radiation patterns than large earthquakes, resulting in larger ϕ for smaller earthquakes), reducing ϕ within their proposed model. Such an example is highlighted within this study because failing to capture the influence of earthquake size due to azimuthal variation of ground-motions on ϕ in GMPEs results in greater uncertainty in estimations of κ_0.

Investigating Ground-Motion Variability Using Stochastic Simulations

To investigate how ground motions vary with changes in κ_0, simulations were undertaken using the stochastic method as implemented in the SMSIM software (Boore, 2005). Stochastic simulations were undertaken using Bora et al. (2017)'s stochastic model for Europe with a Brune (1970; 1971) source spectrum model and κ_0 distributions sampled from various published κ_0 models (Table 1). Appropriate κ_0 distributions were sampled from the considered models for an average shear-wave velocity of the top 30 m (V_{s30}) of 620 m/s (roughly equivalent to "soft rock"). Bora et al. (2017) state a reference V_{s30} of 620 m/s was used for the computation of their provided κ_0 distribution, and so a V_{s30} of 620 m/s was used for the computation of the other κ_0 distributions too. Considering a different V_{s30} value is unlikely to affect the results significantly.

For each magnitude, ϕ was computed from the simulations for a hypocentral distance (R_{hypo}) of 40 km for PGA and SA for periods of 0.2 s and 1 s (Figure 1) and moment magnitudes in the range 1 to 6.5. The ϕ values were computed for R_{hypo} = 40 km to eliminate the influence of regional attenuation and because this is close to the center of strong-motion databases used to derive empirical GMPEs for active shallow crustal regions. The absolute rate of change of ϕ with respect to magnitude is used to characterize its magnitude-dependency (Figure 2). A larger rate of change indicates a greater magnitude-dependency of ϕ.

The computed ϕ are compared to values provided by empirical GMPEs developed for similar magnitude ranges (Figure 1; Figure 2). Empirical GMPEs developed for small magnitude ($M_w < 3$) earthquakes are scarce (even more so those with heteroscedastic σ) compared to the number of empirical GMPEs developed for moderate to large magnitude earthquakes. Due to this scarcity of suitable models, and because ϕ generally contributes more to the total aleatory variability than τ, for the GMPE for which ϕ is not provided (Bindi et al., 2007), the value of σ is plotted instead.

For each sampled κ_0 distribution (see Table 1 for details on these κ_0 distributions and all other inputted parameters), stochastic simulations were undertaken using: (1) a fixed $\Delta\sigma$ of 5.65 MPa and (2) a $\Delta\sigma$ distribution sampled from the Bora et al. (2017) stochastic model (Figure 1; Figure 2). Variation in $\Delta\sigma$ was considered because the trade-off between the $\Delta\sigma$ and κ_0 parameters means $\Delta\sigma$ must be varied to determine if it contributes to the magnitude-dependency of ϕ (Rodriguez-Marek et al., 2013). This trade-off between $\Delta\sigma$ and κ_0 is especially significant for small earthquakes due to their high corner frequencies from short rupture durations, which in turn results in the generated ground-motions being more affected by scattering and attenuation (Sumy et al., 2017).

Simulations were also undertaken with a fixed κ_0 of 0.0308 s to examine the effect of varying only stress drop (Figure 1; Figure 2).

