PACIFIC EARTHQUAKE ENGINEERING
RESEARCH CENTER

Epistemic Uncertainty for NGA-West2 Models

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ABSTRACT

Probabilistic seismic hazard studies typically address the epistemic uncertainty in ground motion estimation by using a weighted set of alternative ground motion models. This approach relies on the assumption that the alternative models are developed independently, and the resulting range of model predictions adequately captures the epistemic uncertainty in ground motion estimation. The development of the NGA-West2 ground motion prediction equations (GMPEs) is a collaborative effort with many interactions and exchange of ideas among the developers. Despite the fact that the NGA-West2 models have different functional forms and use different subsets of the available empirical data, the high degree of interaction indicates that the models are not independent. The NGA developers all agree that an additional epistemic uncertainty needs to be incorporated into the median ground motion estimation from these models.

In this report, we present an approach for estimating the minimum epistemic uncertainty in the median NGA-West2 GMPEs based on model-to-model differences and the uncertainty in the median predictions of each GMPE. Results of the model-to-model and within-model uncertainty for the 5 NGA-West2 GMPEs are presented. A model is proposed to incorporate a minimum epistemic uncertainty in the median of individual NGA-West2 GMPEs.

ACKNOWLEDGMENTS

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1 Introduction

In the current practice of probabilistic seismic hazard analysis (PSHA), logic trees are the standard tool used for capturing and representing the epistemic uncertainty in each element of the models for seismic sources and ground motion prediction. Construction of a logic tree usually involves populating the branches with alternative models or parameter values and then assigning weights to them. The final distribution represented by the logic tree must capture both the best estimates of what is known and the potential range of alternatives in light of what is currently not known.

The development of the NGA-West2 models is a collaborative effort with many interactions and exchange of ideas among the developers. Despite the fact that the NGA-West2 models have different functional forms and use different subsets of the available empirical data, their use as a set of weighted alternative ground motion models in logic trees underestimates the epistemic uncertainty needed to represent the potential range of alternative GMPEs. As part of the NGA-West1 project, the GMPE developers recommended that additional epistemic uncertainty be incorporated into median ground motion estimation when applying the NGA-West1 model set. Bob Youngs estimated this additional epistemic uncertainty in BC Hydro, Inc., [2012] based on the statistics of the model fit and the empirical data distribution of the Chiou and Youngs [2008] GMPE for the rupture geometries shown in Figure 1.1. A simple model of constant epistemic uncertainty of the median of 0.15 natural log units was assigned to each of the NGA-West1 models in hazard analysis for periods of 0.01 to 1.0 sec. This uncertainty was increased to 0.2 for periods of 2.0 to 3.0 sec and 0.3 for periods of 5.0 sec and longer. The recommended epistemic uncertainty in the median NGA-West1 models was represented by a three-point discrete approximation to a normal distribution with the branches and the weights shown in Figure 1.2.

Similarly to the work done for the 2008 NGA models, we estimate the minimum additional epistemic uncertainty to be added to the NGA-West2 GMPE set by first evaluating the model-to-model differences in the median predictions of the 5 models: Abrahamson et al. [2013] (ASK13), Boore et al. [2013] (BSSA13), Campbell and Bozorgnia [2013] (CB13), Chiou and Youngs [2013] (CY13), and Idriss [2013] (Id13). The uncertainty in the median prediction of each GMPE is then calculated statistically based on the model fit and the data distribution while taking into account the imposed model constraints. The model-to-model differences are compared to the uncertainty in the median prediction of each GMPE and an epistemic uncertainty model is proposed for use with the set of 5 NGA-West2 models. The rupture geometries used to compute the ground motion estimates and the resulting epistemic uncertainty for the NGA-West2 models are shown in Figure 1.3. The analysis is performed for V_{S30} of 760 m/sec similar to the shear wave velocity used in the 2008 study.

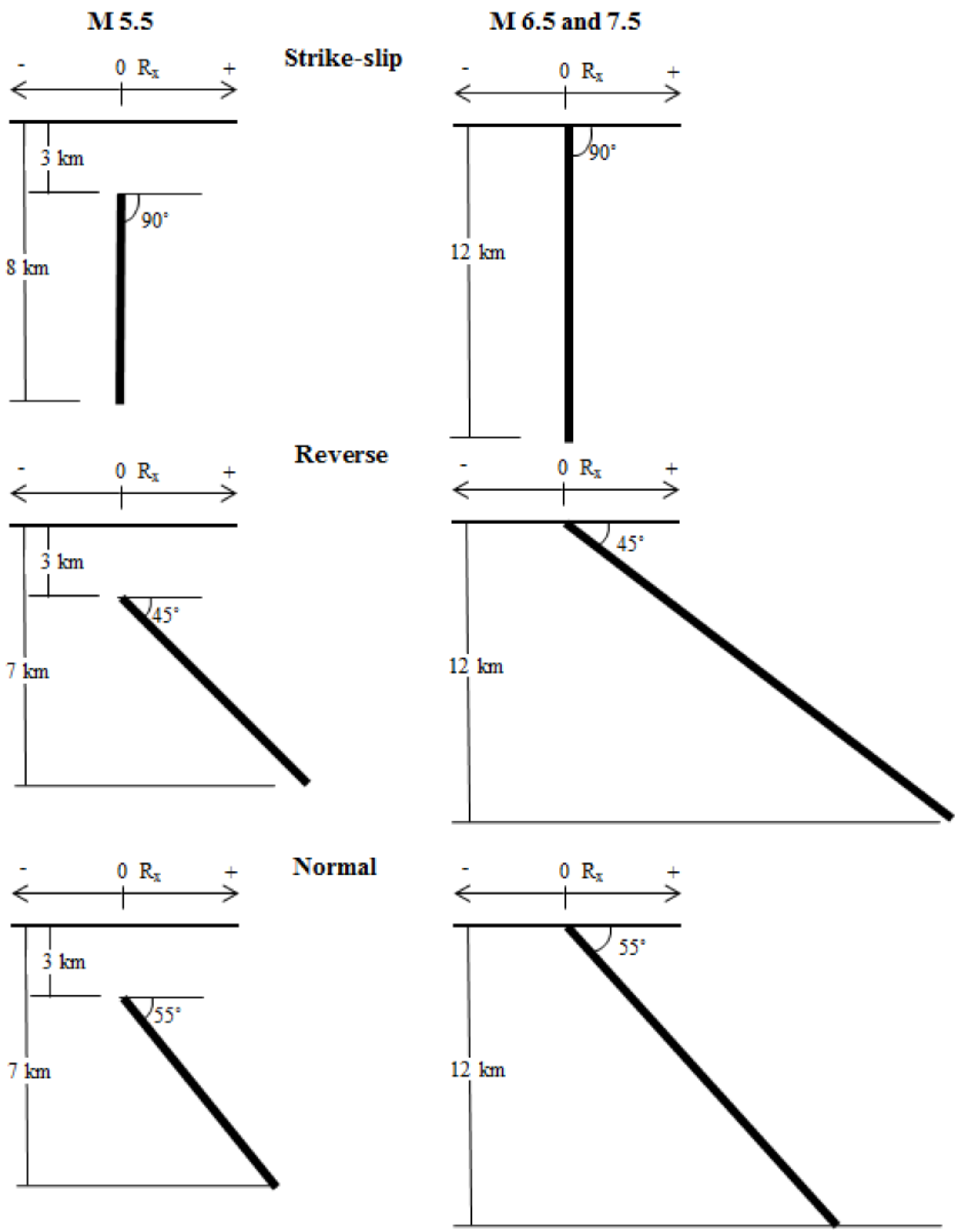


Figure 1.1 **Rupture geometries used for calculating the median predictions and evaluating the epistemic uncertainty for NGA-West1 GMPEs [BC Hydro, Inc., 2012].**

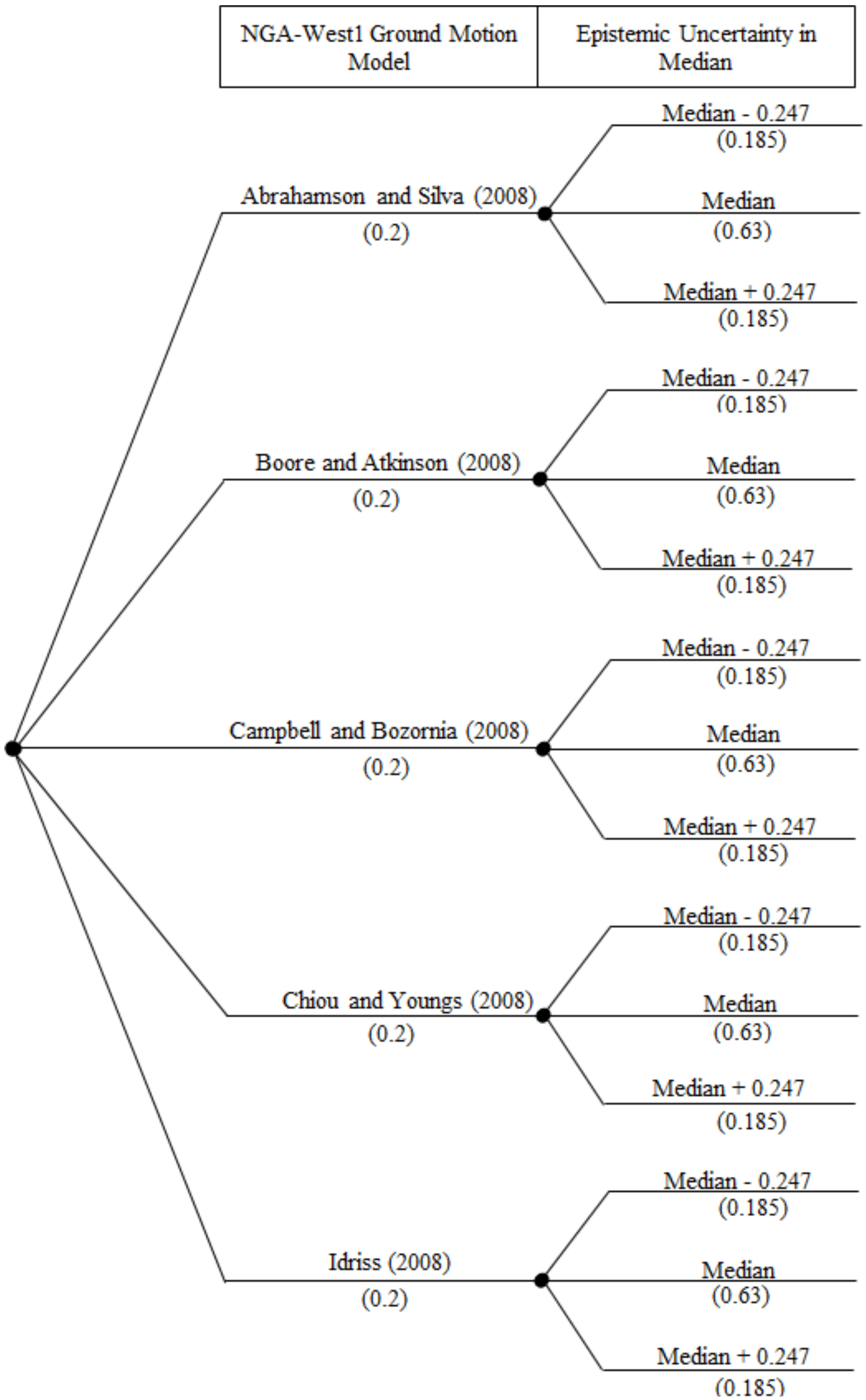


Figure 1.2 Logic tree for NGA-West1 models [BC Hydro, Inc., 2012].

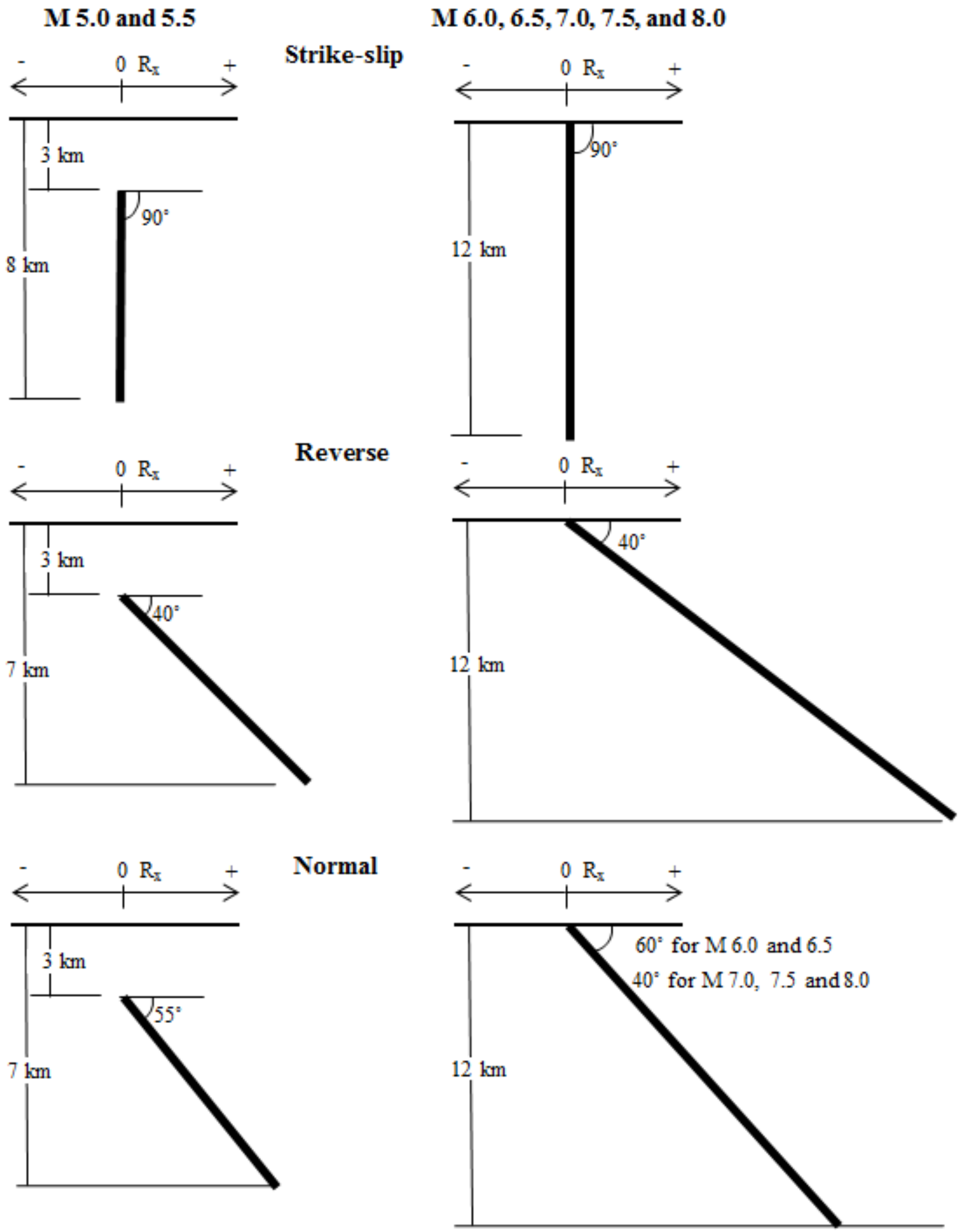


Figure 1.3 **Rupture geometries used for calculating the median predictions and evaluating the epistemic uncertainty for NGA-West2 GMPEs.**

2 Variability among NGA-West2 Models

The model-to-model variability in the median predictions of the NGA-West2 GMPEs is estimated in terms of the standard deviation in the natural logarithm of the predicted median ground motion and is termed $\sigma_{\mu \ln(SA)}$. It is calculated as:

$$\sigma_{\mu \ln(psa)} = \sqrt{\frac{\sum_i w_i \left[\mu_{\ln(psa)_i} - \overline{\mu_{\ln(psa)}} \right]^2}{\sum_i w_i}} \tag{2.1}$$

with

$$\overline{\mu_{\ln(psa)}} = \frac{\sum_i w_i \mu_{\ln(psa)_i}}{\sum_i w_i} \tag{2.2}$$

where $\mu_{\ln(psa)_i}$ is the natural logarithm of the median ground motion predicted by the i^{th} GMPE and w_i is the probability weight assigned for the i^{th} model. Assigning equal weights to the NGA-West2 models, Figures 2.1 through 2.6 show the variability among the NGA-West2 median predictions for the rupture geometries given in Figure 1.3 with magnitudes 5.5, 6.5, and 7.5 at peak ground acceleration (PGA) and spectral periods of 0.03, 0.05, 0.10, 0.20, 0.30, 0.50, 1.0, 2.0. 3.0, 5.0, and 10.0 sec. Model-to-model variability is evaluated for a range of horizontal distances from the top of rupture measured perpendicular to fault strike (R_x) of 1 to 300 km on the hanging wall.

Figures 2.1 to 2.6 show that the variability for dip slipping earthquakes is generally larger than that for strike-slip events reflecting the smaller dataset available for dipping faults and the different treatment of ground motion on hanging wall among the NGA-West2 models. Similarly, the variability for normal faulting is slightly larger than that of reverse faulting. Figures 2.1–2.6 show that the variability in median predictions of the 5 NGA-West2 models increases at long spectral periods.

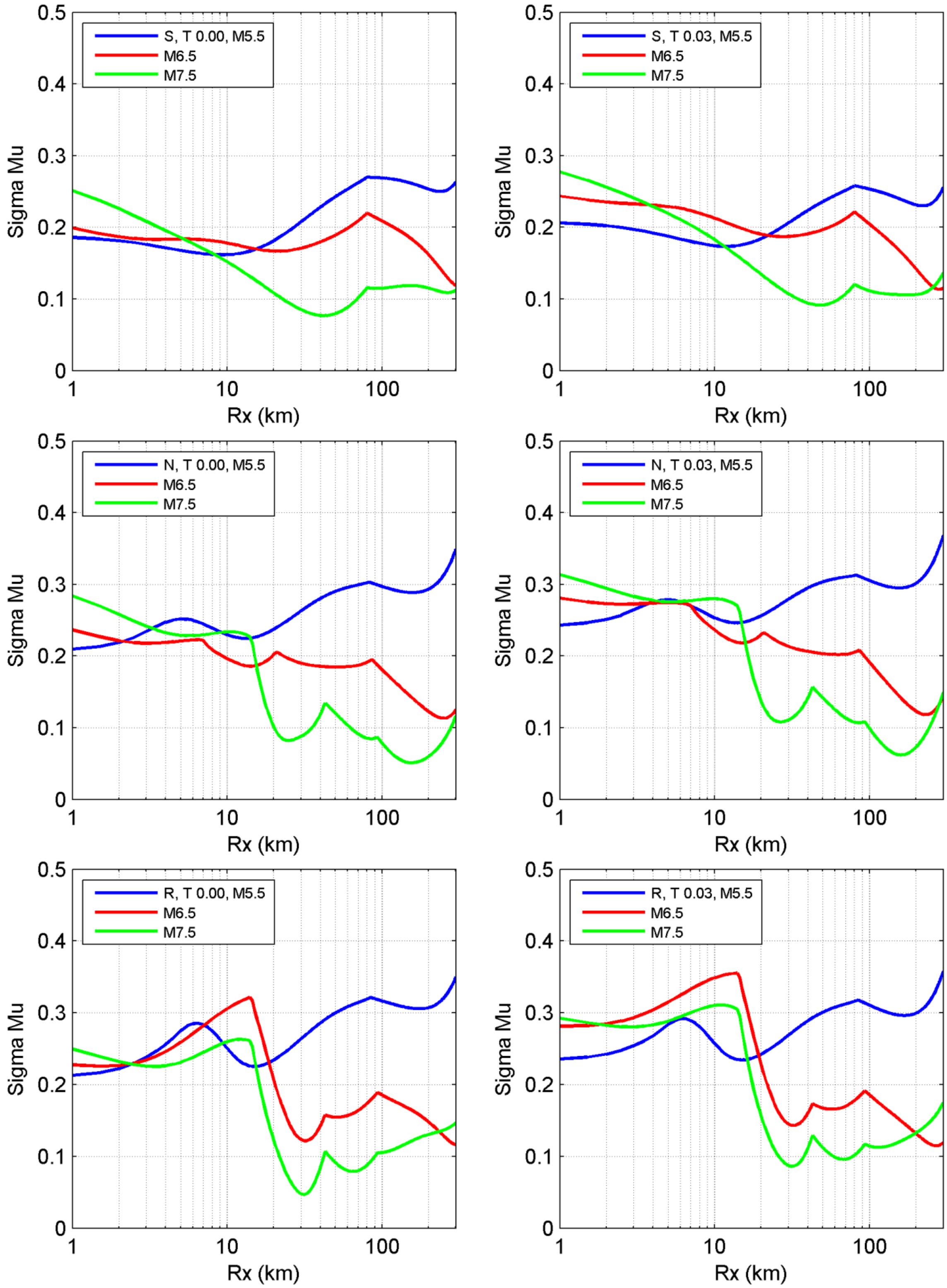


Figure 2.1 **Variability among the median ground motion estimates of the NGA-West2 models at PGA and spectral period of 0.03 sec for the rupture scenarios shown in Figure 1.3.**

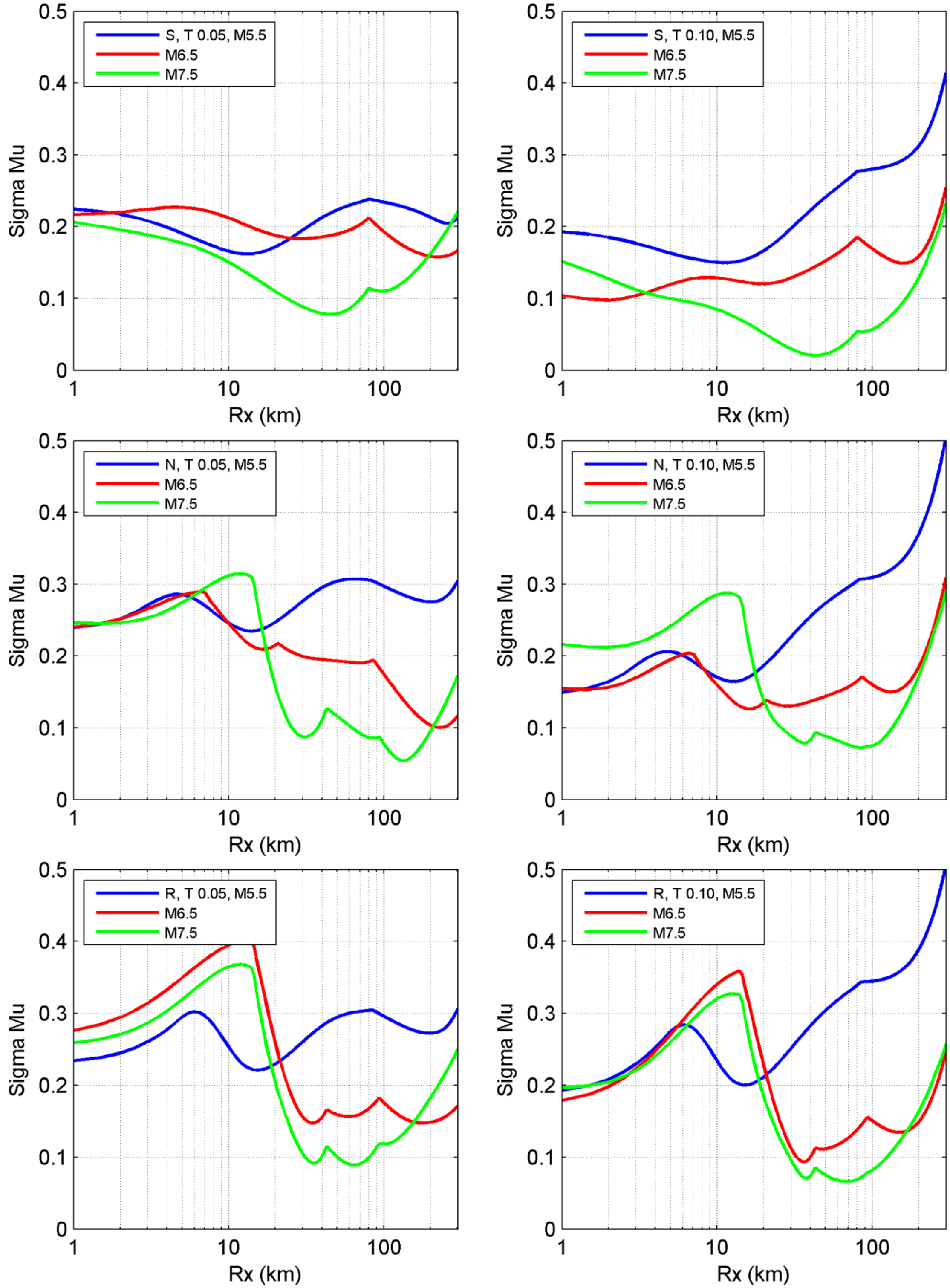


Figure 2.2 **Variability among the median ground motion estimates of the NGA-West2 models at spectral periods of 0.05 and 0.10 sec for the rupture scenarios shown in Figure 1.3.**