Results and Discussion

For a fixed κ_0 and a $\Delta\sigma$ distribution sampled from Bora et al. (2017), the computed ϕ for PGA, SA(0.2 s) and SA(1 s) are all small and show minimal magnitude-dependency, with ϕ increasing slightly with magnitude (Figure 1; Figure 2). This weak magnitude-dependency observed when only κ_0 is fixed suggests that $\Delta\sigma$ contributes minimally to the magnitude-dependency of ϕ for PGA, SA(0.2 s) and SA(1 s). The ϕ computed for PGA for a sampled κ_0 distribution and a $\Delta\sigma$ distribution sampled from Bora et al. (2017) show minimal difference to the corresponding ϕ computed with the same κ_0 distributions and a fixed $\Delta\sigma$. This further supports the view that $\Delta\sigma$ has a minimal influence on the magnitude-dependency of ϕ for PGA. The magnitude-dependency of ϕ with varying κ_0 is considerably stronger for PGA than for SA(0.2 s) or SA(1 s) (Figure 2). Variations in κ_0 potentially lead to stronger magnitude-dependency of ϕ for PGA than for SA(0.2 s) or SA(1 s) because κ_0 describes the decay of specifically high-frequency ground-motions, and therefore PGA is more sensitive to said variations in κ_0 than SA(0.2 s) or SA(1 s), resulting in stronger magnitude-dependency being observed for PGA. The seemingly limited influence of $\Delta\sigma$ on the magnitude-dependency of ϕ observed within this study is supportive of Kotha et al. (2017)'s findings that $\Delta\sigma$ has a noticeable influence on the magnitude-dependency of τ, therefore lending support to their expanded physical explanation of how $\Delta\sigma$ influences τ too. However, due to the complex mapping of magnitude-dependency onto both ϕ and τ, an expanded investigation into the influence of $\Delta\sigma$ on the magnitude-dependency of both components of σ should be undertaken in the future.

The computed ϕ for PGA, SA(0.2 s) and SA(1 s) are all larger for smaller magnitudes because as discussed above, ground-motions generated from smaller earthquakes are more affected by scattering and attenuation (Sumy et al., 2017). The magnitude-dependency of ϕ is inherently stronger when a κ_0 distribution with greater variability is considered (Figure 2). For example, the maximum magnitude-dependency of ϕ for PGA with the Bora et al. (2017) κ_0 distribution (highest variability) is approximately 30% stronger than the maximum magnitude-dependency of ϕ with the Edwards et al. (2011) κ_0 distributions (lowest variability). The observation of stronger magnitude-dependency of ϕ for PGA than for SA(0.2 s) or SA(1 s) due to solely variation in κ_0 (Figure 2) suggests, as first proposed by Douglas and Jousset (2011), that κ_0 is at least partly responsible for observed heteroscedastic ϕ in GMPEs for short-period SAs.

For PGA, ϕ computed from the simulated ground-motions are larger at lower magnitudes than the values provided by the considered GMPEs, whereas for SA(0.2 s) and SA(1 s) ϕ computed from the simulated ground-motions are more similar to those in the considered GMPEs (Figure 1), with this being more so for SA(1 s) than for SA(0.2 s). ϕ for PGA computed from the simulated ground-motions with the Chandler et al. (2006) and Edwards et al. (2011) κ_0 distributions are larger than the values provided by the considered GMPEs below approximately M_w 2.5. As discussed above, the larger ϕ computed using the Bora et al. (2017) κ_0 distribution is inherently due to its wider distribution. Of the considered GMPEs, the models which provide values most similar to ϕ computed from the simulated ground-motions are: Ameri et al. (2017), Chiou et al. (2010), Boore et al. (2014) and Ambraseys et al. (2005). Of these, only the Ameri et al. (2017) GMPE was developed for earthquakes of $M_w < 2.5$, and therefore was the only one of these GMPEs that does not need extrapolation (Figure 1). Extrapolation of GMPEs below their designated magnitude ranges cannot be the sole factor responsible for the difference between ϕ for PGA from the simulated ground-motions and the GMPEs for $M_w < 2.5$. The observation that the simulated ϕ values for SA(0.2 s) and SA(1 s) are more similar to the ϕ provided by the considered GMPEs can be partly attributed to κ_0 having a more significant impact on PGA than SA(0.2 s) or SA(1 s), and hence by default, variations in κ_0 are better modeled in GMPEs for SA(0.2 s) and SA(1 s) than for PGA. The better modelling for SA(0.2 s) and SA(1 s) is likely due to κ_0 being a parameter describing the decay of high frequency ground-motions, rather than low frequency ground-motions.