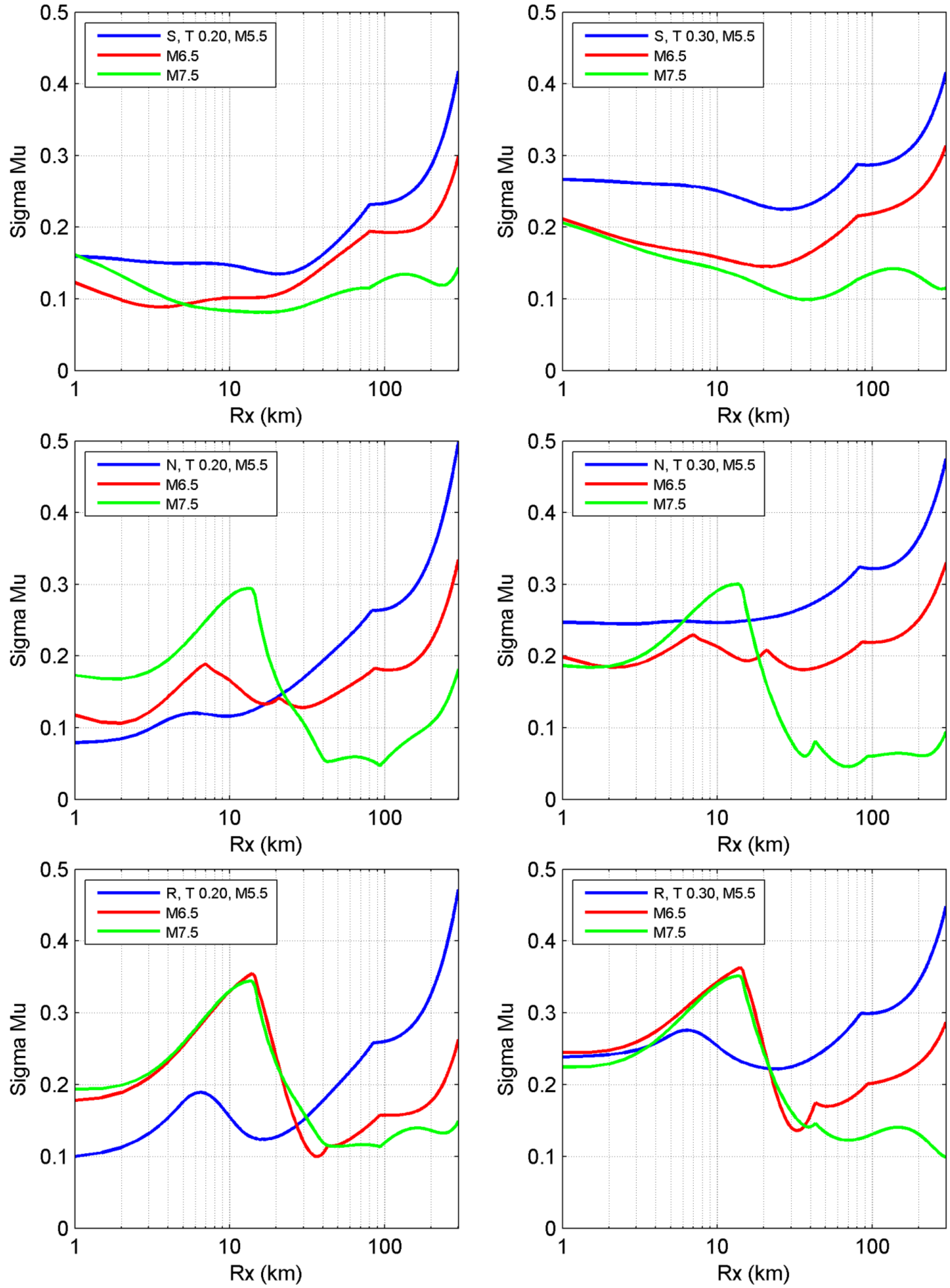


Figure 2.3 **Variability among the median ground motion estimates of the NGA-West2 models at spectral periods of 0.20 and 0.30 sec for the rupture scenarios shown in Figure 1.3.**

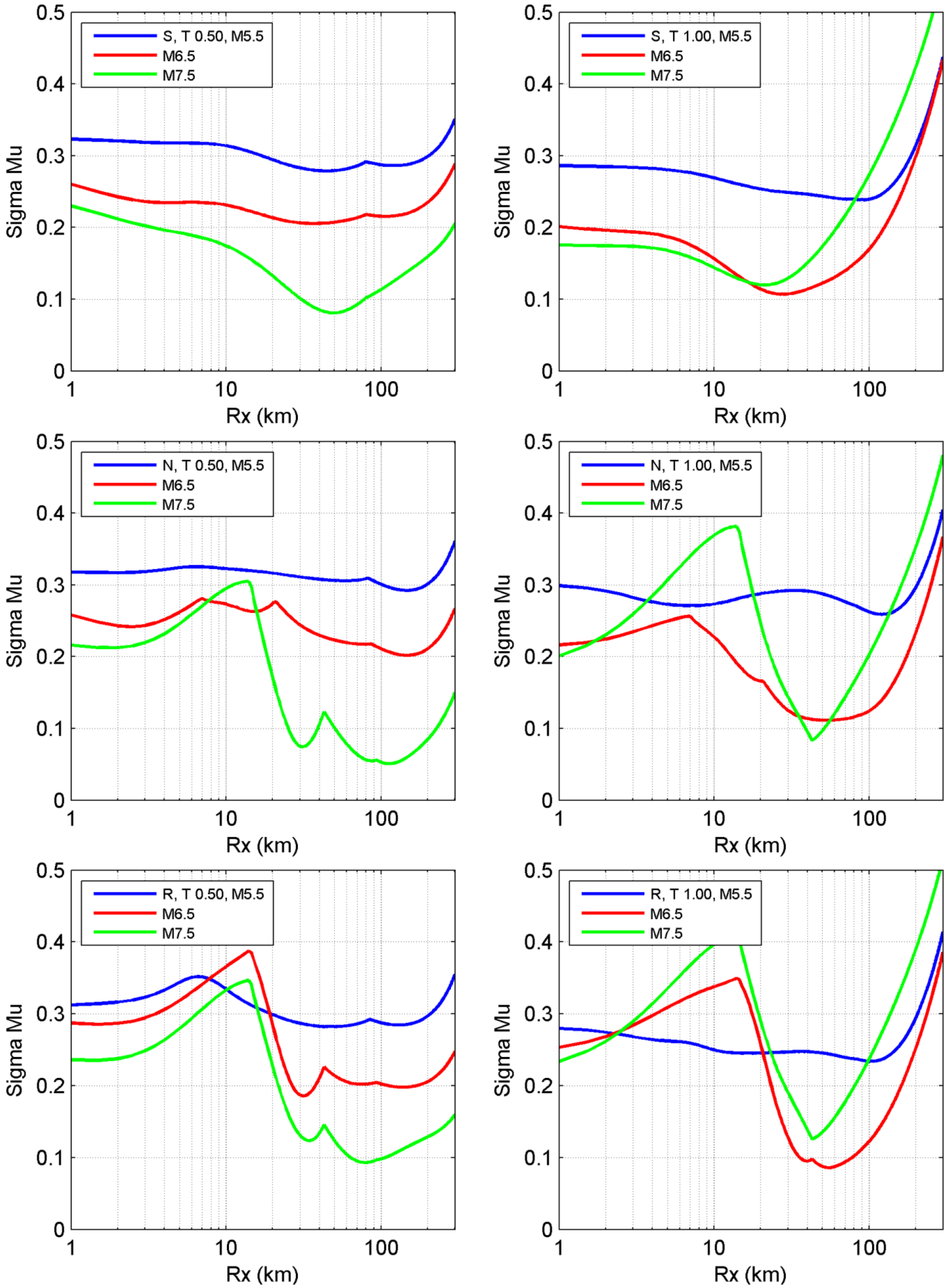


Figure 2.4 **Variability among the median ground motion estimates of the NGA-West2 models at spectral periods of 0.50 and 1.0 sec for the rupture scenarios shown in Figure 1.3.**

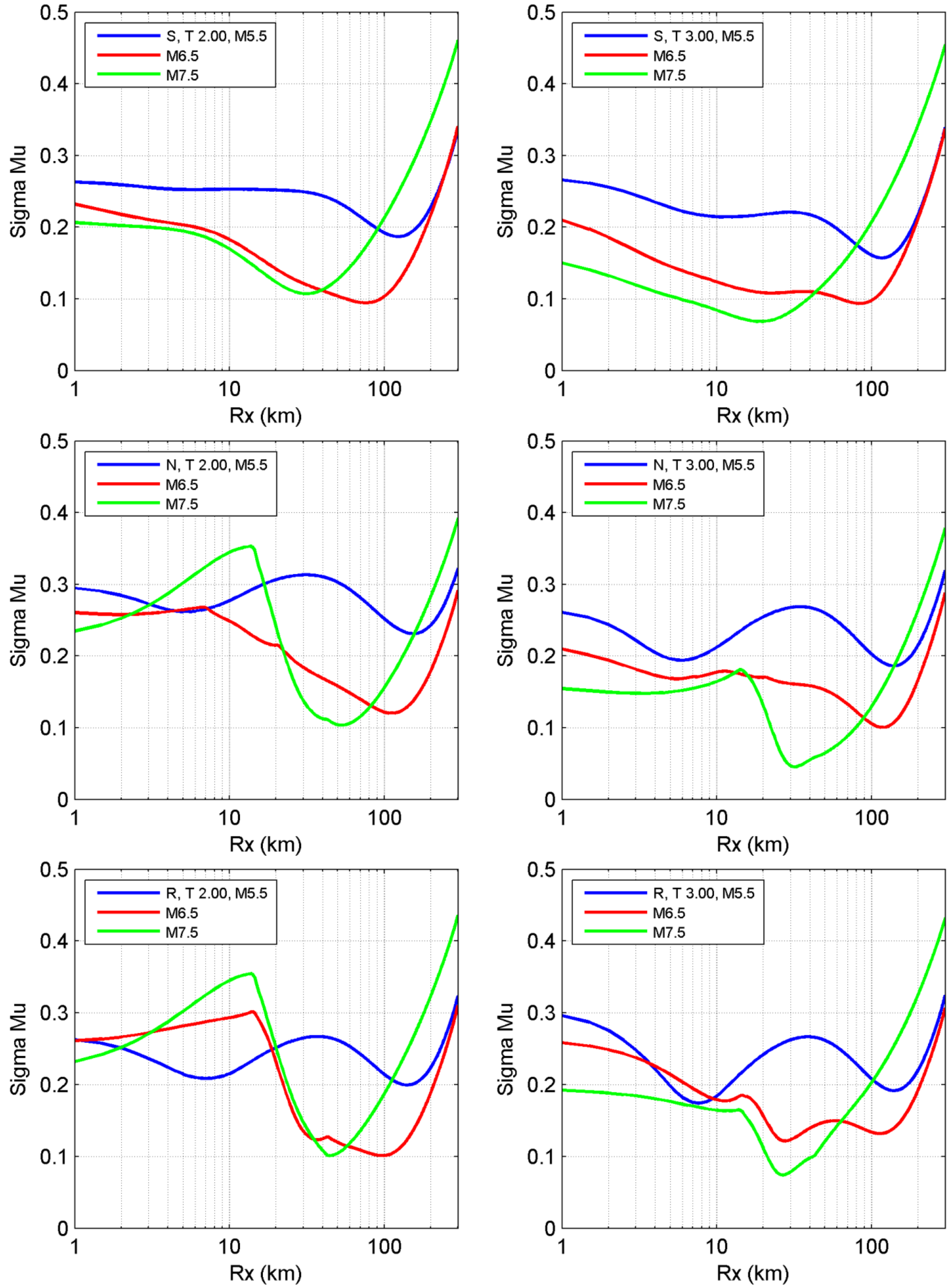


Figure 2.5 Variability among the median ground motion estimates of the NGA-West2 models at spectral periods of 2.0 and 3.0 sec for the rupture scenarios shown in Figure 1.3.

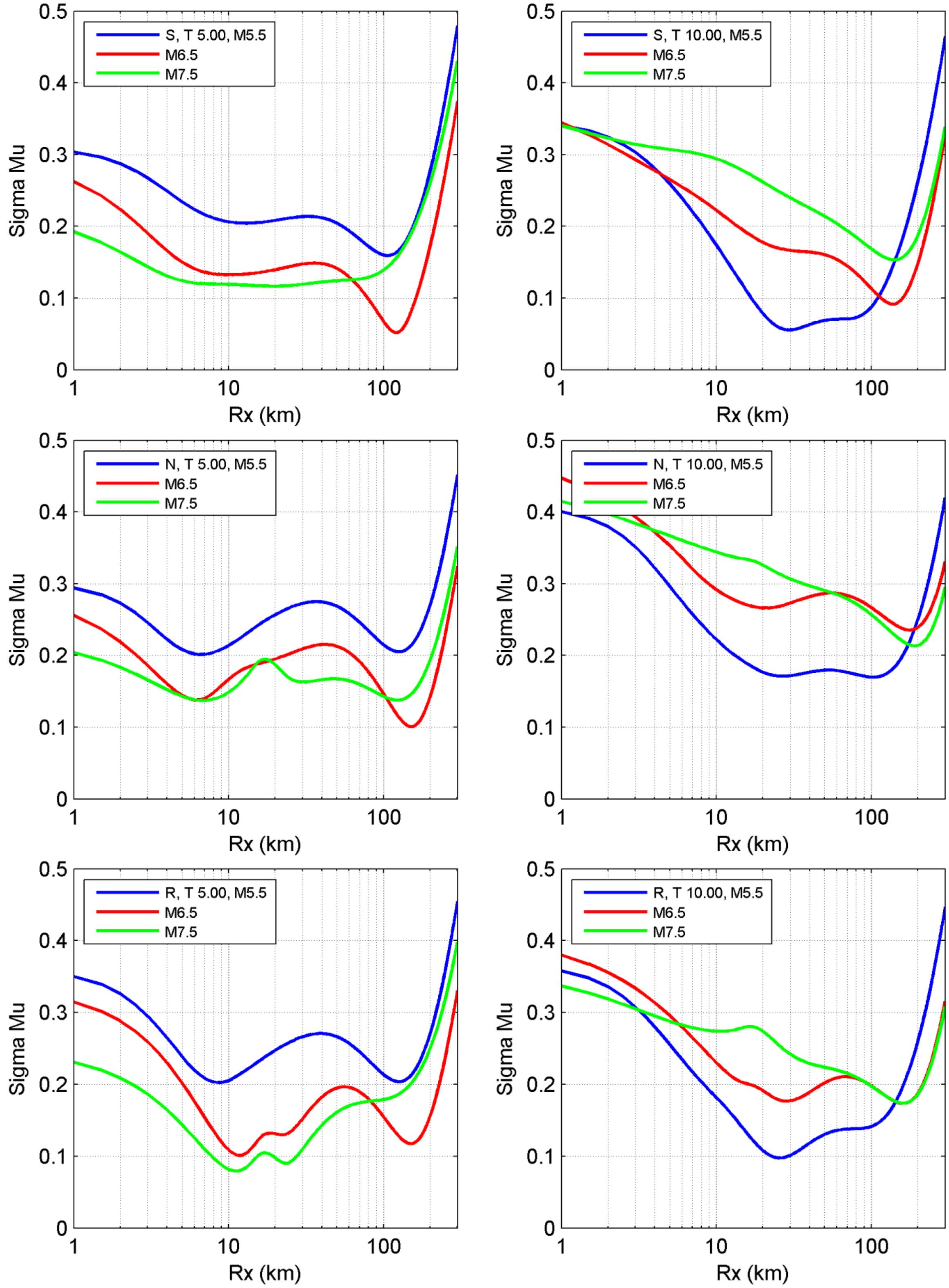


Figure 2.6 Variability among the median ground motion estimates of the NGA-West2 models at spectral periods of 5.0 and 10.0 sec for the rupture scenarios shown in Figure 1.3.

3 Epistemic Uncertainty in Single NGA-West2 Models

The uncertainty in the median prediction of each of the 5 NGA-West2 models can be evaluated based on the statistics of the model fit and the empirical data distribution used for the model. This approach, which was applied in BC Hydro, Inc., [2012], evaluates how well the empirical data constrains each model while incorporating the additional constraints imposed on the model. The asymptotic standard error of median prediction for each model is approximated by:

$$\sigma^2_{\overline{\ln(y)}|x_0} = \mathbf{f}^T \left[\mathbf{F}^T \mathbf{V}^{-1} \mathbf{F}\right]^{-1} \mathbf{f} \tag{3.1}$$

where

$$\mathbf{F} = \left.\frac{\partial \overline{\ln(y)}}{\partial \mathbf{C}}\right|_{\mathbf{x}_i} \tag{3.2}$$

and

$$\mathbf{f} = \left.\frac{\partial \overline{\ln(y)}}{\partial \mathbf{C}}\right|_{\mathbf{x}_0} \tag{3.2}$$

F is a matrix of the gradient of the median ground motion model with respect to the model coefficients **C** evaluated at the data points used in the model development, $\mathbf{x_i}$; **V** is the block diagonal variance matrix of the data used in the model development, $\mathbf{x_i}$; and **f** is a matrix of the gradient of the median ground motion model with respect to the model coefficients **C** evaluated at a specific set of predictor variables, $\mathbf{x_o}$.

The uncertainty in the median prediction of each of the 5 NGA-West2 models is evaluated for the scenarios shown in Figure 1.3 on the hanging wall and for V_{S30} of 760 m/sec. The set of coefficients that are considered fixed (constrained) in each model are presented in Table 3.1. These coefficients were not determined from the regression analysis but obtained from simulations (ex., hanging wall simulations) or pre-selected by the model developers. Figures 3.1–3.6 show the within-model uncertainty in median prediction of each of the 5 NGA-West2 models compared to the model-to-model variability for the strike-slip rupture scenarios in Figure 1.3 for magnitude 5.5, 6.5, and 7.5 at PGA and spectral periods of 0.03, 0.05, 0.10, 0.20, 0.30, 0.50, 1.0, 2.0, 3.0, 5.0, and 10.0 sec. Figures 3.7–3.12 and Figures 3.13–3.18 show the within-model uncertainty and the model-to-model variability for the reverse and normal scenarios of Figure 1.3, respectively.

Figures 3.1–3.18 show that the asymptotic standard error in median prediction of all 5 NGA-West2 models is larger for normal faults on the hanging wall than for strike slip and reverse faults due to the smaller number of normal events in the NGA-West2 database. Similarly, the within-model uncertainty is larger for the magnitude 7.5 scenarios due to the limited number of earthquakes with magnitude 7 to 8 in the NGA-West2 database. These figures also show that the mode-to-model variability for strike-slip, reverse, and normal earthquakes is generally larger than the asymptotic standard errors in the median predictions of the GMPEs. The within-model uncertainty is different for each of the 5 GMPEs for the same scenario reflecting differences in subsets of the NGA-West2 database used, functional forms and model constraints among the GMPEs. While all the models show some distance dependence in the within-model uncertainty, CY13 has the strongest distance dependence particularly for dipping faults and larger magnitudes with larger uncertainty at close distances. The within-model uncertainty in median predictions of the GMPEs rapidly increases at distances larger than 200 km. This behavior is also reflected in the model-to-model variability.

Table 3.1 Fixed coefficients in NGA West-2 Models.