The magnitude-dependency of ϕ for PGA computed from the simulated ground-motions is overall far stronger than the magnitude-dependency observed in the considered empirical GMPEs with heteroscedastic ϕ (Figure 2). For example, the maximum magnitude-dependency of ϕ for PGA computed from the simulations with the Edwards et al. (2011) κ_0 distribution is 200% stronger and 130% stronger than the magnitude-dependency of ϕ in the Bommer et al. (2007) and Ambraseys et al. (2005) GMPEs, respectively. The only exception to this observation is over the moment magnitude interval M_w 4.5 - M_w 5.5, within which the magnitude-dependency of ϕ for PGA is far greater for the Boore et al. (2014) GMPE than the simulated ground-motions with any of the considered κ_0 distributions (Figure 2). The simulated magnitude-dependencies of ϕ for PGA are likely stronger overall than from the considered empirical GMPEs because the functional forms of the considered GMPEs lack terms modeling variations in κ_0.

More varied results are observed for the magnitude-dependency of ϕ for SA(0.2 s) and SA(1 s) computed from the ground-motion simulations when compared to the considered heteroscedastic GMPEs than for PGA. For SA(0.2 s), the magnitude-dependency of ϕ computed from the simulated ground-motions is lower than for the Ambraseys et al. (2005) or Bommer et al. (2007) GMPEs, but lower than the Boore et al. (2014) GMPE, except over the magnitude interval M_w 4.5

- M_w 5.5, within which as for PGA and SA(1 s) it is far greater than ϕ computed from the simulated ground-motions. For SA(1 s), the magnitude-dependencies of ϕ computed from the ground-motion simulations can only be compared to the Boore et al. (2014) GMPE due to the other considered GMPEs lacking heteroscedastic ϕ for SA(1 s). Therefore, for SA(1 s), limited comparisons can be made with respect to the magnitude-dependency of ϕ computed from the ground-motion simulations and the considered GMPEs. As for PGA and SA(0.2 s), the magnitude-dependency of ϕ is far smaller for the Boore et al. (2014) GMPE than the magnitude-dependency of ϕ computed from the simulated ground-motions with any of the considered κ_0 distributions, except over the magnitude interval M_w 4.5 - M_w 5.5 when magnitude-dependency of ϕ is far greater for the Boore et al. (2014) GMPE. The magnitude-dependency of ϕ computed from the ground-motion simulations is overall more similar to the Boore et al. (2014) GMPE for SA(1 s) than for PGA or SA(0.2 s). This greater similarity for SA(1 s) can potentially be explained by κ_0 describing the decay of specifically high frequency ground-motions; if variations in κ_0 have a limited influence on longer period ground-motions, then such variations will likely not have as pronounced an effect for SA(1 s) as they do for PGA. This supports the reasoning above that the absence of terms which model variations in κ_0 within the considered GMPEs will result in more pronounced differences between the magnitude-dependencies of ϕ for PGA and SA(0.2 s) compared to SA(1 s).

Variations in κ_0 result in the magnitude-dependency of ϕ being marginally smaller for SA(0.2 s) than for SA(1 s). The magnitude-dependency of ϕ would be expected to be greater for SA(0.2 s) than for SA(1 s) because κ_0 describes the decay of high-frequency ground-motions. This could be explained by a trade-off between the influence of κ_0 and $\Delta\sigma$ on ϕ at moderate spectral periods, in which κ_0 has a stronger influence on ϕ at smaller spectral periods and $\Delta\sigma$ has a stronger influence on ϕ at larger spectral periods. The presence of such a trade-off is potentially supported by the observations that (1) as the spectral period increases, the magnitude at which peak magnitude-dependency ϕ for a fixed κ_0 and a $\Delta\sigma$ distribution sampled from Bora et al. (2017) increases and (2) for SA(0.2 s), the peak magnitude-dependency of ϕ computed with a non-fixed κ_0 occurs at a greater magnitude than for either PGA or SA(1 s) whilst also being smaller than for either PGA or SA(1 s).

The magnitude-dependency of ϕ for PGA due solely to variation in κ_0 being far stronger than the magnitude-dependency observed within the considered GMPEs (regardless of whether they have heteroscedastic or homoscedastic ϕ) suggests: (1) future empirical GMPEs should include terms to model variation in κ_0 [there are some recent models in this direction (Laurendeau et al., 2013; Hassani and Atkinson, 2018)] and (2) that empirical GMPEs with homoscedastic ϕ are inadequate for regions with high variability in κ_0 because high variability in κ_0 results in strong magnitude-dependency of ϕ particularly at short periods (Figure 2).