Model	Fixed Coefficients
ASK13	Vlin, b, n, c, M1, M2
BSSA13	Mh, Mref, Rref, Vref, Vc, e0
CB13	k1, k2, k3, n, c, a2, h1, h2, h3, h4, h5, h6
CY13	c2, c4, c4a, c9, cRB, cHM, phi7, phi8
Id13	None

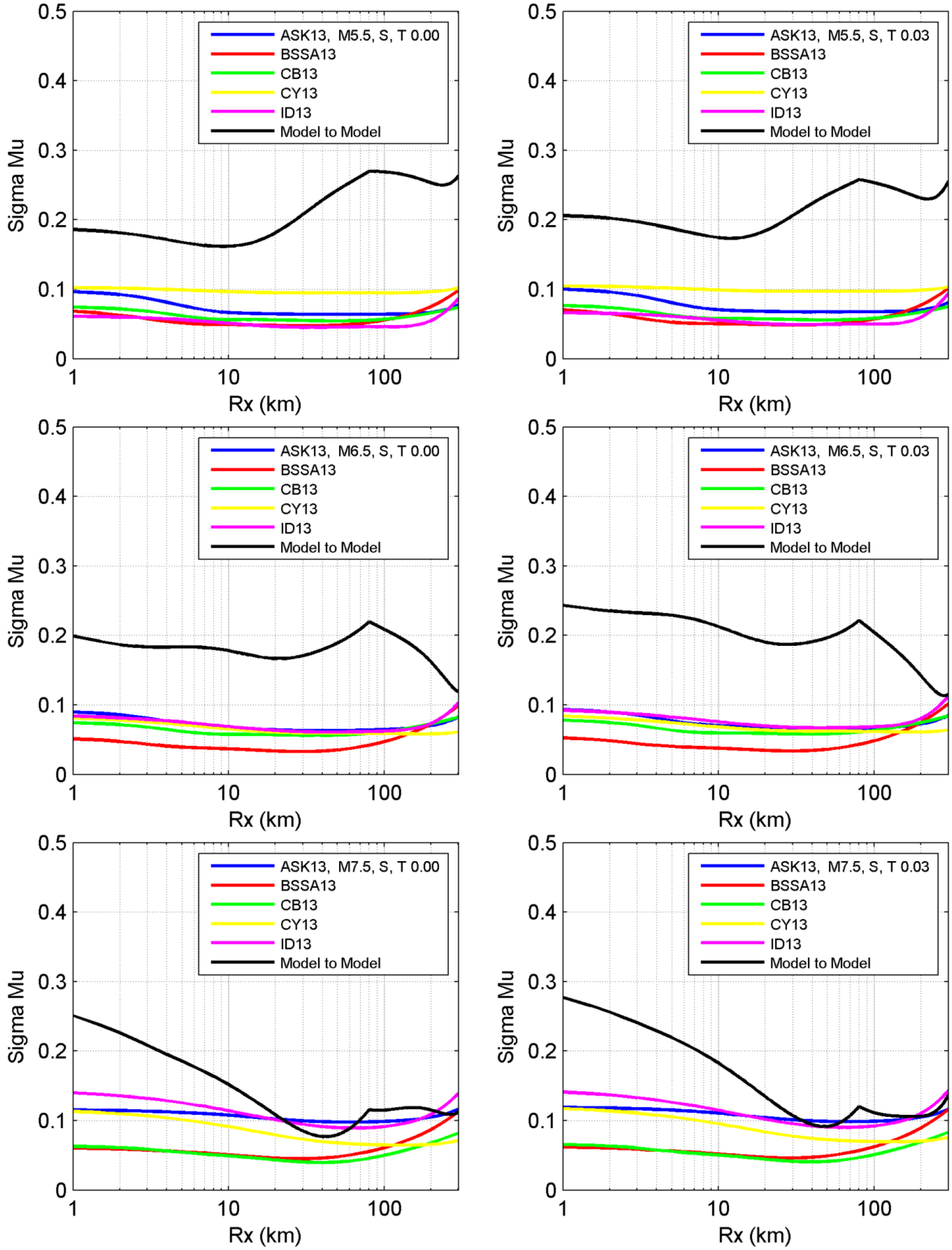


Figure 3.1 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the strike-slip rupture scenarios shown in Figure 1.3 at PGA and spectral period of 0.03 sec.**

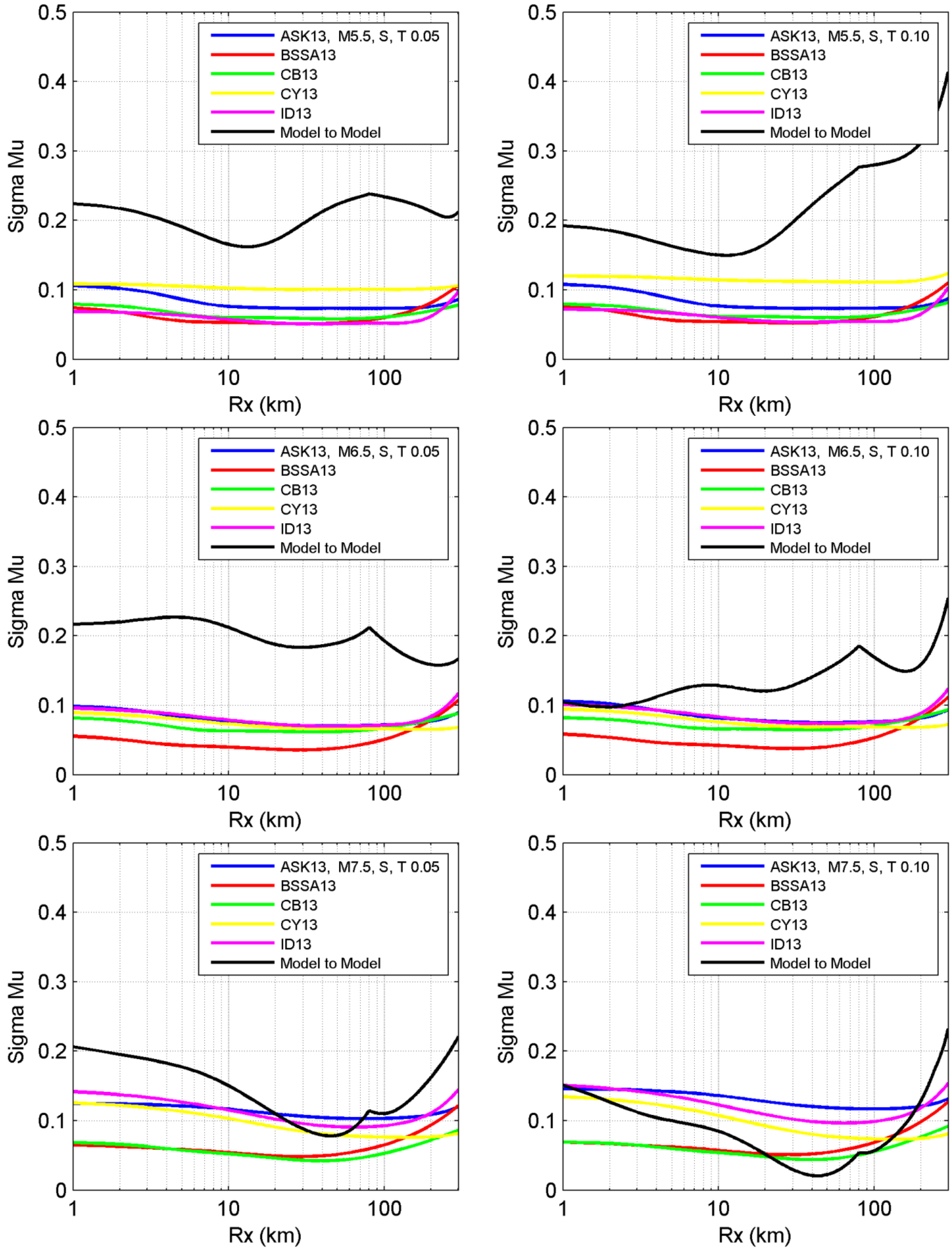
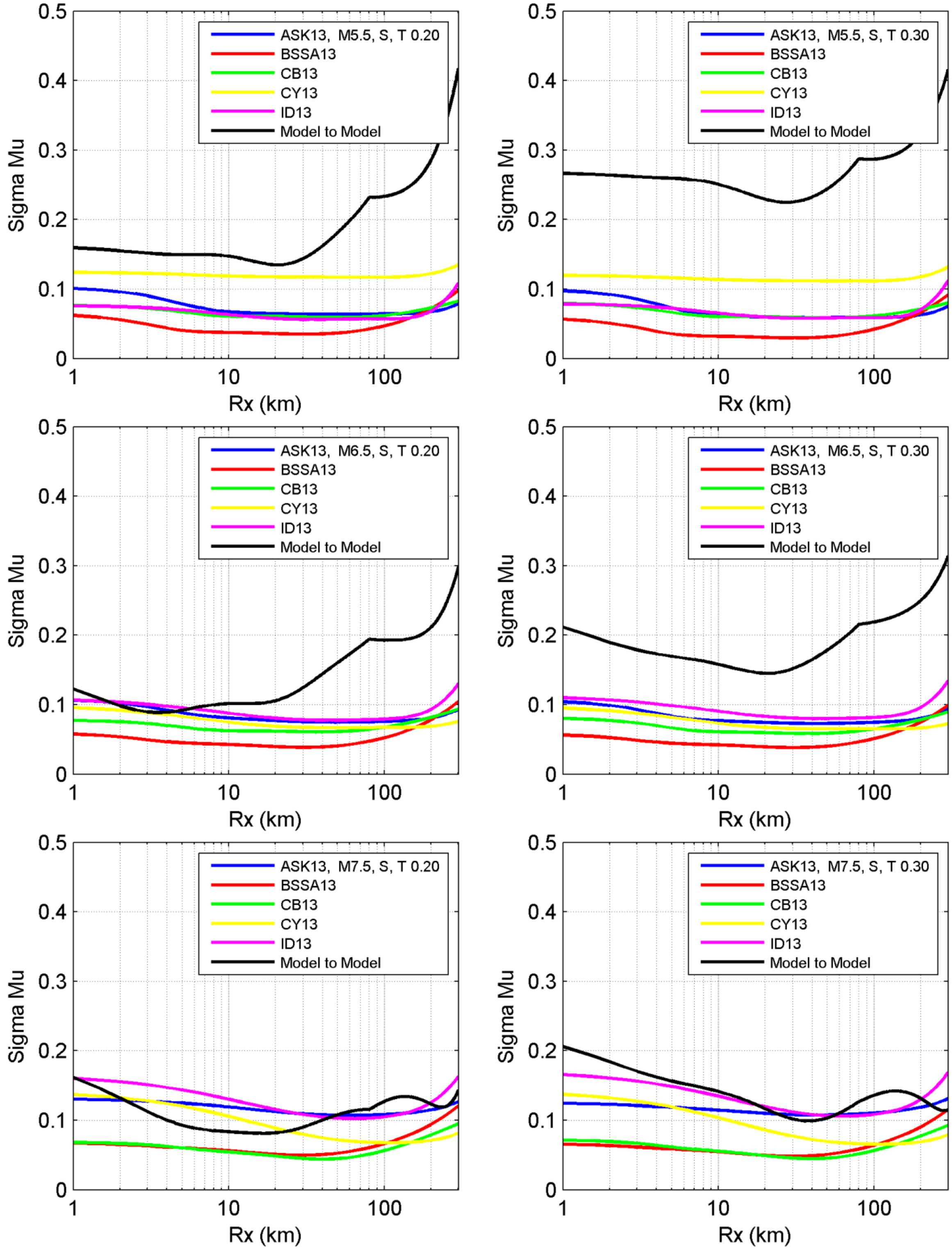


Figure 3.2 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the strike-slip rupture scenarios shown in Figure 1.3 at spectral periods of 0.05 and 0.10 sec.**



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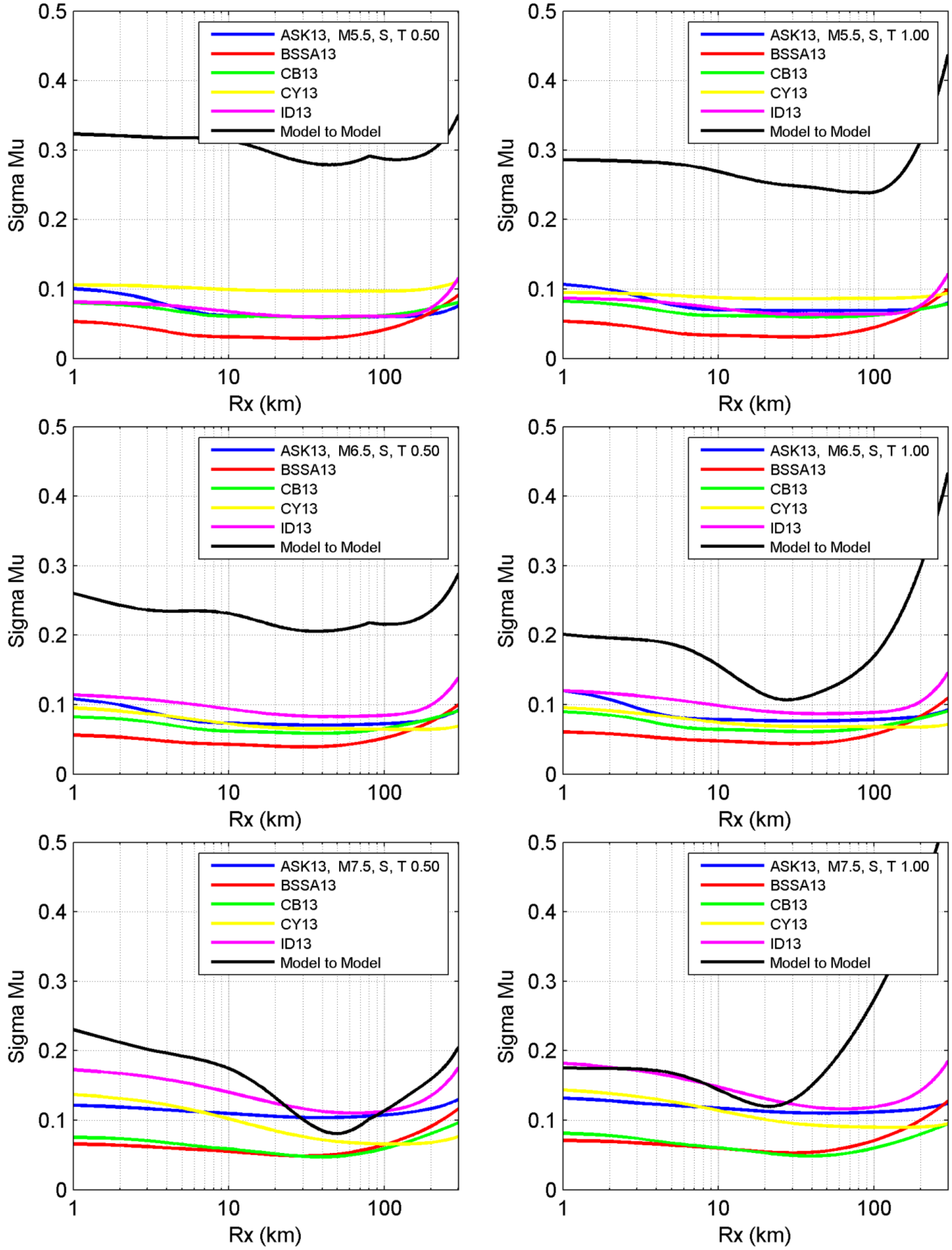


Figure 3.4 Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the strike-slip rupture scenarios shown in Figure 1.3 at spectral periods of 0.50 and 1.0 sec.

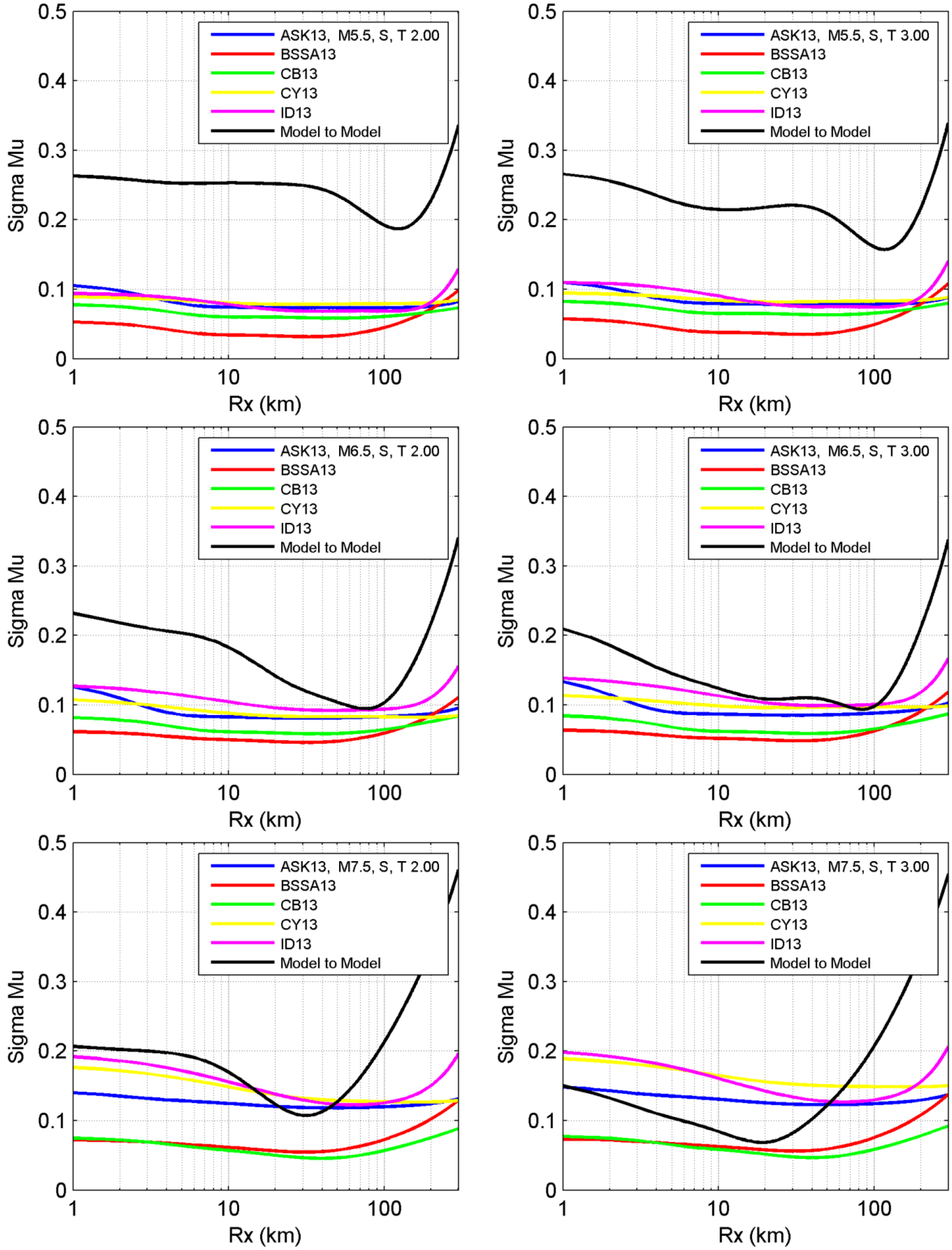


Figure 3.5 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the strike-slip rupture scenarios shown in Figure 1.3 at spectral periods of 2.0 and 3.0 sec.**

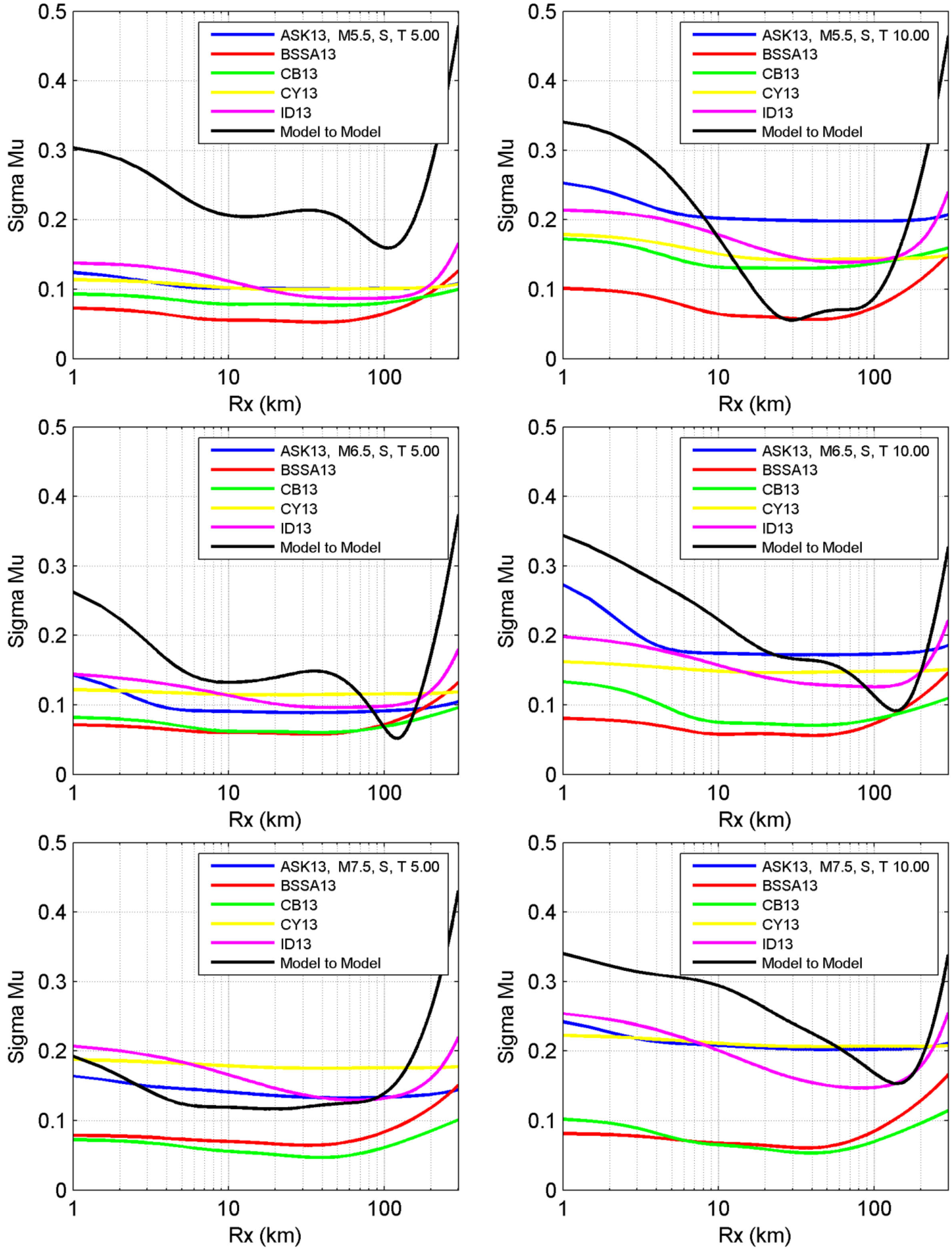


Figure 3.6 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the strike-slip rupture scenarios shown in Figure 1.3 at spectral periods of 5.0 and 10.0 sec.**