It should be acknowledged that there is potential for a circular argument associated with the sampled distributions for both κ_0 and $\Delta\sigma$ used within the ground-motion simulations. The sampled distributions have been developed based on models fit to data. These models are then used to examine the influence of κ_0 and $\Delta\sigma$ on the magnitude-dependency of ϕ. If these distributions have been well modeled (i.e. $\Delta\sigma$), then a minimal impact on the magnitude-dependency is observed, whereas if the distribution has been less well modelled (i.e. κ_0) a considerably greater influence on magnitude-dependency could be observed. However, the observations resulting from variation in κ_0 are reasonably well explained. This suggests that κ_0 is sufficiently modelled for examining its influence upon the magnitude-dependency of ϕ despite the larger uncertainty generally associated with the modelling of κ_0 compared to $\Delta\sigma$.

Conclusions

In this short article, the hypothesis that variations in κ_0, modeling high-frequency attenuation, amongst sites could be a least partly responsible for the magnitude-dependency in within-event variabilities in some ground-motion models is examined. To examine this hypothesis a series of ground-motion simulations using the stochastic method were conducted using various distributions of the key input parameters. Despite the variabilities computed from the simulated ground-motions being higher than those in the considered ground-motion models and the magnitude-dependency being stronger, this study lends support to the hypothesis that κ_0 is a contributing factor to the magnitude-dependent variability of earthquake ground motions, particularly for short-period response spectral accelerations. The mismatch between the variabilities from the simulations and the empirical ground-motion models suggests that there are unmodelled correlations between the key input parameters that lead to reduced variabilities in observed ground motions. This study highlights once again the importance of accounting for variations in κ_0 within ground-motion predictions, including when using empirical ground-motion models.

Data and Resources

All data generated in the simulations undertaken in this paper used information from published sources listed in the references.

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Table 1 *Parameters of the Bora et al. (2017) stochastic model for Europe and the considered k_0 distributions.*

Parameter	**Estimate of Parameter**
Source Spectrum Model	Brune Point Source
Stress Drop ($\Delta\sigma$)	Mean = 5.65 MPa, Standard Deviation = log(0.33)
Geometric Spreading	$R^{-1.14}$ $for\ R \leq 70\ km$ $R^{-0.50}$ $for\ R\ > 70\ km$
Anelastic Attenuation (Q_0)	$610\ for\ R \leq 40\ km$ $1152\ for\ R\ > 40\ km$
Near-Source Shear Wave Velocity (β)	3500 m/s
Near-Source Density (p)	2800 kg/m^3
Sampled κ_0 Distributions*	B17: 0.0341 s, standard deviation 0.024 s (Bora et al., 2017 - k_0 model for Europe) C06: 0.0636 s, standard deviation 0.022 s (Chandler et al., 2006 - k_0 model for global application) E11: 0.0218 s, standard deviation 0.020 s (Edwards et al., 2011 – k_0 for foreland Switzerland)
Site V_{s30}	620 m/s

*The provided means and standard deviations are those for the sampled k_0 values used within the ground-motion simulations, rather than the published means and standard deviations of the considered k_0 distributions.