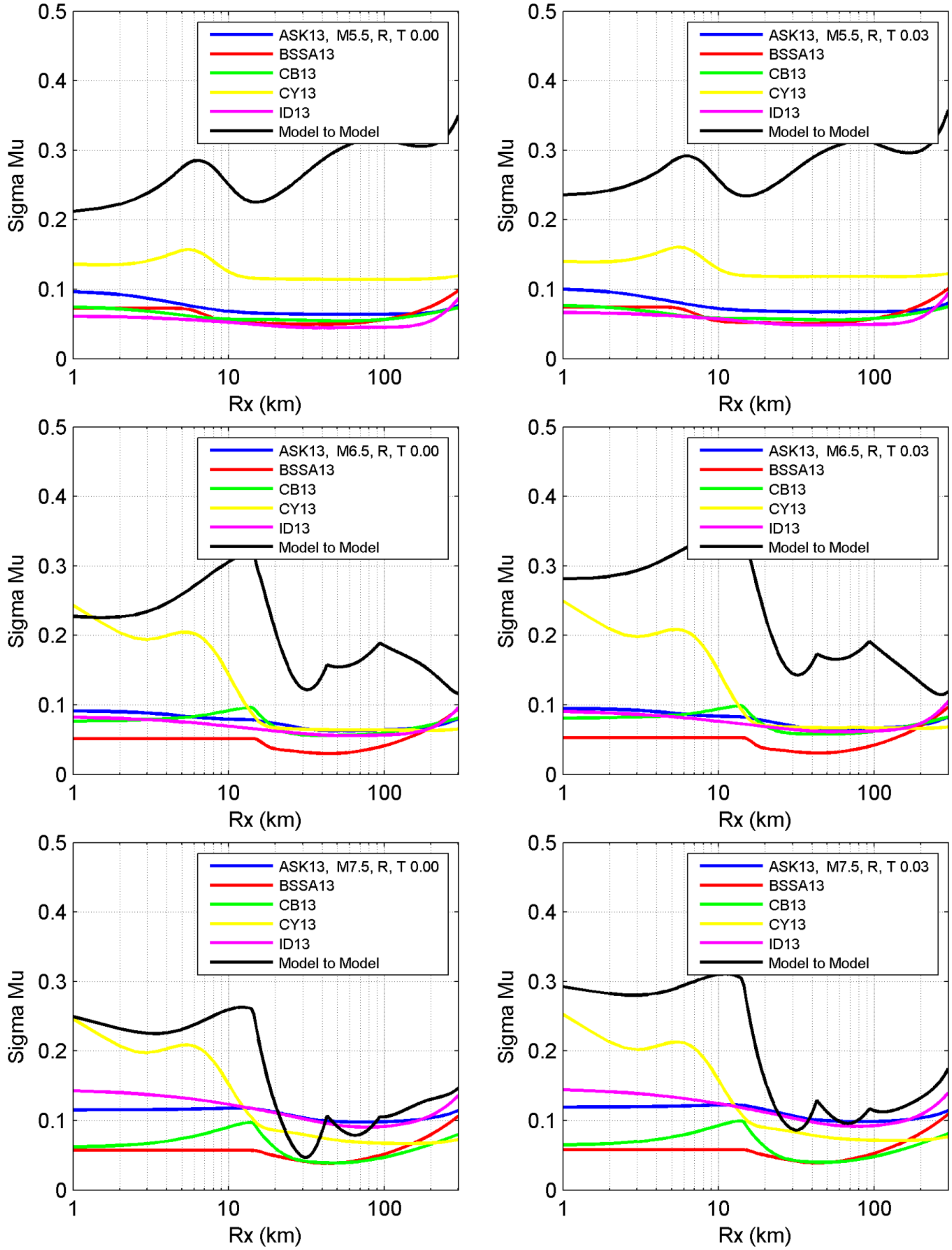
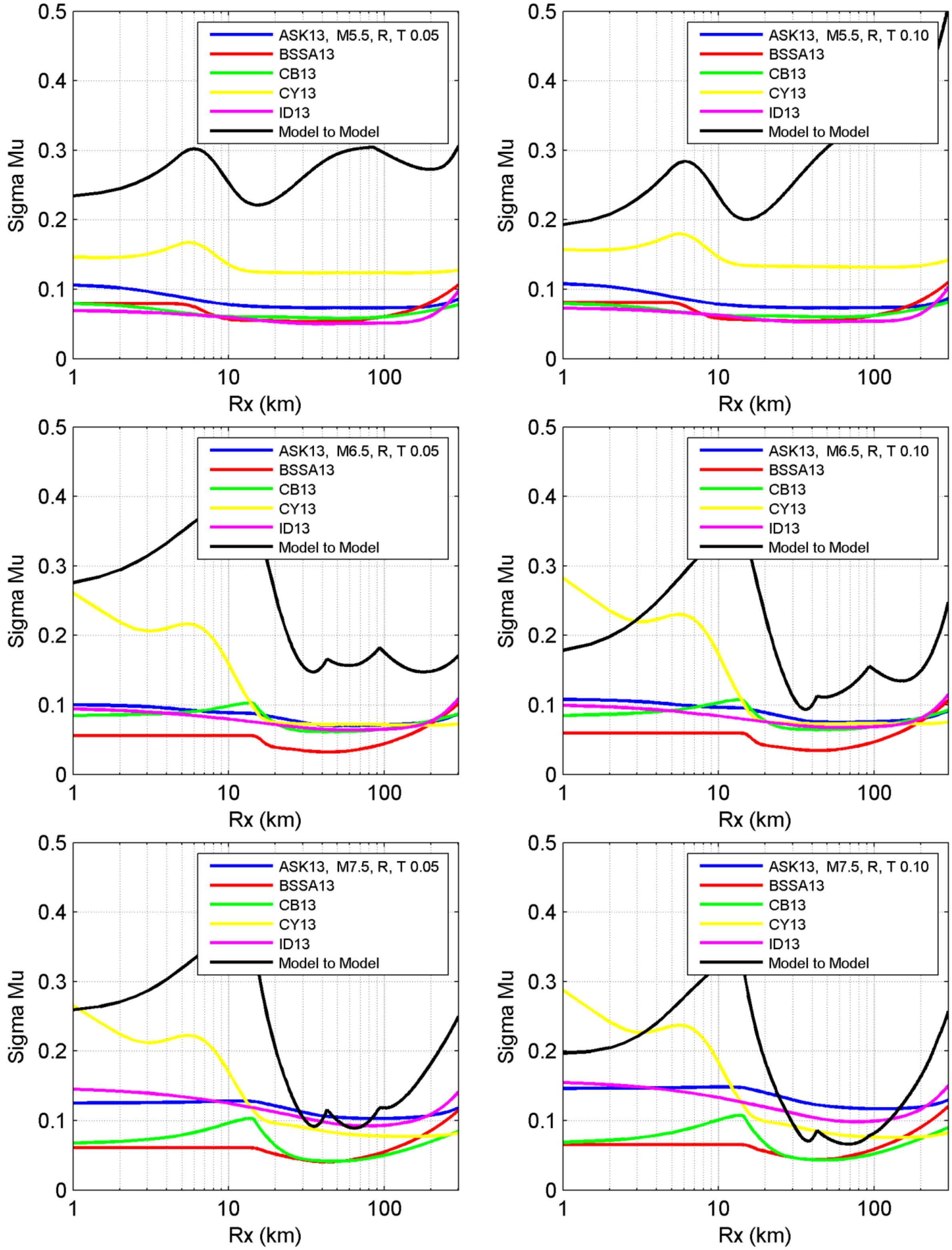


Figure 3.7 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the reverse rupture scenarios shown in Figure 1.3 at PGA and spectral period of 0.03 sec.**



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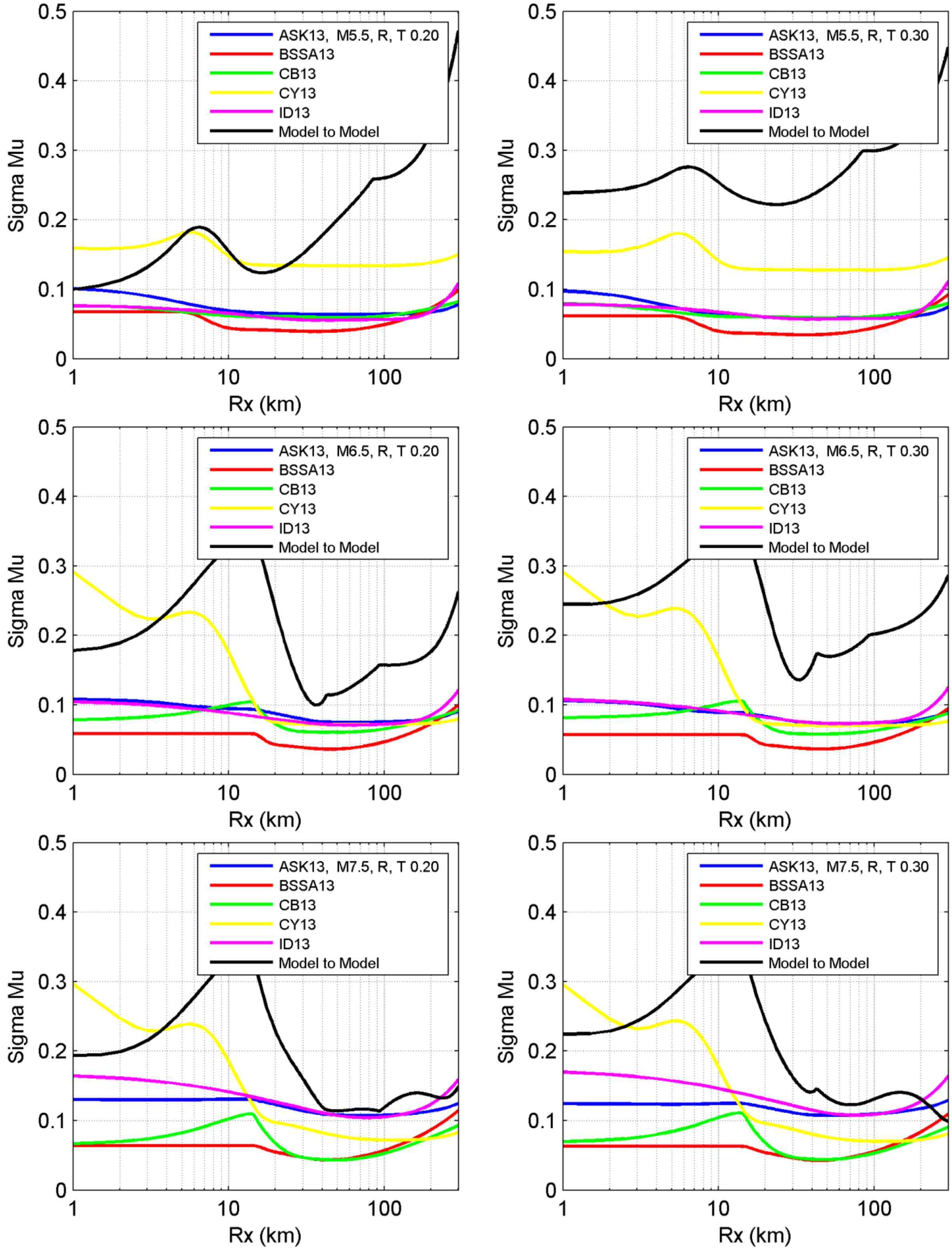


Figure 3.9 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the reverse rupture scenarios shown in Figure 1.3 at period of 0.20 and 0.30 sec.**

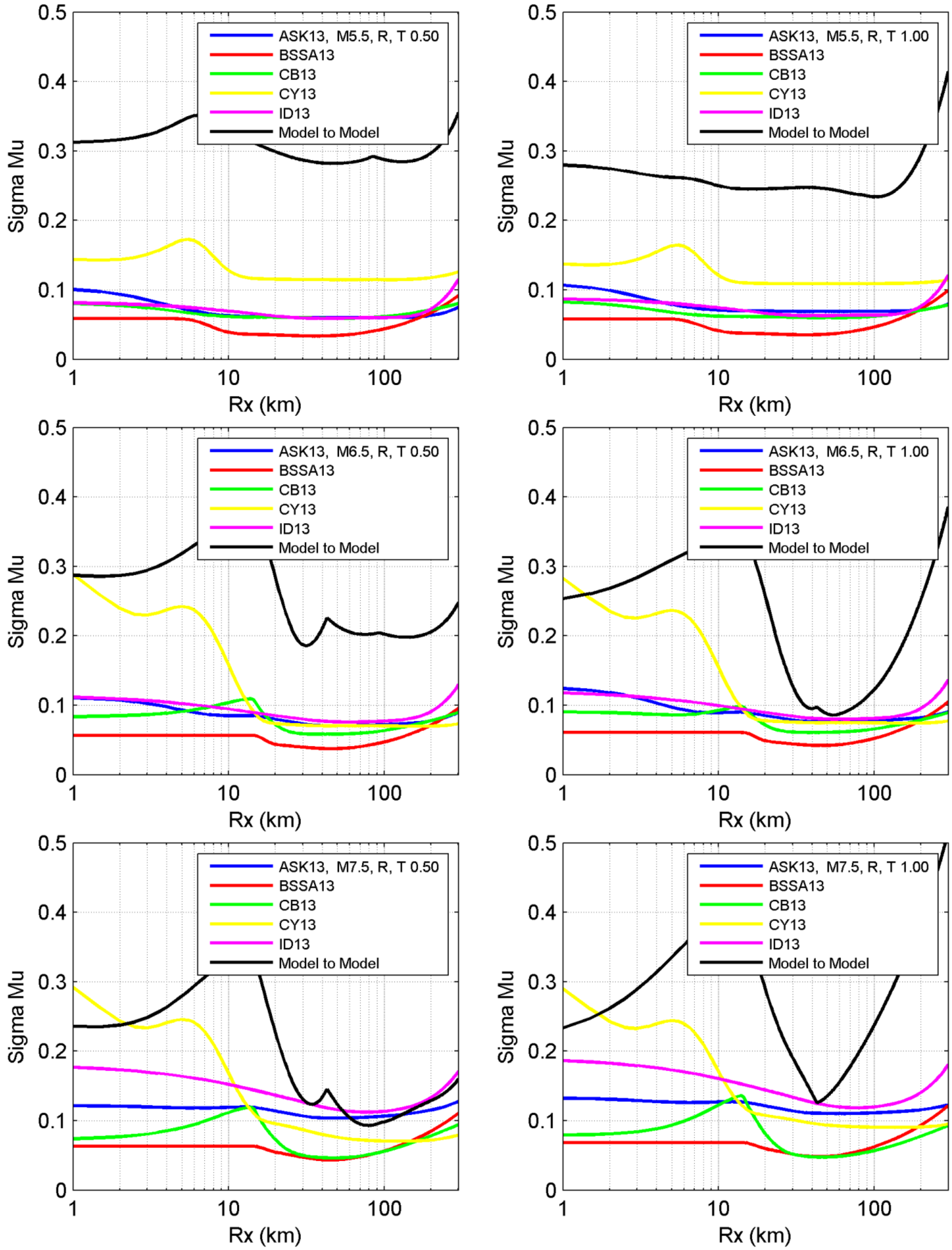
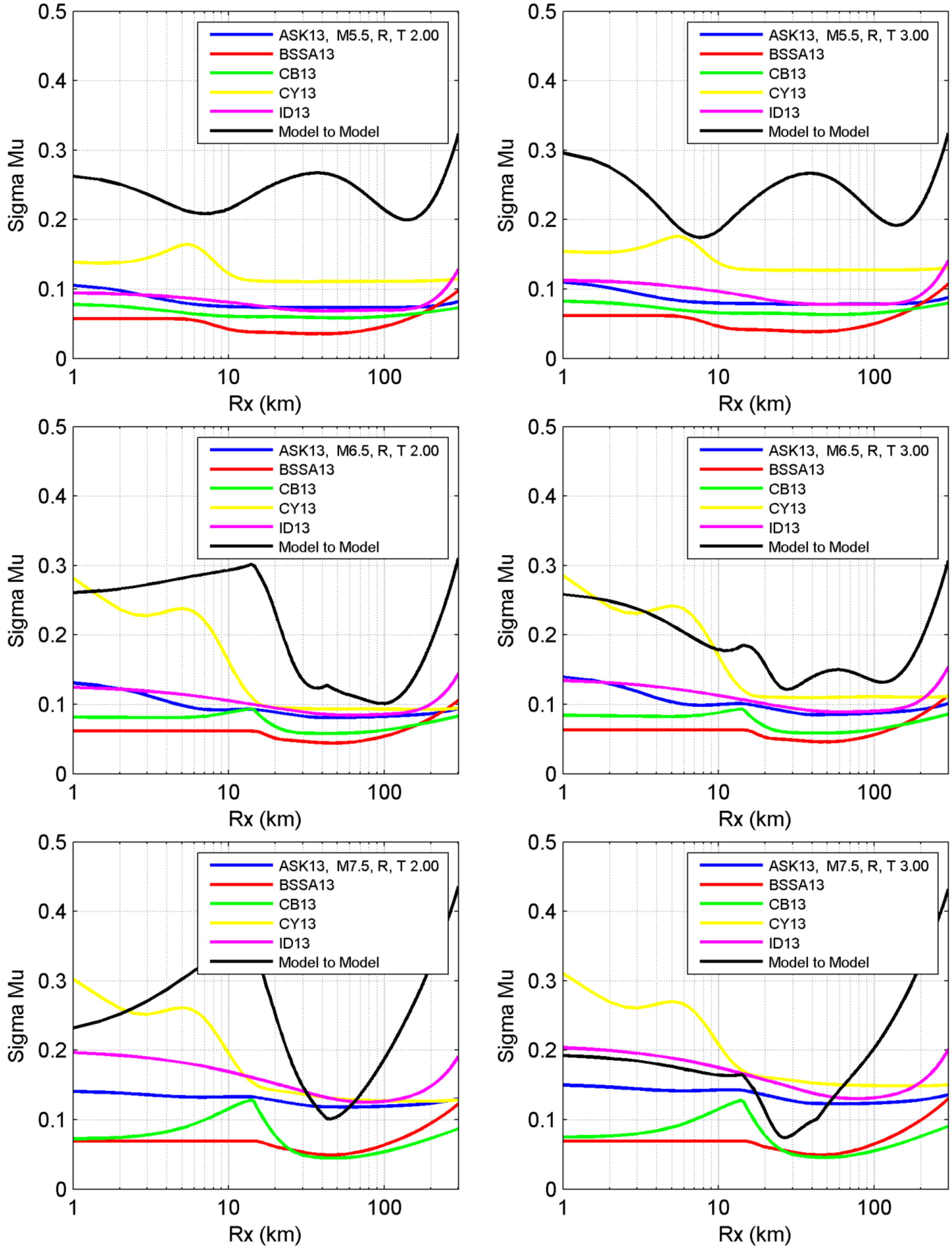


Figure 3.10 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the reverse rupture scenarios shown in Figure 1.3 at period of 0.50 and 1.0 sec.**



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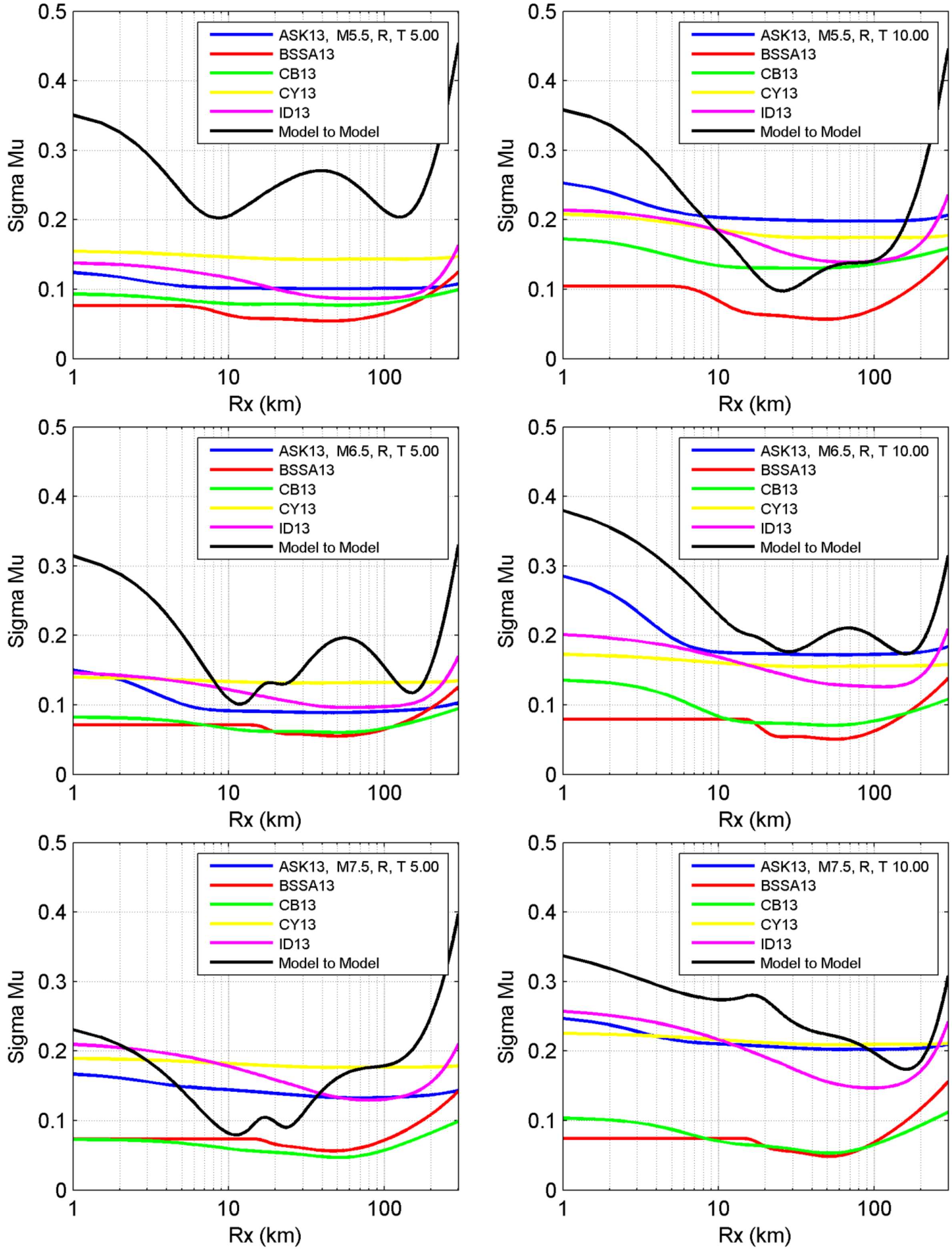

Figure 3.12 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the reverse rupture scenarios shown in Figure 1.3 at period of 5.0 and 10.0 sec.**

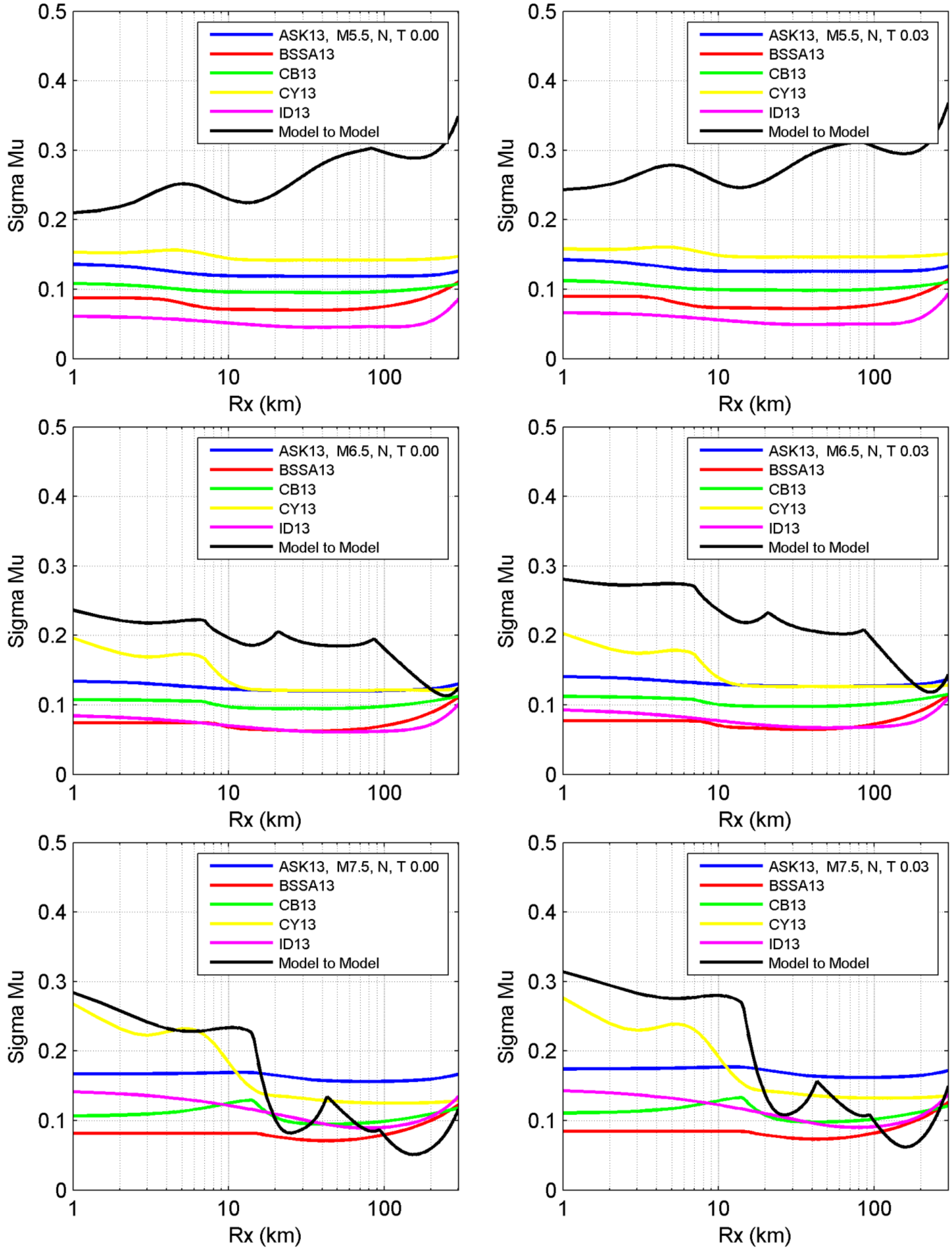

Figure 3.13 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the normal rupture scenarios shown in Figure 1.3 at PGA and spectral period of 0.03 sec.**