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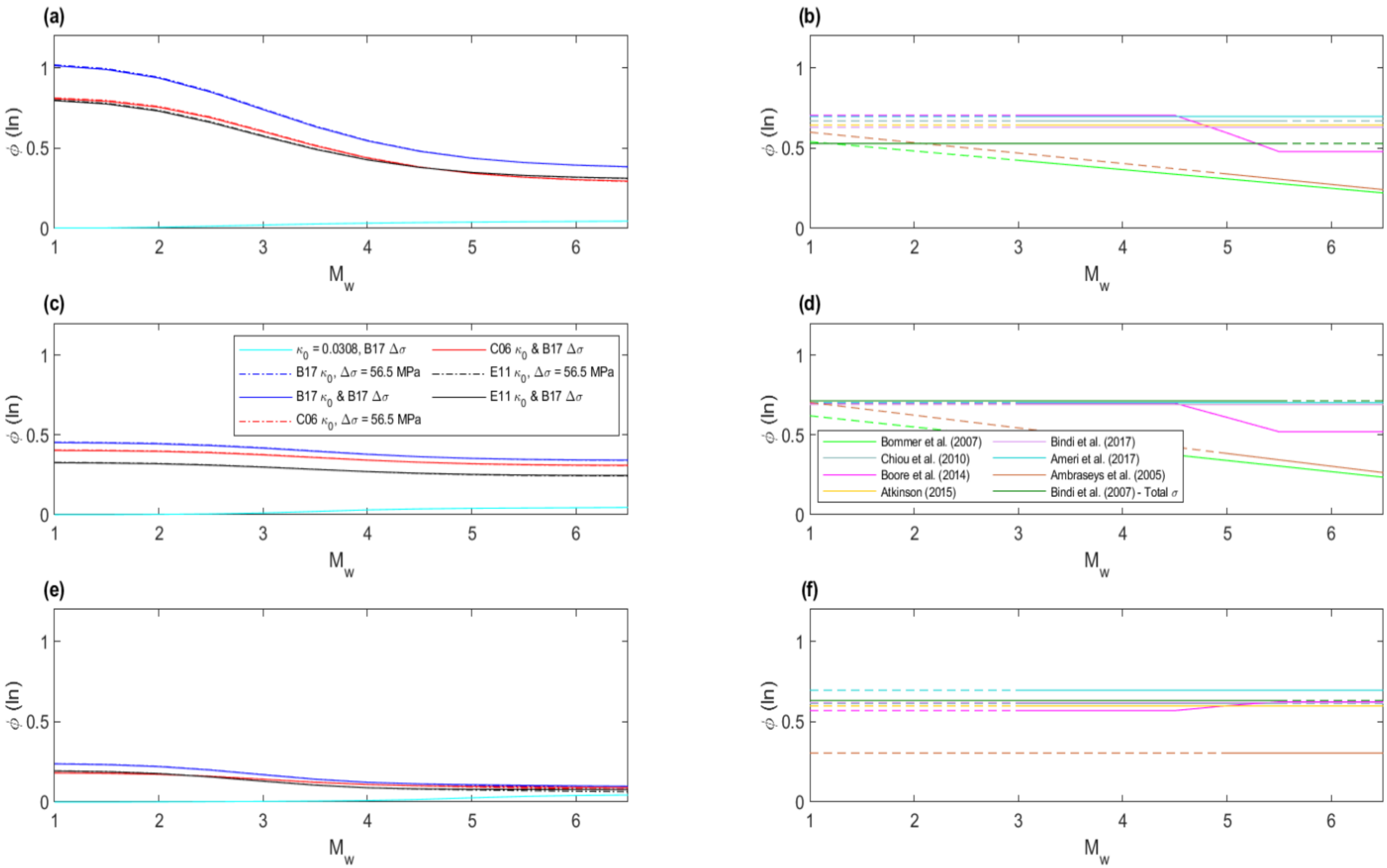
Figure 1 *(a) ϕ for PGA from the simulated ground-motions, (b) ϕ for PGA from the considered GMPEs, (c) ϕ for SA(0.2 s) from the simulated ground-motions, (d) ϕ for SA(0.2 s) from the considered GMPEs, (e) ϕ for SA(1 s) from the simulated ground-motions and (f) ϕ for SA(1 s) from the considered GMPEs*. B17 = Bora et al. (2017), C06 = Chandler et al. (2006) and E11 = Edwards et al. (2011). Dashed lines indicate extrapolation of GMPE standard deviation beyond the model's magnitude range.

Figure 2 *(a) Rate of change of ϕ with respect to magnitude for PGA, (b) rate of change of ϕ with respect to magnitude for SA(0.2 s) and (c) rate of change of ϕ with respect to magnitude for SA(1 s).* B17 = Bora et al. (2017), C06 = Chandler et al. (2006) and E11 = Edwards et al. (2011). Dashed lines indicate extrapolation of GMPE standard deviation beyond the model's magnitude range of applicability. The considered GMPEs with homoscedastic ϕ were not plotted. The Ameri et al. (2017) GMPE was not plotted due to only τ being heteroscedastic with respect to magnitude.