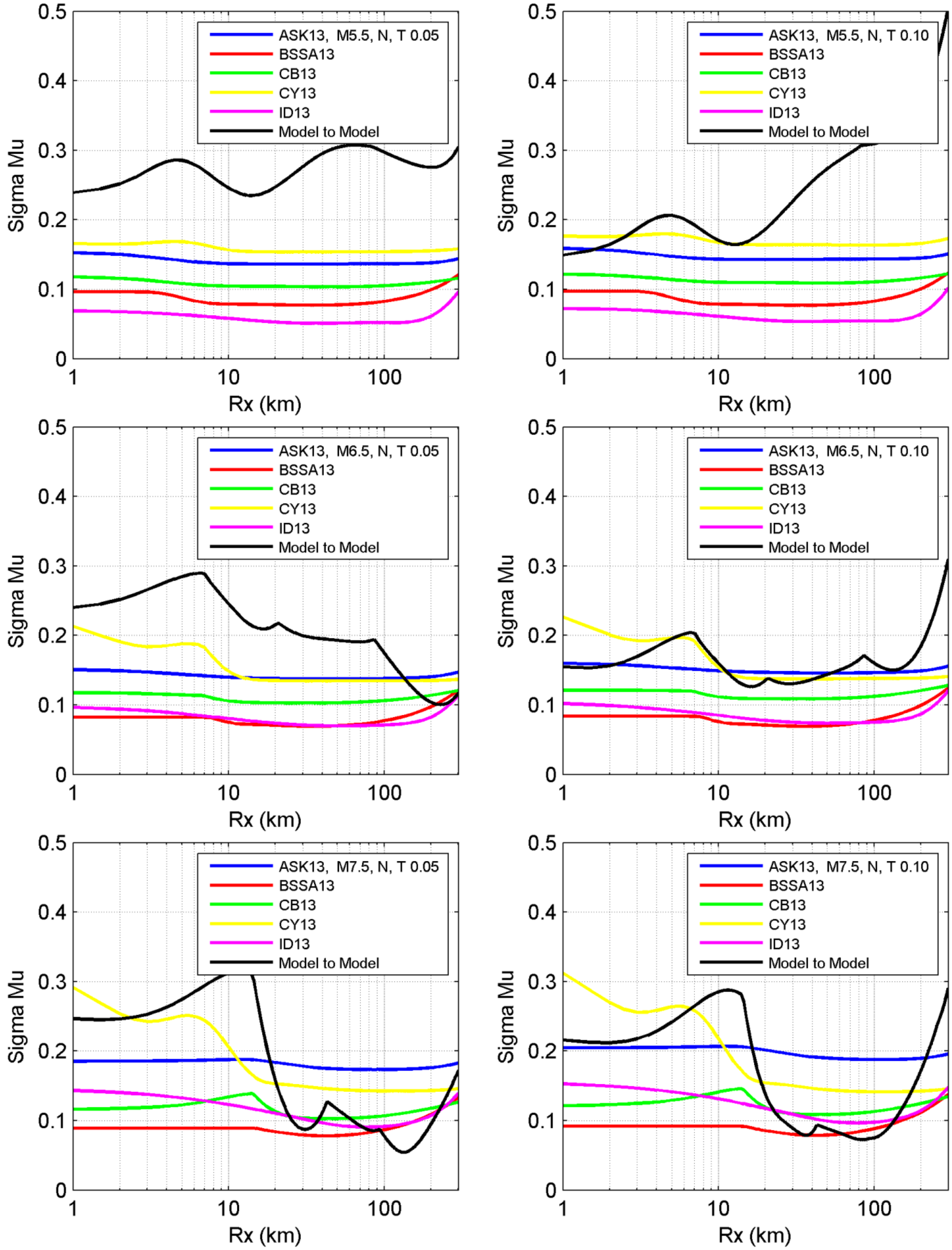

Figure 3.14 Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the normal rupture scenarios shown in Figure 1.3 at spectral periods of 0.05 and 0.10 sec.

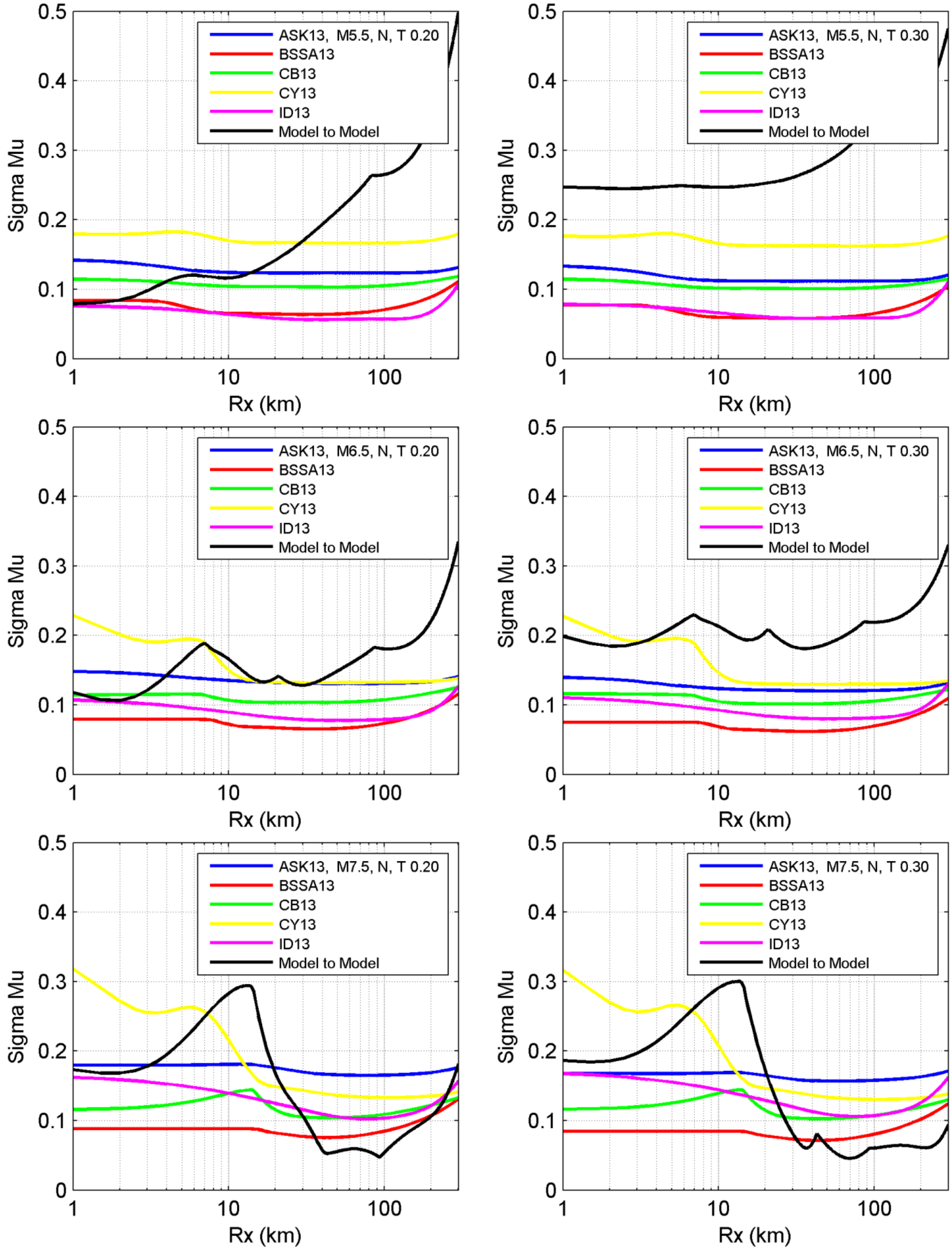

Figure 3.15 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the normal rupture scenarios shown in Figure 1.3 at spectral periods of 0.20 and 0.30 sec.**

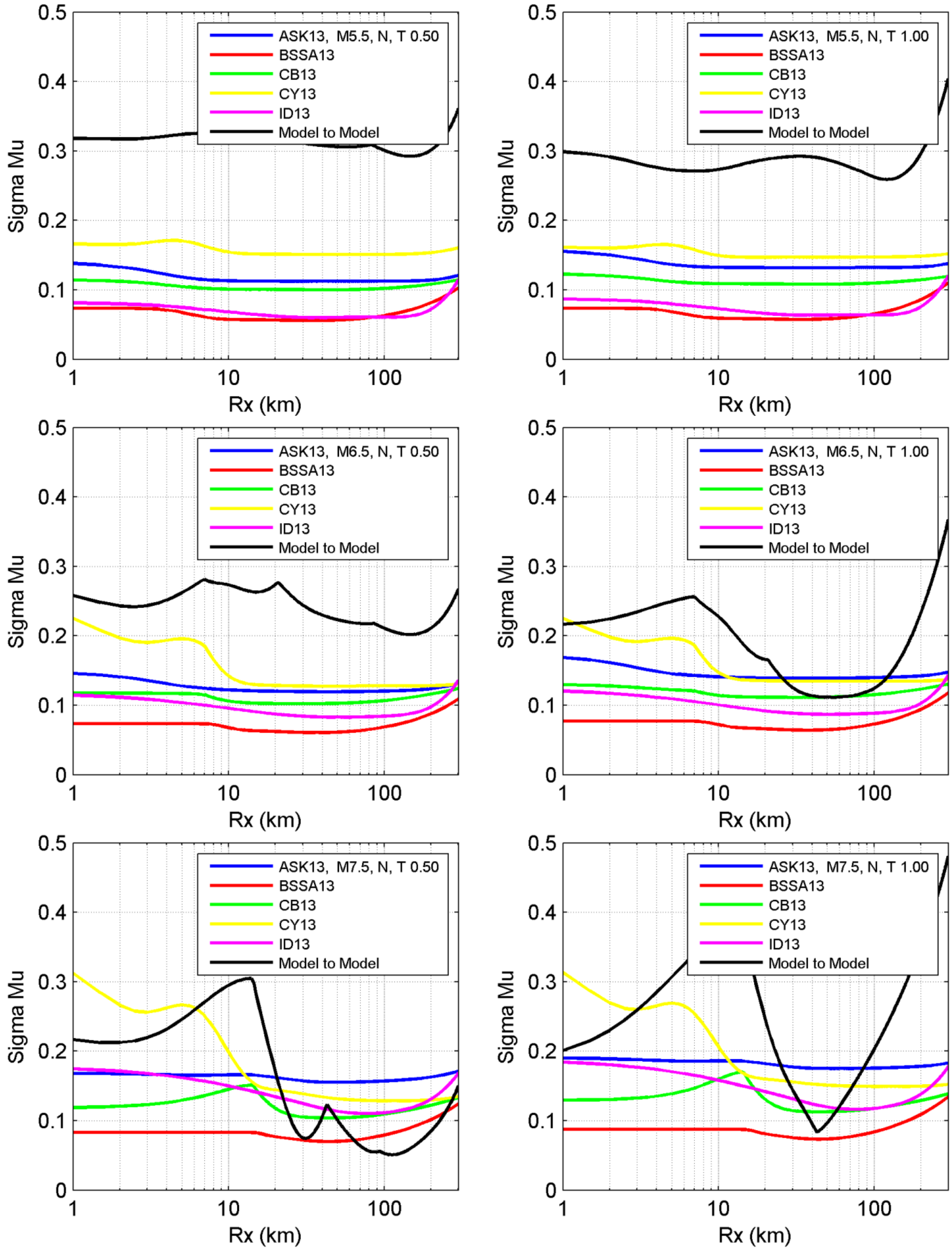

Figure 3.16 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the normal rupture scenarios shown in Figure 1.3 at spectral periods of 0.50 and 1.0 sec.**

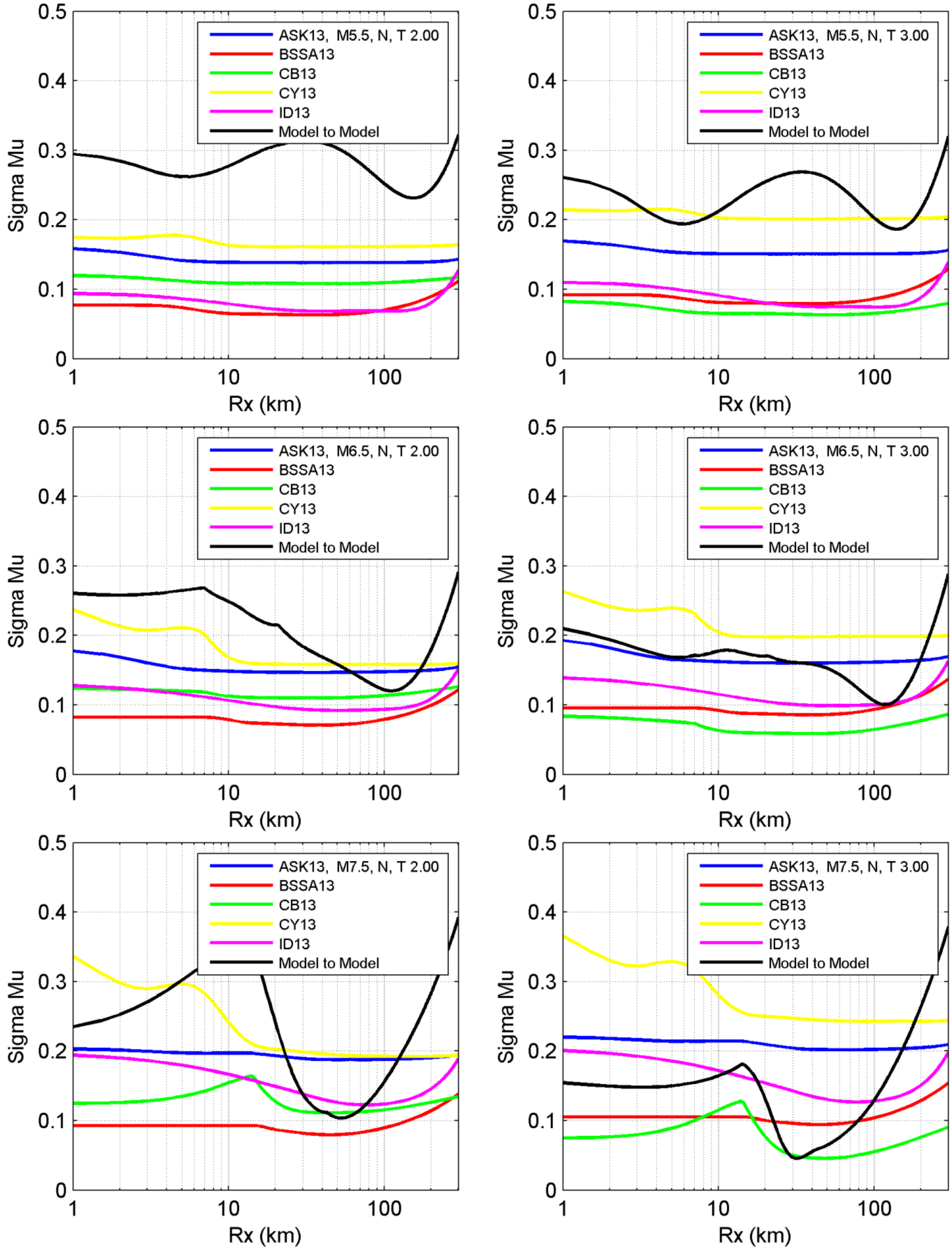

Figure 3.17 Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the normal rupture scenarios shown in Figure 1.3 at spectral periods of 2.0 and 3.0 sec.

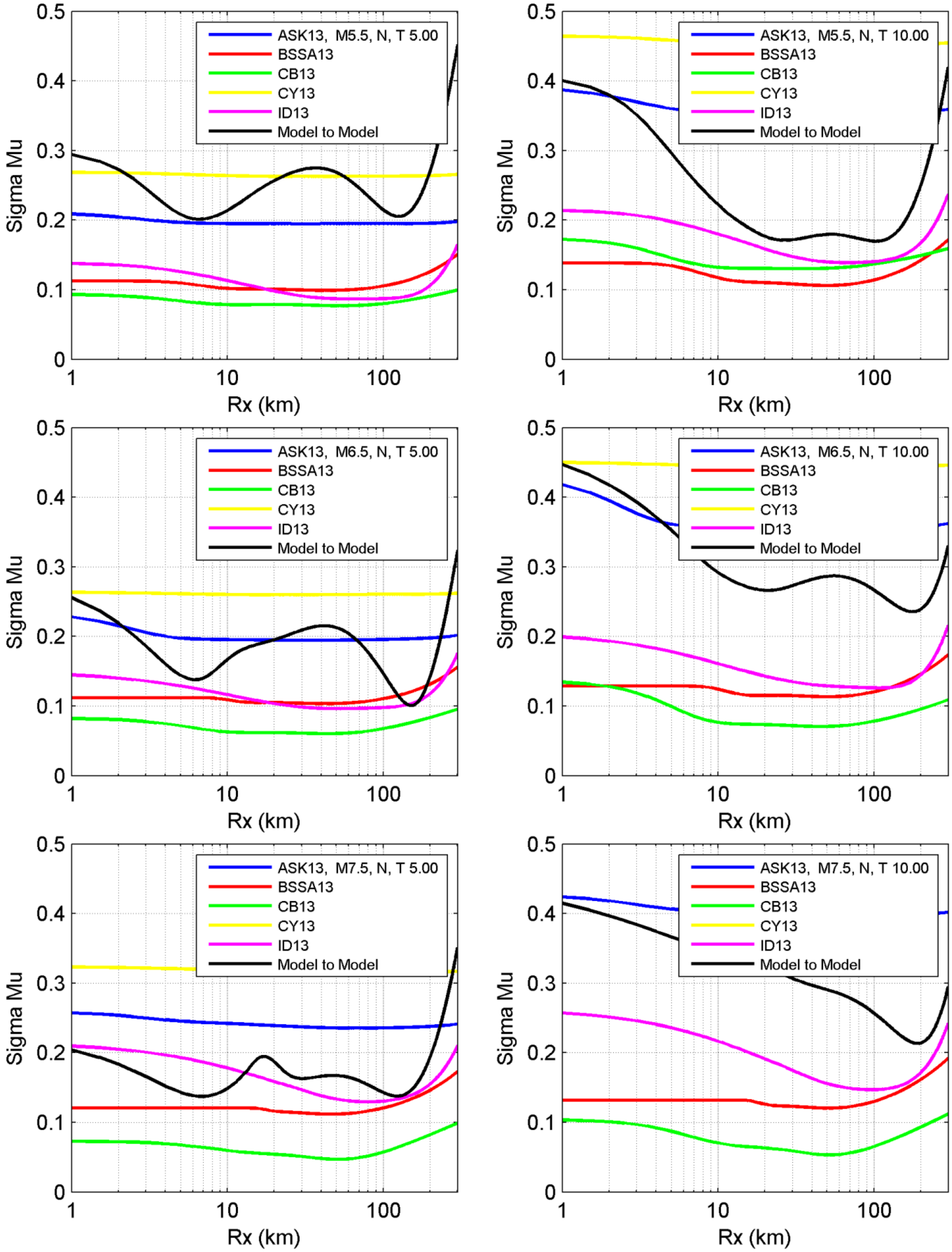

Figure 3.18 **Asymptotic standard errors and model-to-model variability in median Ln(PSA) for the 5 NGA-West2 models for the normal rupture scenarios shown in Figure 1.3 at spectral periods of 5.0 and 10.0 sec.**

4 Epistemic Uncertainty Model

In this section, we present an evaluation of the sensitivity of the within-model uncertainty of median predictions to different parameters such as dip angle, hanging wall/footwall, magnitude, distance, style of faulting, and spectral periods. Based on this evaluation, a simple model of the epistemic uncertainty of the median of NGA-West2 GMPEs is proposed. The goal of this study was to propose a relatively simple model to represent the minimum epistemic uncertainty in median predictions to be added to the set of 5 NGA-West2 GMPEs while capturing the main features of the uncertainty. A single model is proposed to be applied to all 5 GMPEs.

4.1 SENSITIVITY TO DIP ANGLE

Table 4.1 shows the average dip angles in the NGA-West2 database for normal and reverse faults for magnitude bins 5 to 6, 6 to 7, and 7 to 8. Based on these average dip angles, a dip angle of 40 degrees was chosen for the reverse fault scenarios in Figure 1.3, and 55, 60, and 40 degrees were chosen for the normal fault scenarios shown in Figure 1.3.

Table 4.1 Average dip angles for normal and reverse faults in the NGA-West2 database.

Magnitude Bin	Avg. Dip Angle RV	Avg. Dip Angle NM
5 to 6	42 deg	54 deg
6 to 7	41 deg	61 deg
7 to 8	39 deg	40 deg

The sensitivity of the within-model uncertainty in median predictions of the NGA-West2 models to the choice of dip angle is evaluated by estimating the asymptotic standard errors in median Ln(PSA) for CB13 for rupture geometries shown in Figure 1.3 and for the dip angles shown in Table 4.1 compared to a dip angle of 25 degrees. Figures 4.1 and 4.2 show a comparison of the within-model uncertainty for magnitude 5.5, 6.5, and 7.5 at PGA and spectral periods of 0.2, 1.0, and 2.0 sec. Figures 4.3 and 4.4 show a comparison of the corresponding model-to-model uncertainty in median predictions of the 5 NGA-West2 models for the 2 dip angle scenarios.

Figures 4.1 and 4.2 show that the CB13 within-model uncertainty in median prediction is larger for the shallower dip angle scenarios at distances of 10 to 30 km. This difference is mainly due to the fact that using the same geometry with a shallower dip angle leads to a wider fault rupture. Figures 4.3 and 4.4 show that the model-to-model variability is also larger for the shallower dip angle. The model-to-model variability is therefore considered adequate in capturing the increase in uncertainty in median predictions for shallower dip angles and the average dip angles in the NGA-West2 database shown in Table 4.1 are used for proposing an epistemic uncertainty model.

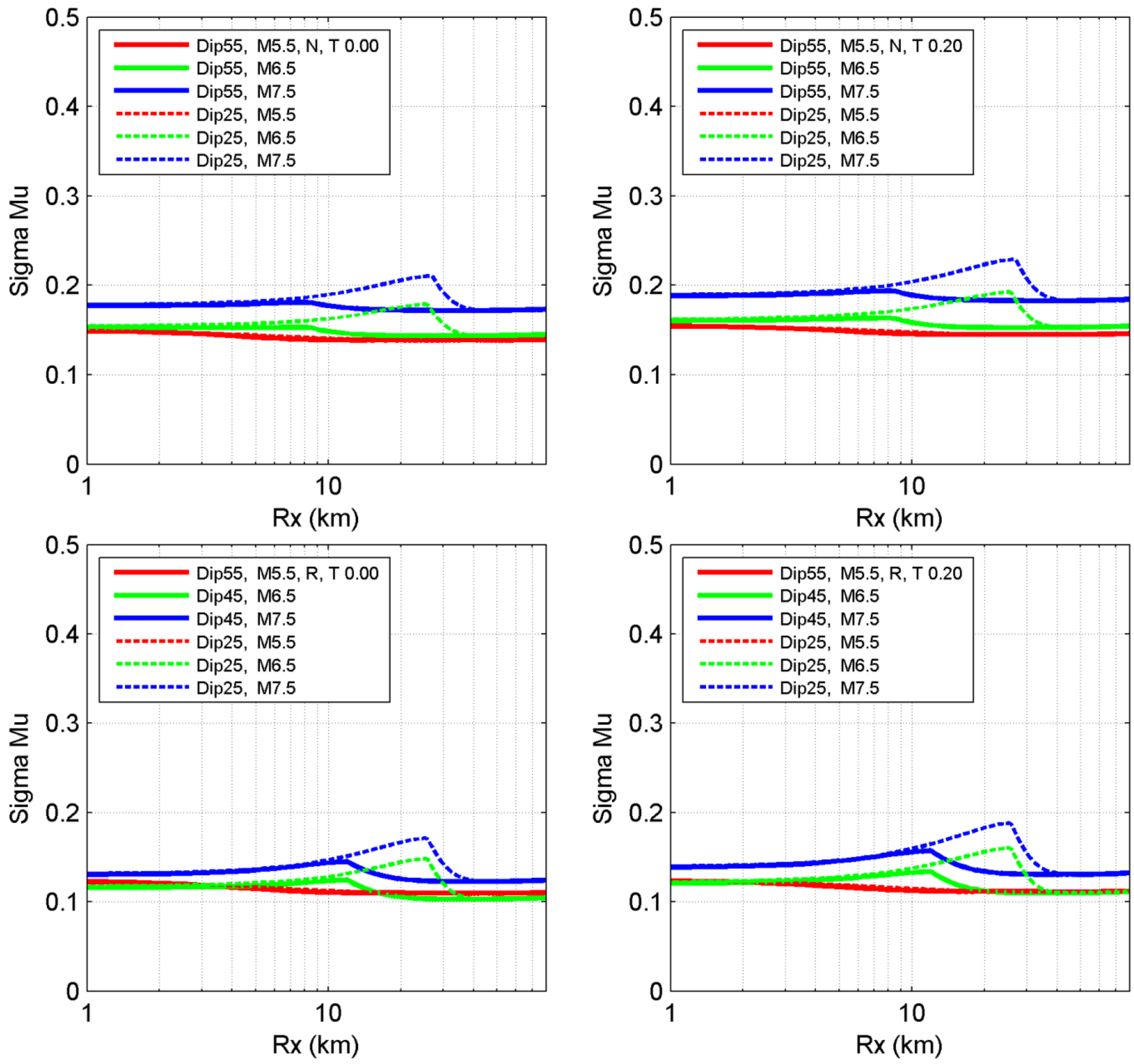

Figure 4.1 **Comparison of asymptotic standard errors in median Ln(PSA) for CB13 for the normal and reverse rupture scenarios in Figure 1.3 with different dip angles at PGA and spectral periods of 0.20 sec.**

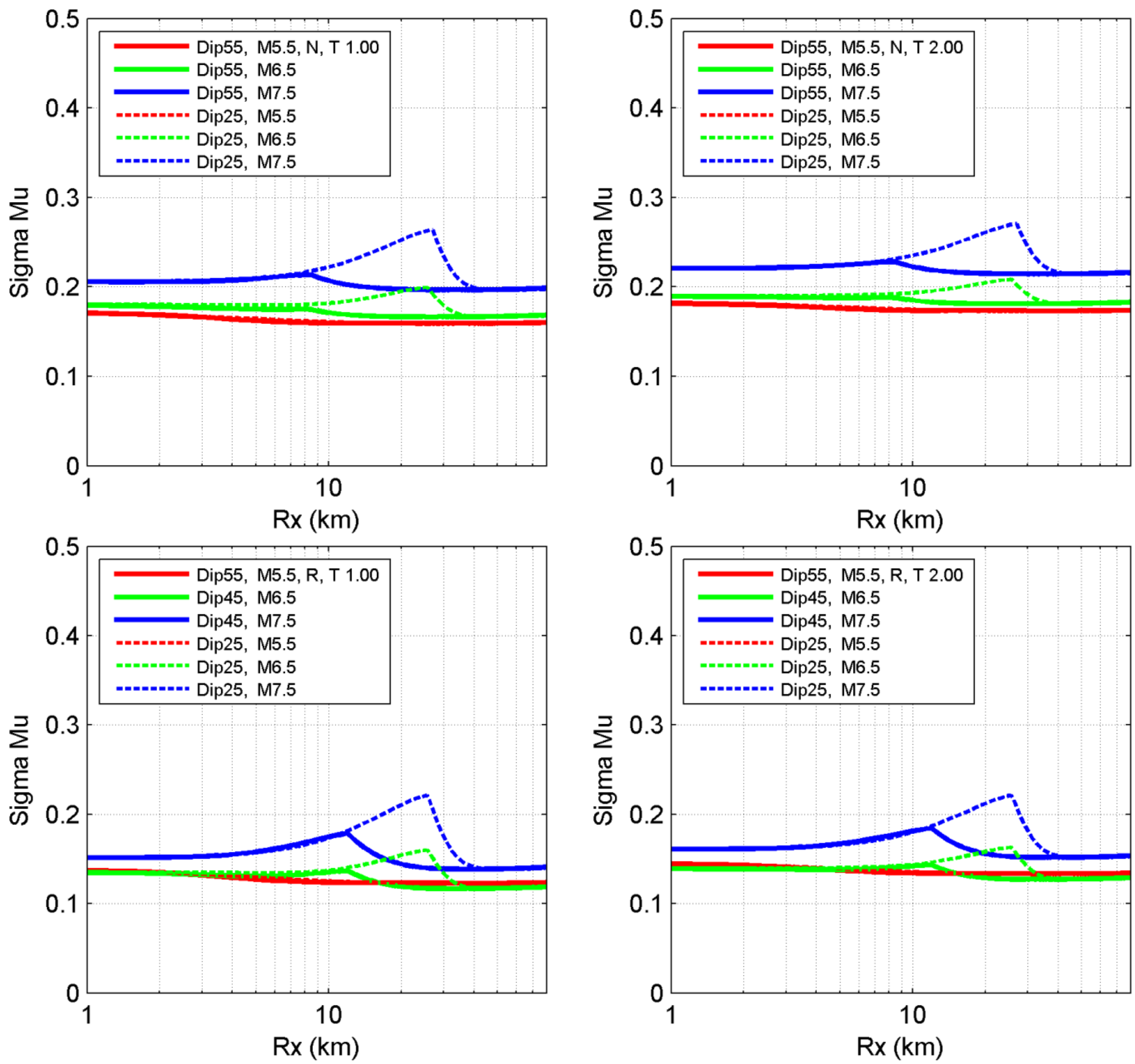

Figure 4.2 **Comparison of asymptotic standard errors in median Ln(PSA) for CB13 for the normal and reverse rupture scenarios in Figure 1.3 with different dip angles at spectral periods of 1.00 and 2.00 sec.**

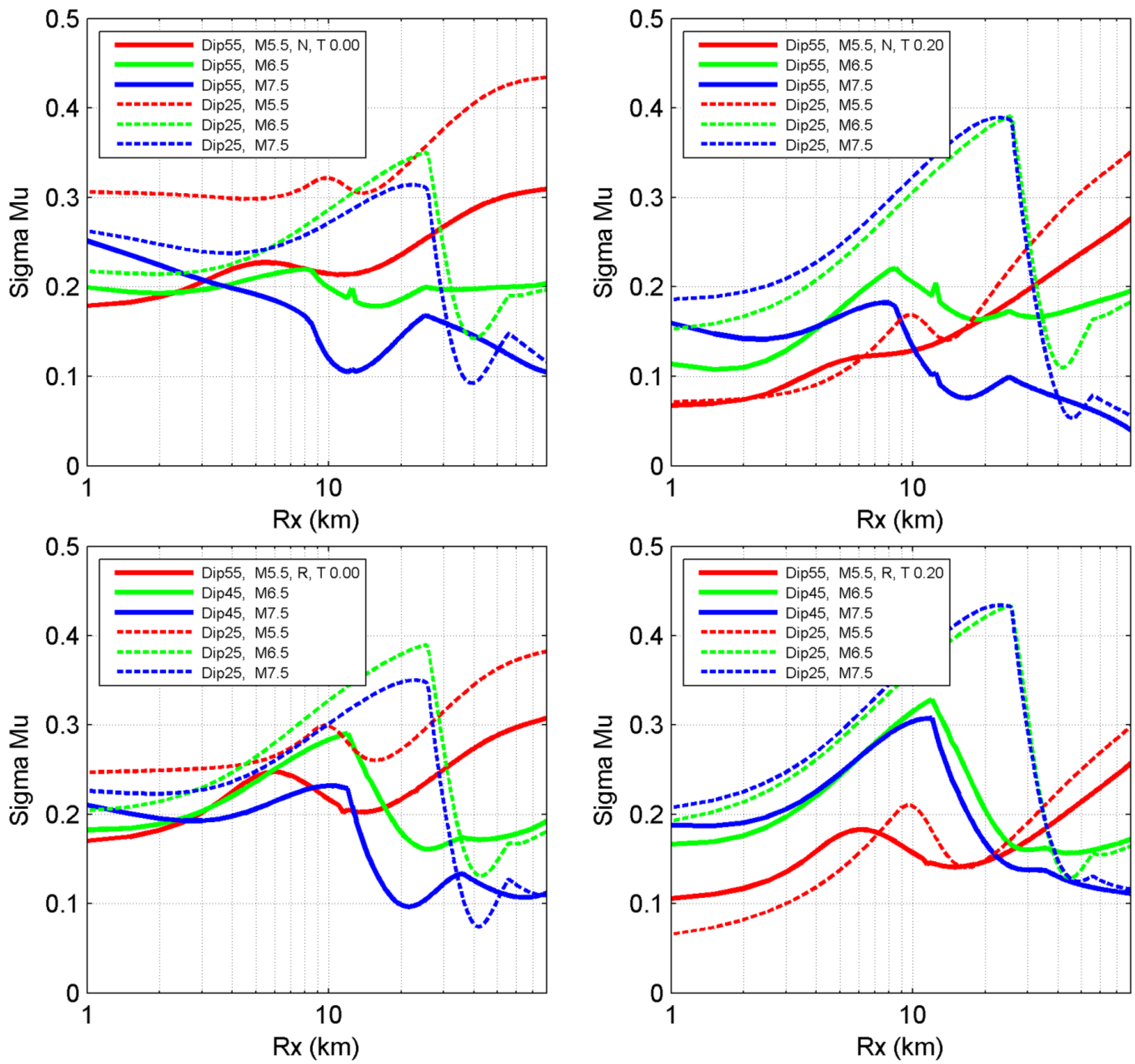

Figure 4.3 **Comparison of model-to-model variability in median Ln(PSA) of the 5 NGA-West2 GMPEs for the normal and reverse rupture scenarios in Figure 1.3 with different dip angles at PGA and spectral period of 0.20 sec.**

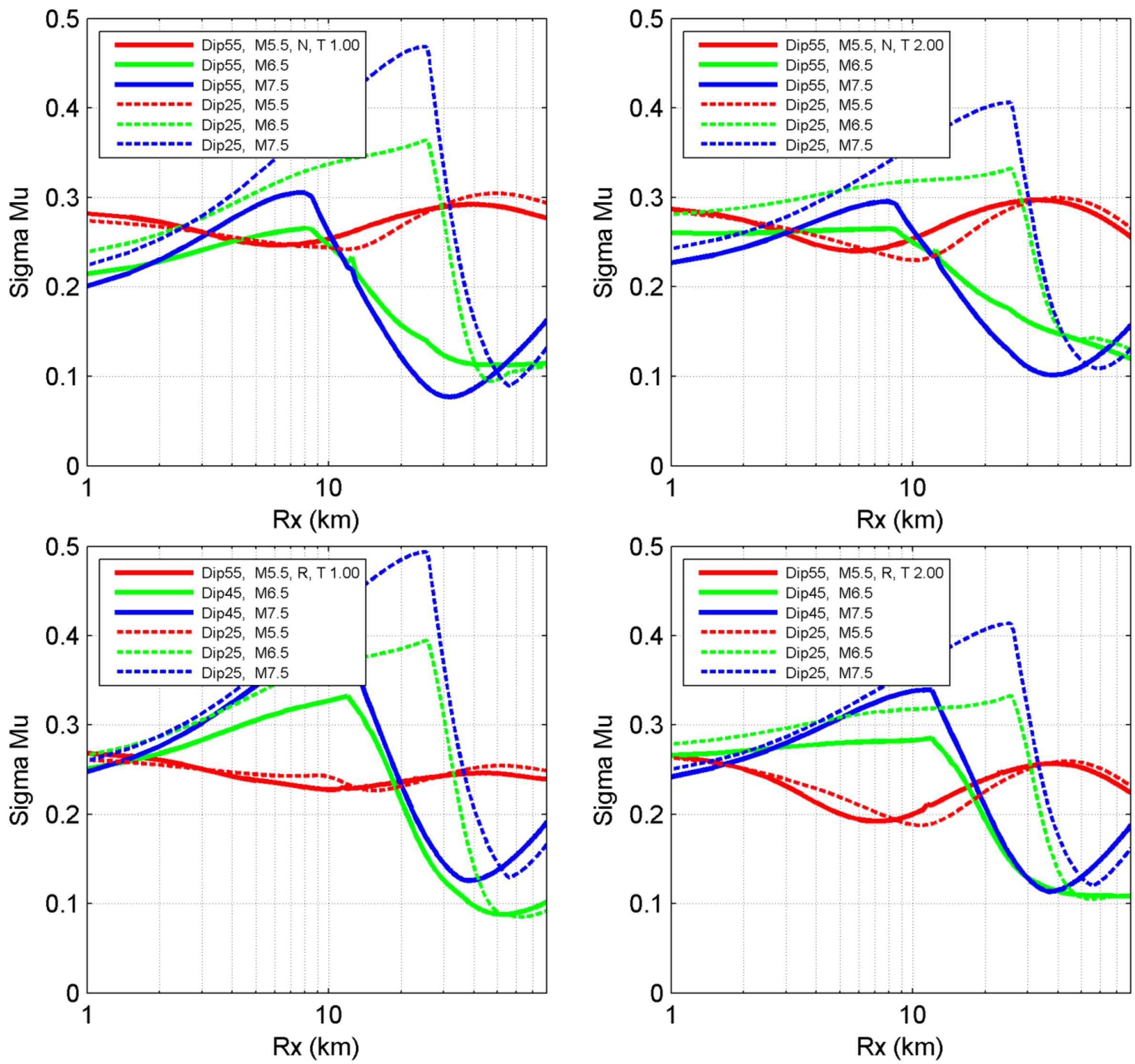

Figure 4.4 **Comparison of model-to-model variability in median Ln(PSA) of the 5 NGA-West2 GMPEs for the normal and reverse rupture scenarios in Figure 1.3 with different dip angles at spectral periods of 1.0 and 2.0 sec.**

4.2 SENSITIVITY TO HANGING WALL/FOOTWALL

The sensitivity of the within-model uncertainty in median predictions of the NGA-West2 models to the site being located on the hanging wall versus the footwall is evaluated by estimating the asymptotic standard errors in median Ln(PSA) for CB13 for rupture geometries shown in Figure 1.3. Figures 4.5 and 4.6 show a comparison of the within-model uncertainty in median predictions for magnitude 5.5, 6.5, and 7.5 at PGA and spectral periods of 0.2, 1.0, and 2.0 sec for hanging wall and footwall sites. Figures 4.5 and 4.6 show that the within-model uncertainty on the hanging wall is slightly larger than that on the footwall and that the within-model uncertainty on the footwall is nearly distance-independent. Therefore, in building an epistemic uncertainty model, we will only consider hanging wall scenarios and apply the same model for footwall scenarios.

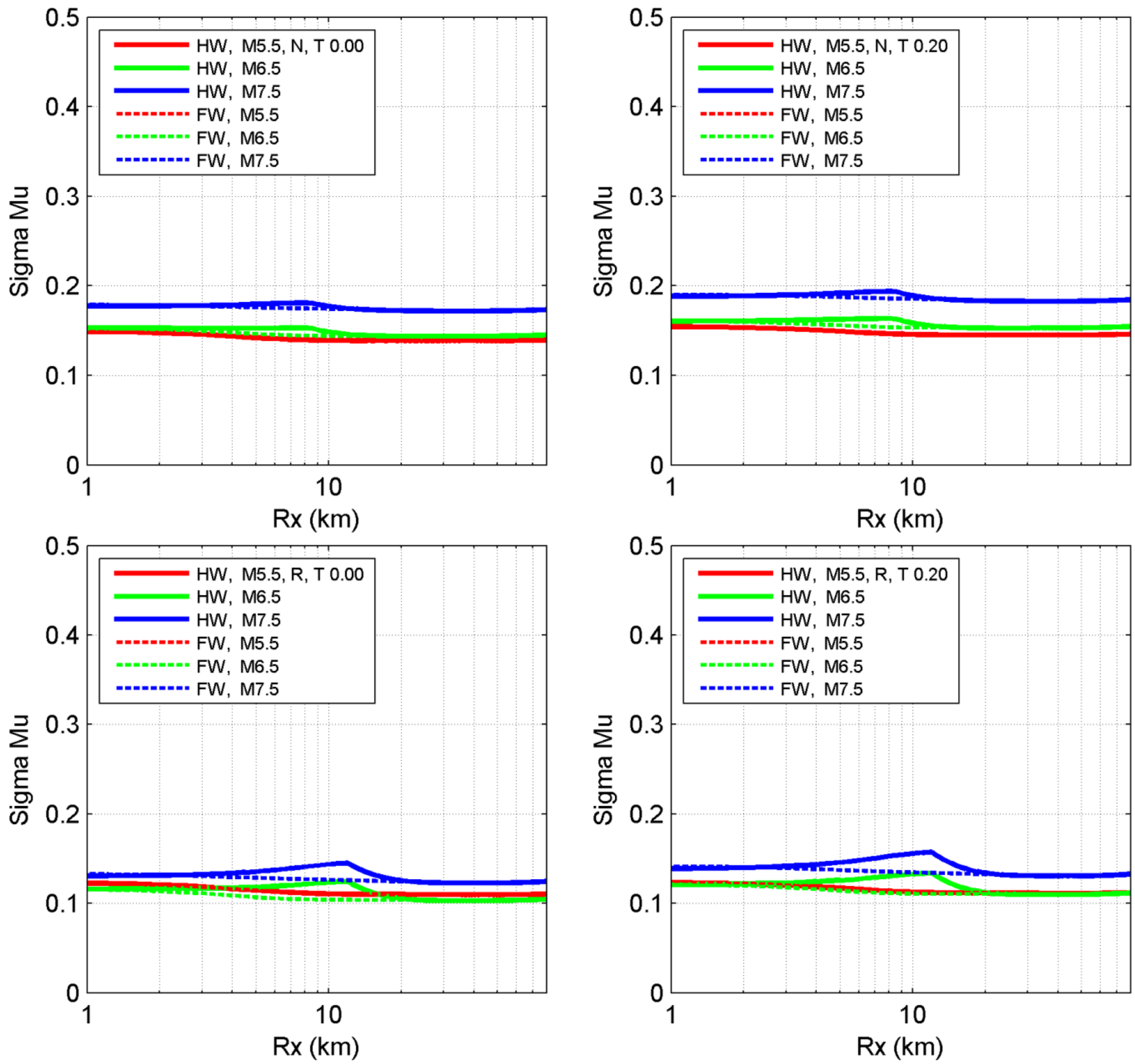

Figure 4.5 **Comparison of asymptotic standard errors in median Ln(PSA) for CB13 for the normal and reverse rupture scenarios in Figure 1.3 with hanging wall and footwall sites at PGA and spectral periods of 0.20 sec.**

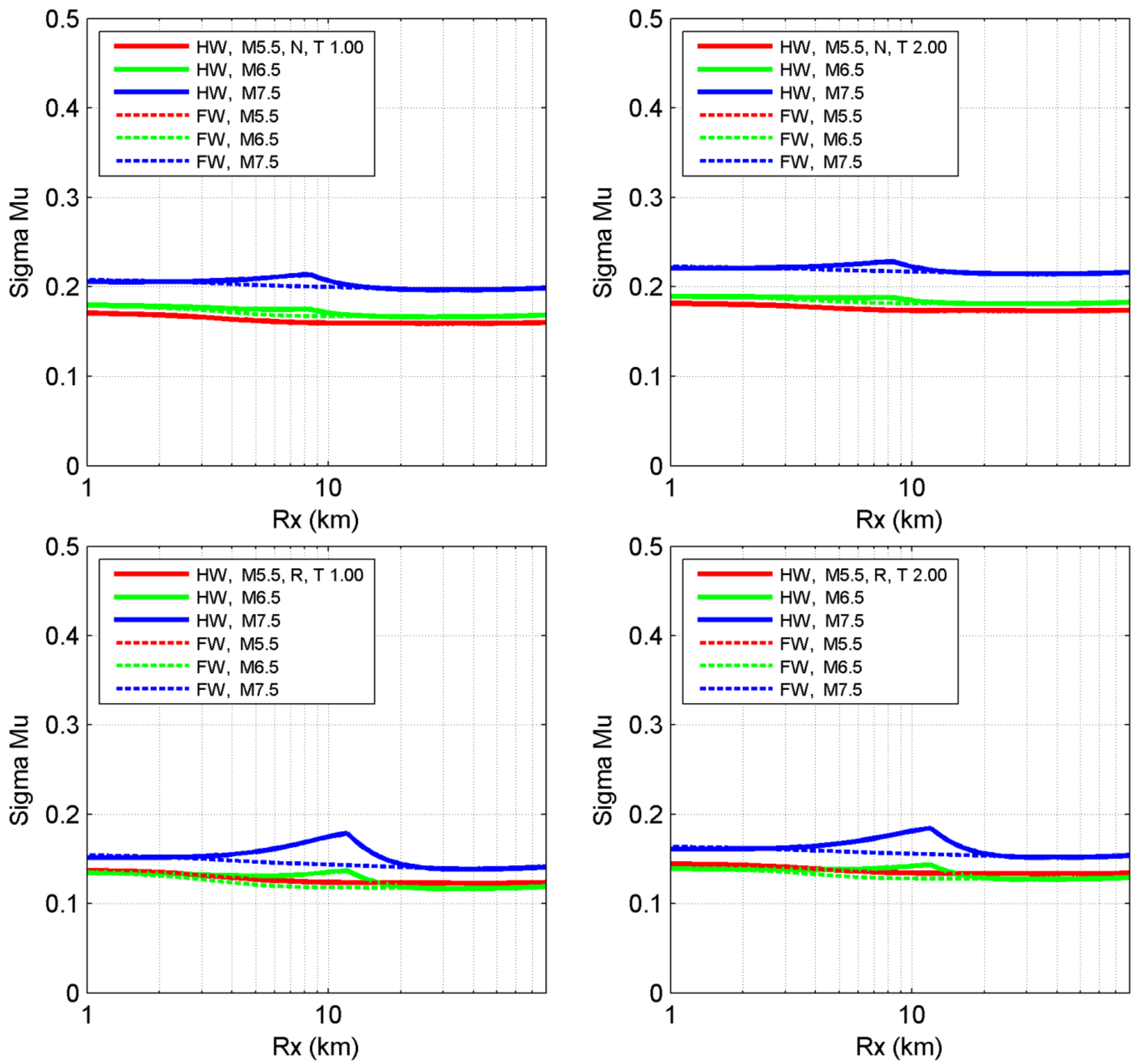

Figure 4.6 **Comparison of asymptotic standard errors in median Ln(PSA) for CB13 for the normal and reverse rupture scenarios in Figure 1.3 with hanging wall and footwall sites at spectral periods of 1.00 and 2.00 sec.**

4.3 DISTANCE DEPENDENCE

The within-model uncertainty in median predictions is averaged for all 5 NGA-West2 models for each magnitude, distance and style-of-faulting scenario. The average within-model uncertainty in median predictions is shown in Figures 4.7 and 4.8 for the rupture scenarios in Figure 1.3 with magnitude 5 through 8 at PGA and spectral periods of 0.2, 1.00, and 2.00 sec. Figures 4.7 and 4.8 show that the average within-model uncertainty in median predictions does not show strong distance dependence for strike-slip faulting. For reverse and normal faulting and particularly for magnitudes greater than 6, a stronger distance-dependence is observed with the average within-model uncertainty in median predictions being larger at close distances.