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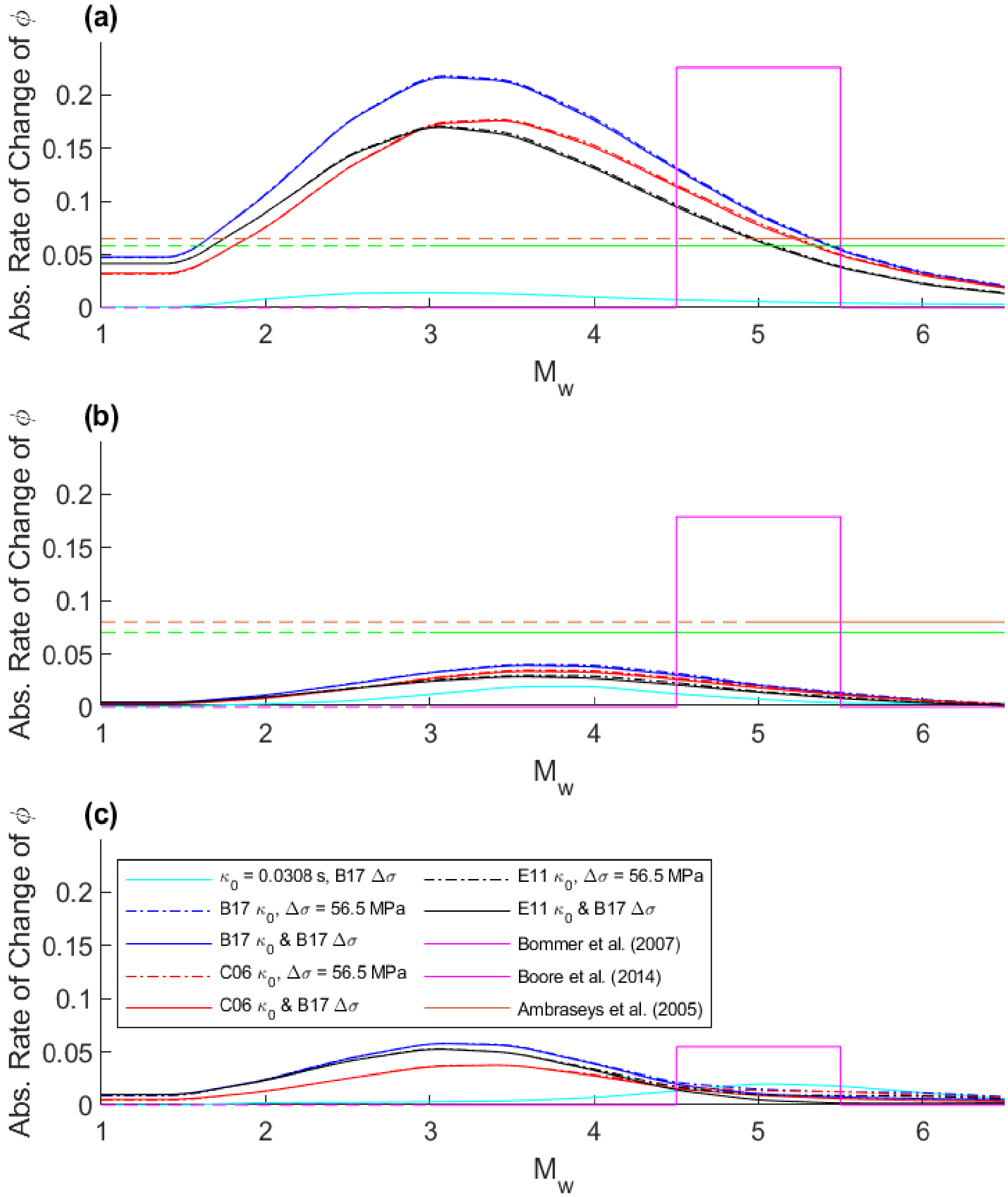

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