Despite this observed distance dependence, the proposed epistemic uncertainty model is distance-independent. This is due to the fact that this distance dependence is generally captured in the model-to-model variability shown in Figures 3.1–3.18. In addition, a single epistemic uncertainty model is proposed for both hanging wall and footwall scenarios. For footwall scenarios, the within-model uncertainty is smaller and distance-independent.

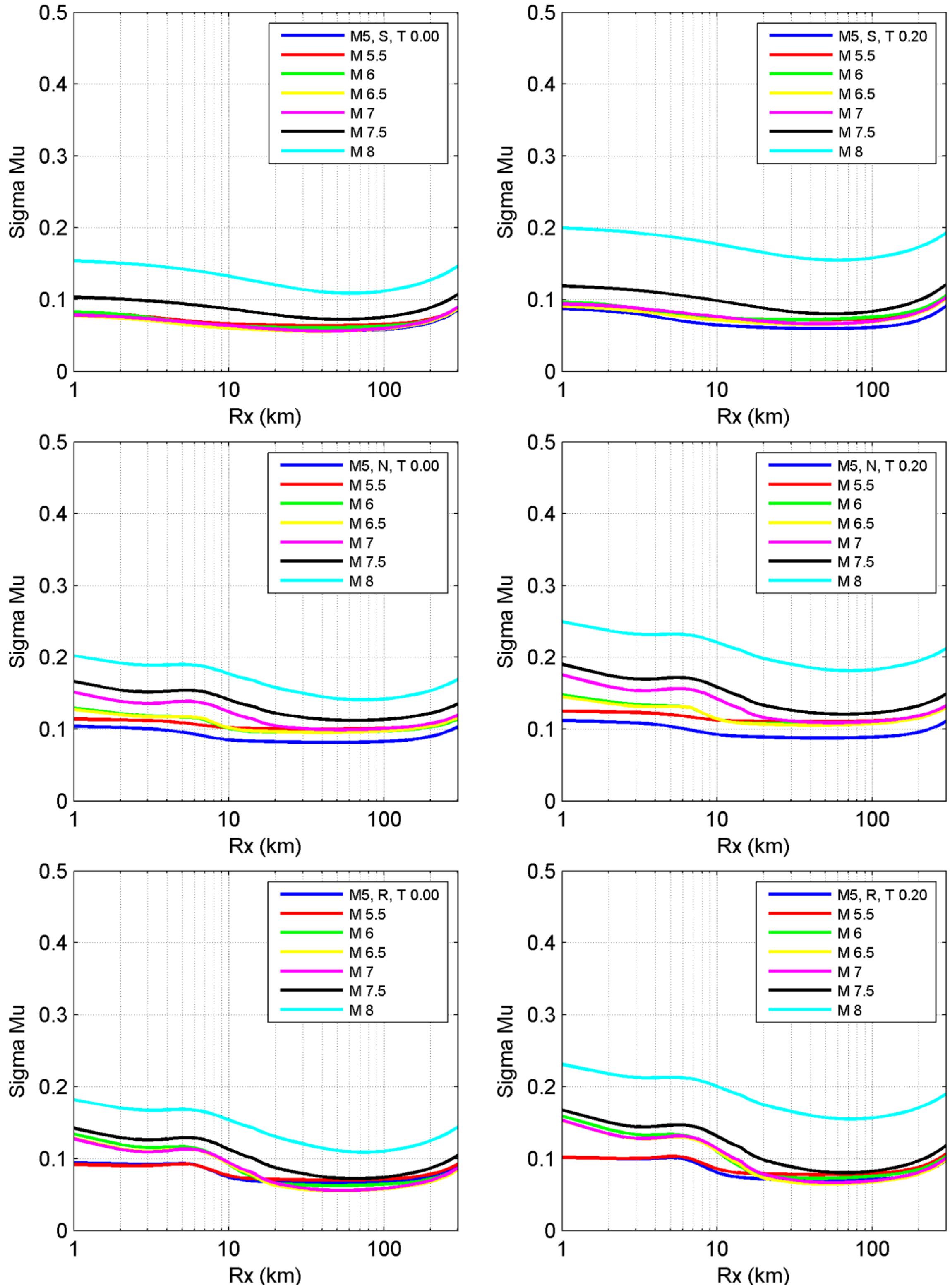

Figure 4.7 **Average asymptotic standard errors in median Ln(PSA) for the 5 NGA-West2 models for the rupture scenarios shown in Figure 1.3 at PGA and spectral period of 0.20 sec.**

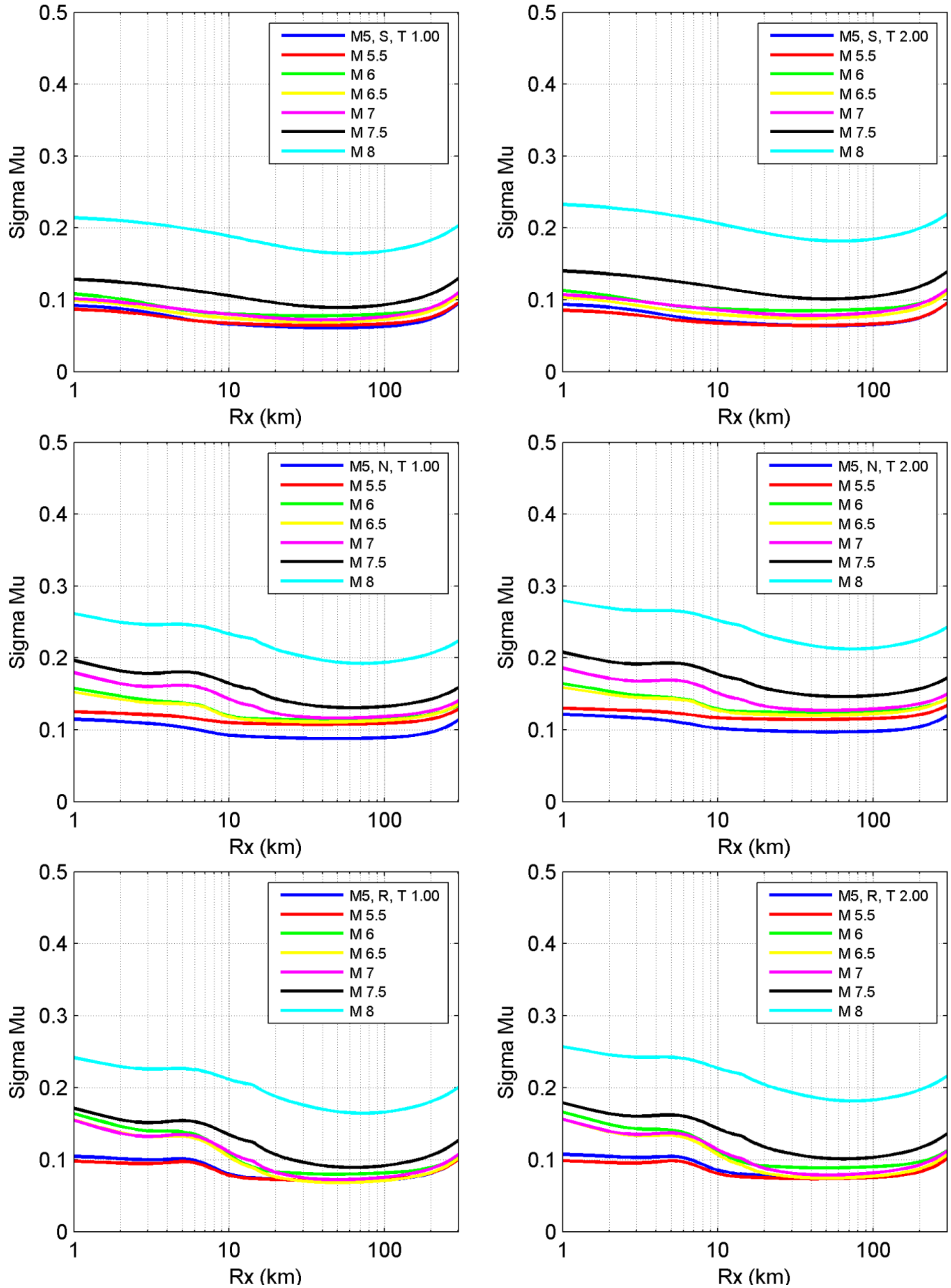

Figure 4.8 **Average asymptotic standard errors in median Ln(PSA) for the 5 NGA-West2 models for the rupture scenarios shown in Figure 1.3 at spectral periods of 1.0 and 2.0 sec.**

4.4 MAGNITUDE AND STYLE-OF-FAULTING DEPENDENCE

The within-model uncertainty in median predictions was averaged arithmetically over distances of 1 to 200 km for each of the 5 NGA-West2 models. The upper limit of 200 km was chosen because it corresponds to the limit of applicability of most of the models. The resulting constant within-model uncertainties with distance were averaged for all 5 NGA-West2 models. This leads to a single average within-model uncertainty in median predictions for all the GMPEs and at all distances for a certain magnitude and style of faulting scenario. Figures 4.9 and 4.10 show the average within-model uncertainty versus magnitude for the rupture geometries in Figure 1.3 for strike-slip, normal and reverse faulting for PGA and spectral periods of 0.03, 0.05, 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 3.0, 5.0, and 10.0 sec.

Figures 4.9 and 4.10 show that within-model uncertainty in median predictions is near constant for magnitudes 5.5 to 7.0 and then increases for magnitudes greater than 7.0. Strike-slip and reverse faulting scenarios have generally similar within-model uncertainty in median predictions and normal faulting scenarios exhibit larger uncertainty. Based on these observations, we propose an epistemic uncertainty model that is constant for magnitudes 5.0 to 7.0 increasing between magnitudes 7.0 and 8.0. The proposed epistemic uncertainty model assigns the same level of uncertainty in median predictions for strike-slip and reverse faulting scenarios with an increase for normal faulting scenarios.

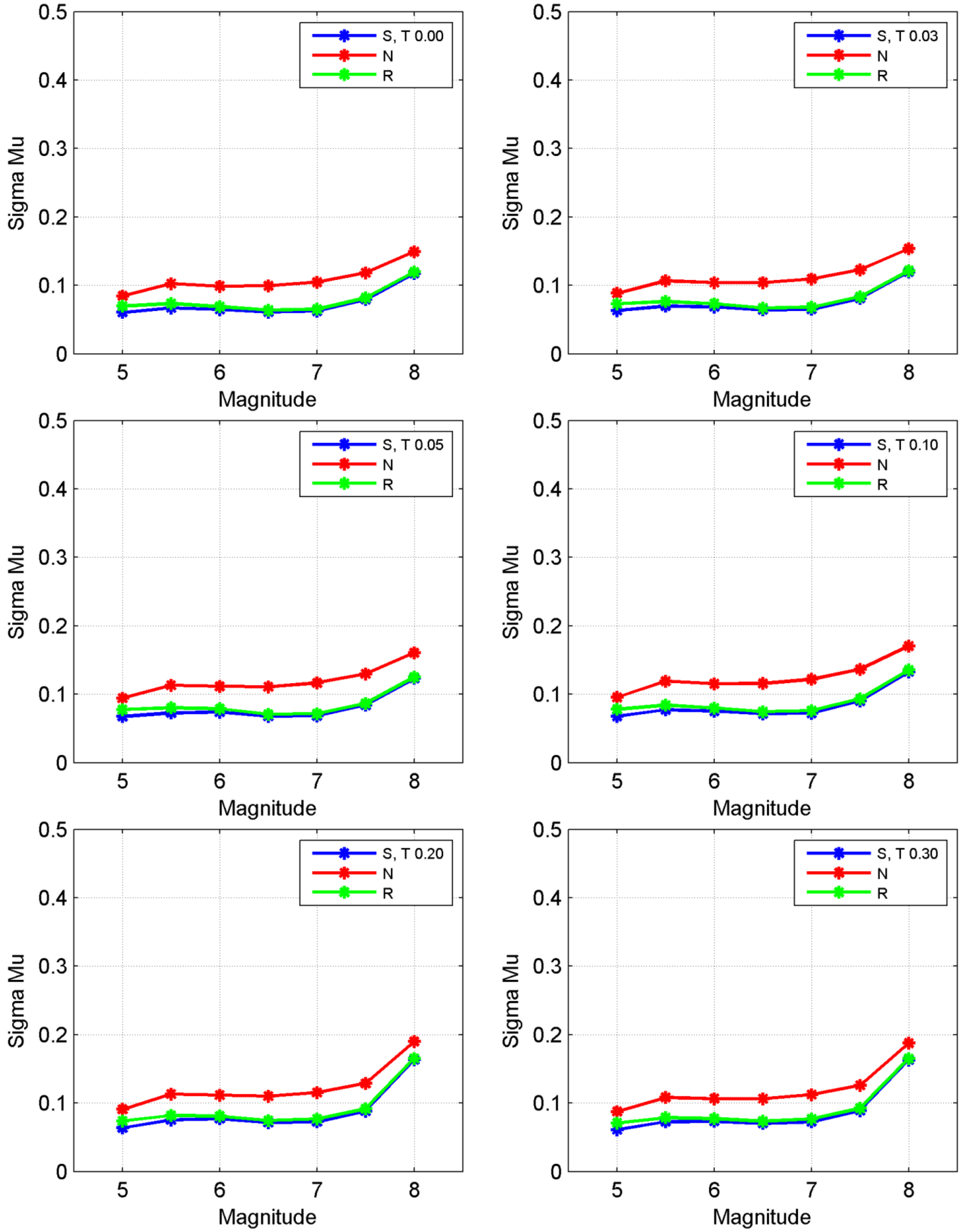

Figure 4.9 **Average within-event uncertainty over distance and over NGA-West2 models versus magnitude for the rupture geometries in Figure 1.3 at PGA and spectral periods of 0.03, 0.05, 0.10, 0.20, and 0.30 sec.**

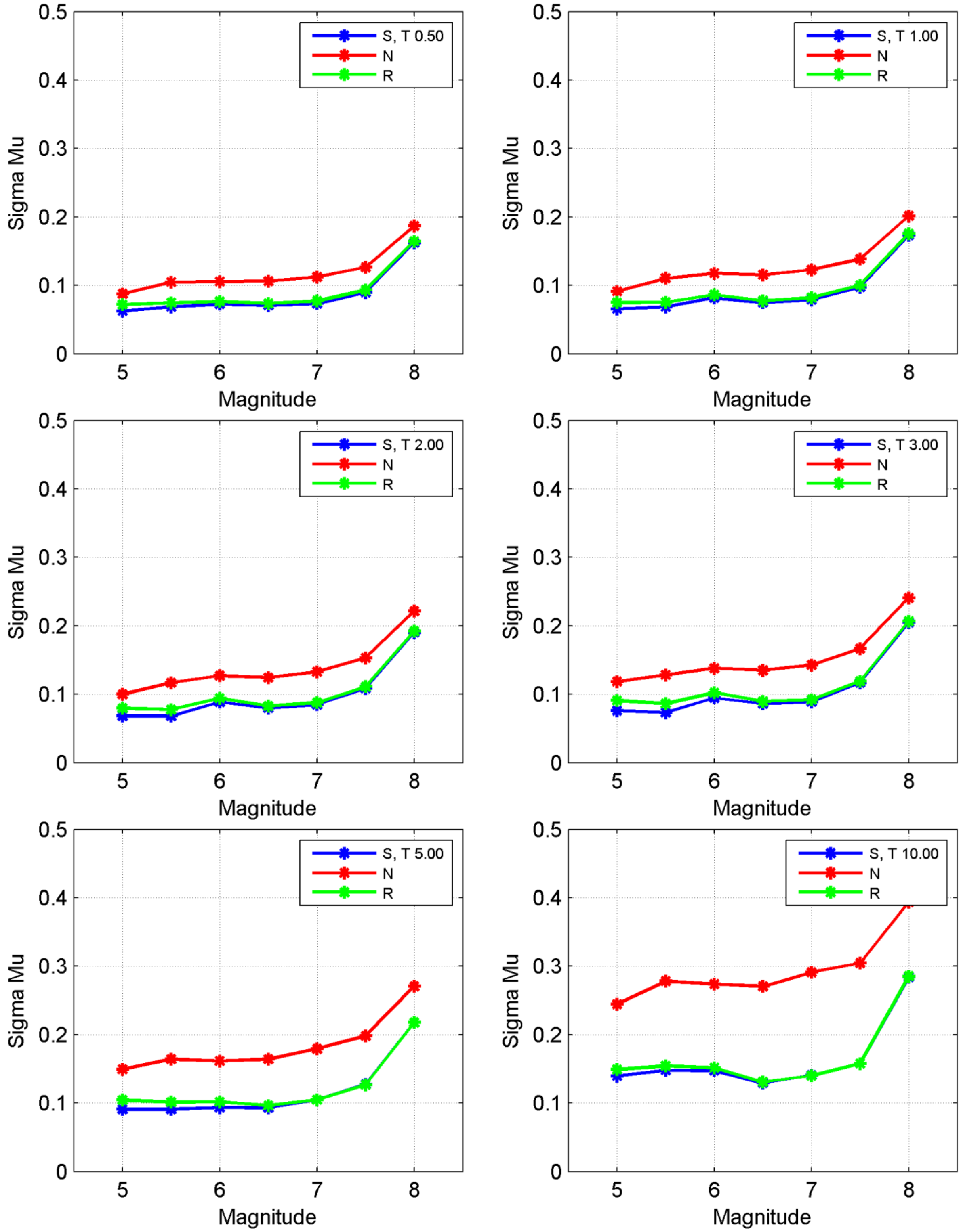

Figure 4.10 **Average within-event uncertainty over distance and over NGA-West2 models versus magnitude for the rupture geometries in Figure 1.3 at spectral periods of 0.50, 1.0, 2.0, 3.0, 5.0, and 10.0 sec.**

4.5 SPECTRAL PERIOD DEPENDENCE

Figure 4.11 shows the average within-model uncertainty in median predictions versus spectral period for the 5 NGA-West2 models for the rupture geometries in Figure 1.3 for magnitudes 5.0 through 8.0. This average within-model uncertainty is constant with distance as described in the previous section. Figure 4.11 shows that the average within-model uncertainty for median predictions of the 5 NGA-West2 models can be approximated by a constant for periods less than 1.0 sec. At longer periods, the within-model uncertainty increases.

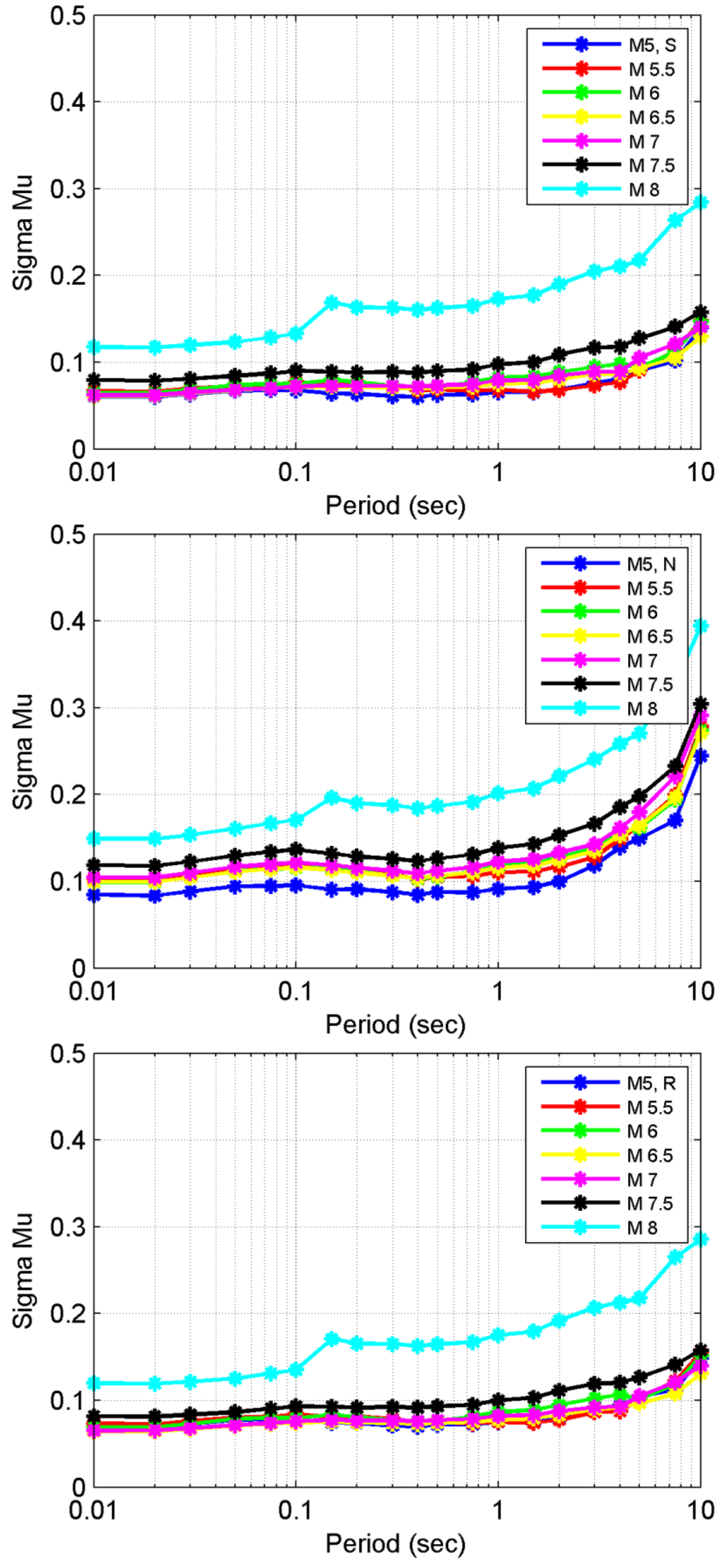

Figure 4.11 Average within-event uncertainty over distance and over NGA-West2 models versus spectral periods for the rupture geometries in Figure 1.3.

4.6 PROPOSED MODEL

Based on the evaluation of magnitude, distance, style-of-faulting, and spectral period dependence of the average within-model uncertainty in median predictions of the NGA-West2 models, a distance-independent epistemic uncertainty model of the median ground motion is assigned to each of the 5 NGA-West2 GMPEs. For strike-slip and reverse faulting scenarios with magnitude 5.0 to 7.0, a constant epistemic uncertainty of the median of 0.072 natural log units is assigned for spectral periods less than 1.0 sec. For larger magnitude and longer periods, this uncertainty is increased as shown in the equations below. For normal faulting scenarios, an additional 0.034 natural log units is added to the uncertainty of strike-slip and reverse faulting scenarios.

For strike-slip and reverse faulting:

- For spectral periods less than 1.0 sec:

$$\sigma_{\mu\ln(psa)} = \begin{cases} 0.072 & \text{for M < 7.0} \\ 0.0665*(M-7.0)+0.072 & \text{for M >= 7.0} \end{cases} \tag{4.1}$$

- For spectral periods greater than or equal to 1.0 sec:

$$\sigma_{\mu\ln(psa)} = \sigma_{\mu\ln(psa)}\left(T<1.0\right)+0.0217*\ln(T) \tag{4.2}$$

For normal faulting:

$$\sigma_{\mu\ln(psa)} = \sigma_{\mu\ln(psa)}\left(RV\right)+0.034 \tag{4.3}$$

where M is the moment magnitude, T is the spectral period in sec and RV refers to reverse faulting.

This proposed uncertainty model captures the general average uncertainty in median predictions of the NGA-West2 models except for conditions with very limited data on the hanging wall at close distance and for very shallow dip angles. The larger uncertainty for these particular cases is generally captured by the larger variability among the 5 NGA-West2 models. Therefore, the larger epistemic uncertainty for these locations is accounted for in the overall estimate.

The epistemic uncertainty in the median NGA-West2 models is modeled using a three-point discrete approximation to a normal distribution [Keefer and Bodily 1983]. This approach places a weight of 0.63 on the median model and weights of 0.185 on the 5th and the 95th percentiles (~1.645 standard deviations). This approach is implemented by developing three alternative models for each NGA-West2 GMPE: one model equal to the original GMPE median and two models with ±1.645* $\sigma_{\mu\ln(psa)}$ added to the median, each with weight 0.185. The resulting logic tree for crustal earthquake ground motion models is shown in Figure 4.12. The resulting total epistemic uncertainty in the median ground motion predictions is compared to the model-to-model variability among the NGA models in Figures 4.13–4.18.

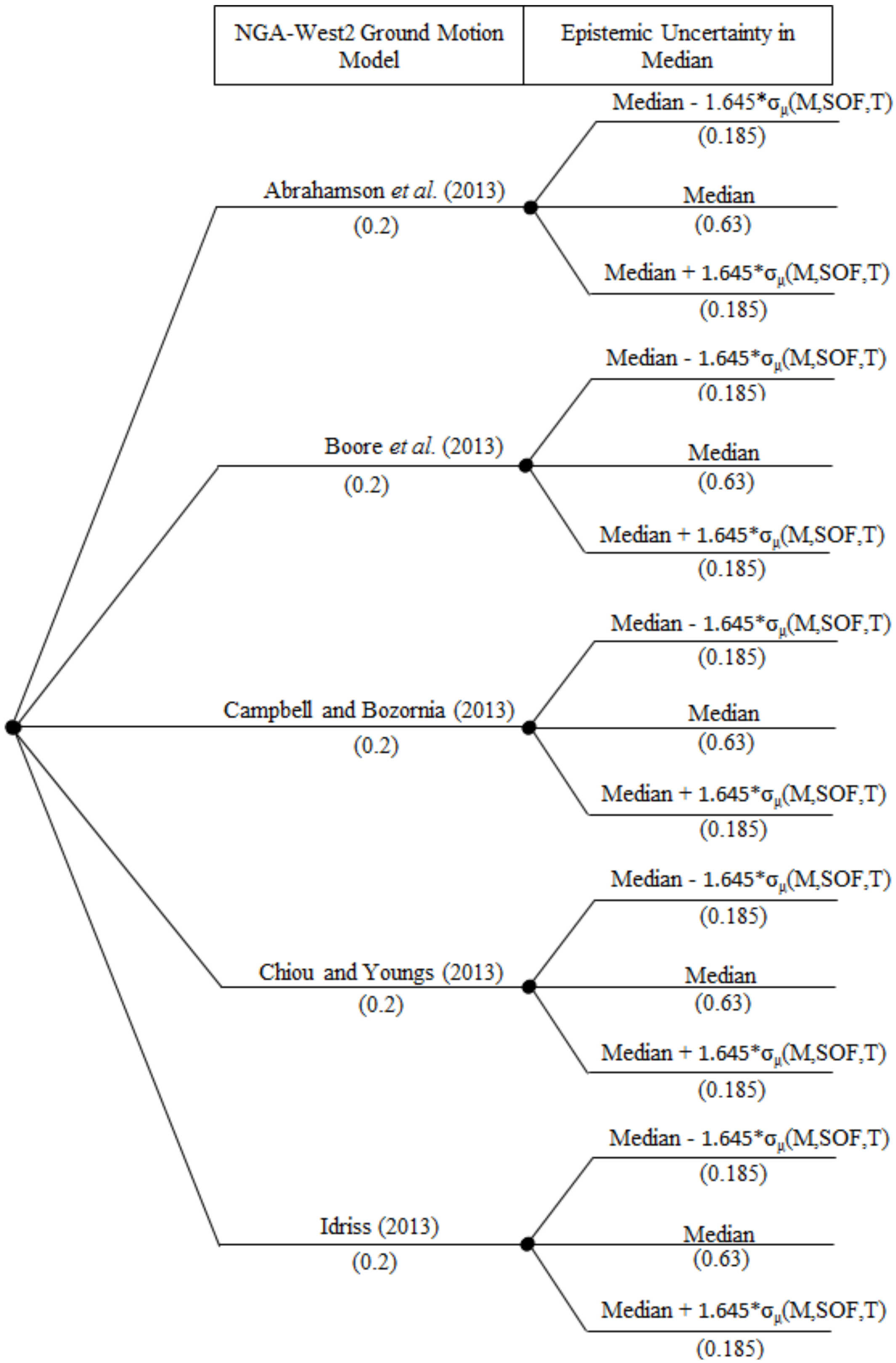

Figure 4.12 Proposed logic tree for NGA-West2 models.

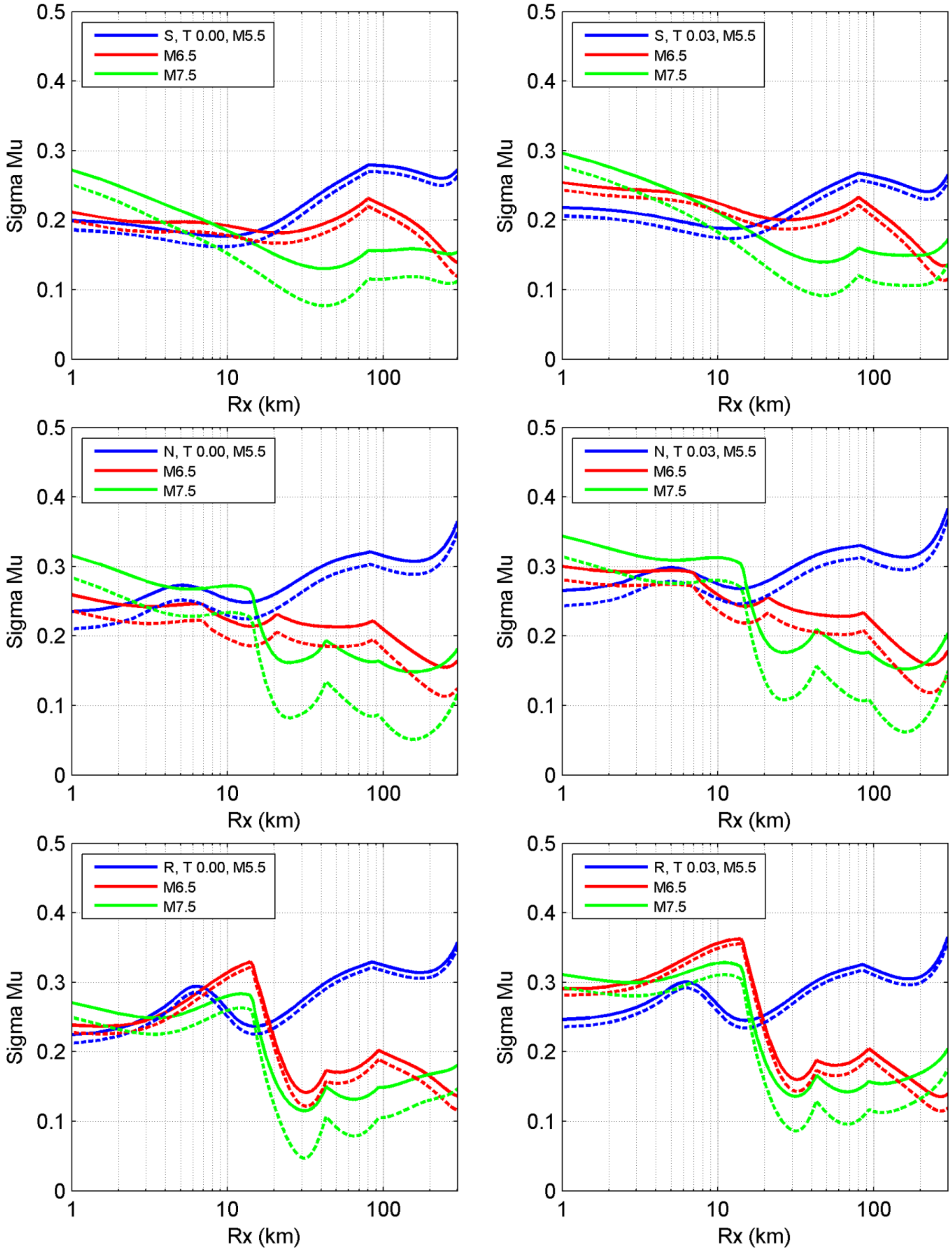

Figure 4.13 **Total epistemic uncertainty in median predictions of the NGA-West2 GMPEs using the logic tree in Figure 4.12 and the rupture geometries in Figure 1.3 at PGA and spectral period of 0.03 sec. Dashed lines show the epistemic uncertainty resulting from just the differences between the 5 models.**

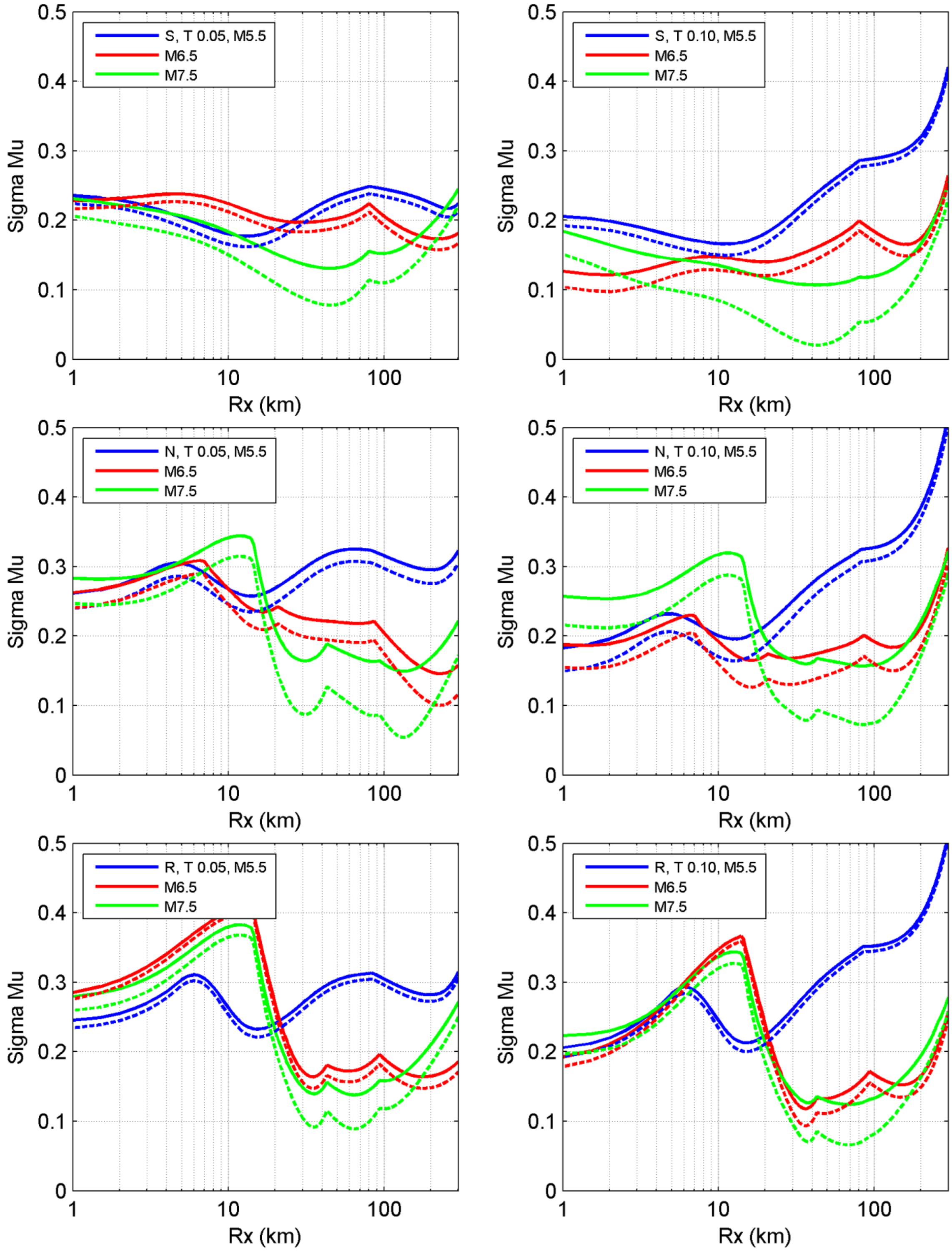

Figure 4.14 **Total epistemic uncertainty in median predictions of the NGA-West2 GMPEs using the logic tree in Figure 4.12 and the rupture geometries in Figure 1.3 at spectral periods of 0.05 and 0.10 sec. Dashed lines show the epistemic uncertainty resulting from just the differences between the 5 models.**

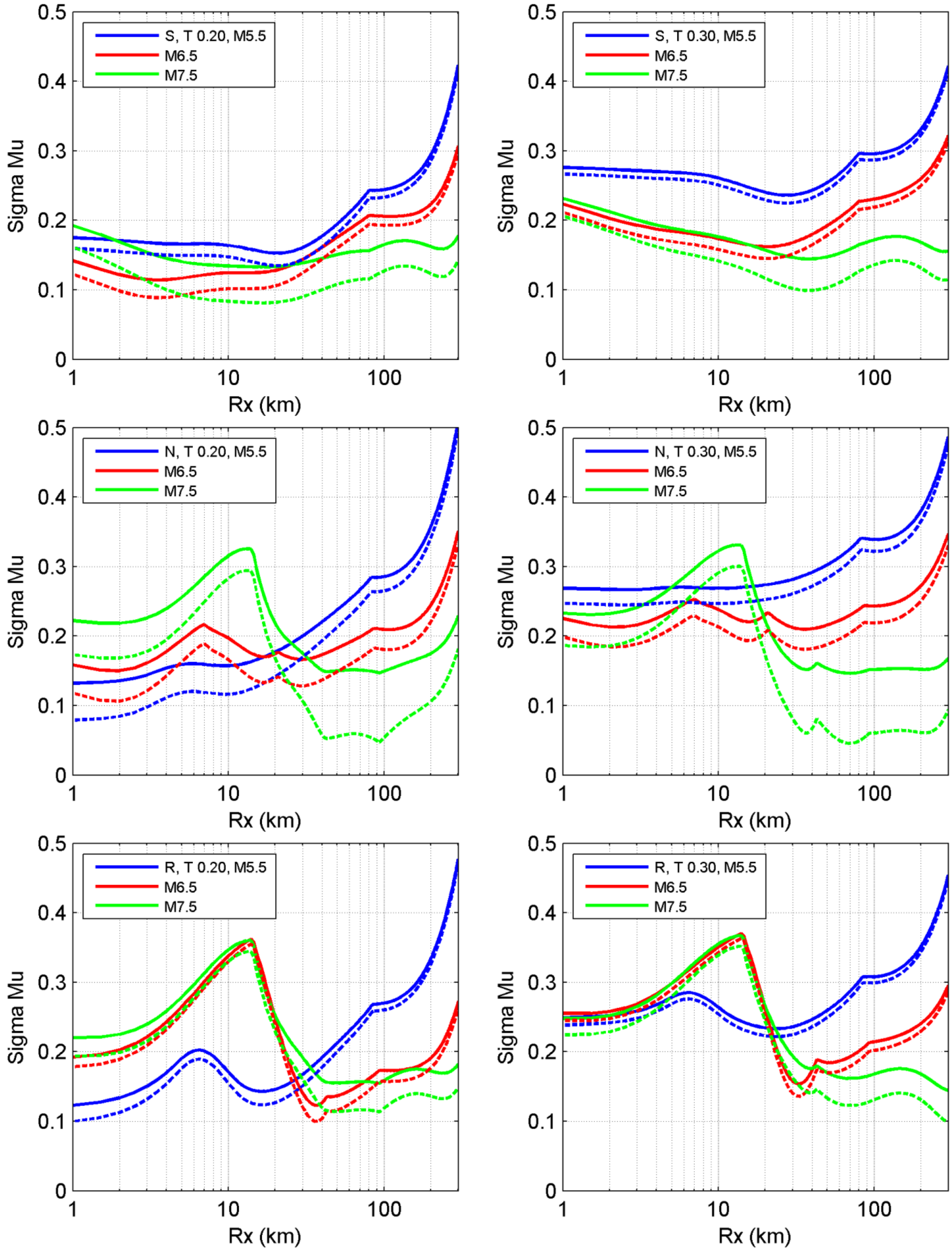

Figure 4.15 **Total epistemic uncertainty in median predictions of the NGA-West2 GMPEs using the logic tree in Figure 4.12 and the rupture geometries in Figure 1.3 at spectral periods of 0.20 and 0.30 sec. Dashed lines show the epistemic uncertainty resulting from just the differences between the 5 models.**

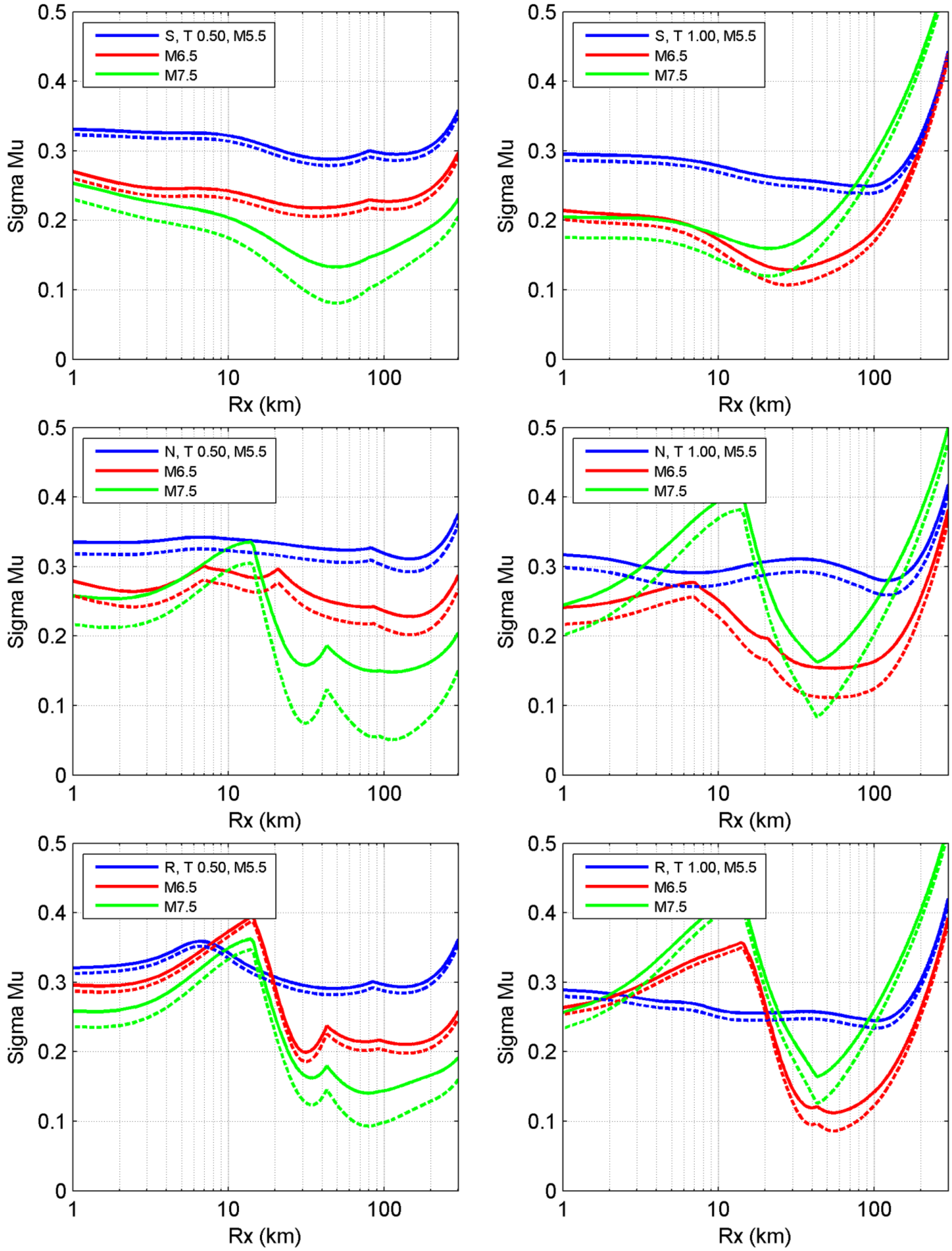

Figure 4.16 Total epistemic uncertainty in median predictions of the NGA-West2 GMPEs using the logic tree in Figure 4.12 and the rupture geometries in Figure 1.3 at spectral periods of 0.50 and 1.0 sec. Dashed lines show the epistemic uncertainty resulting from just the differences between the 5 models.

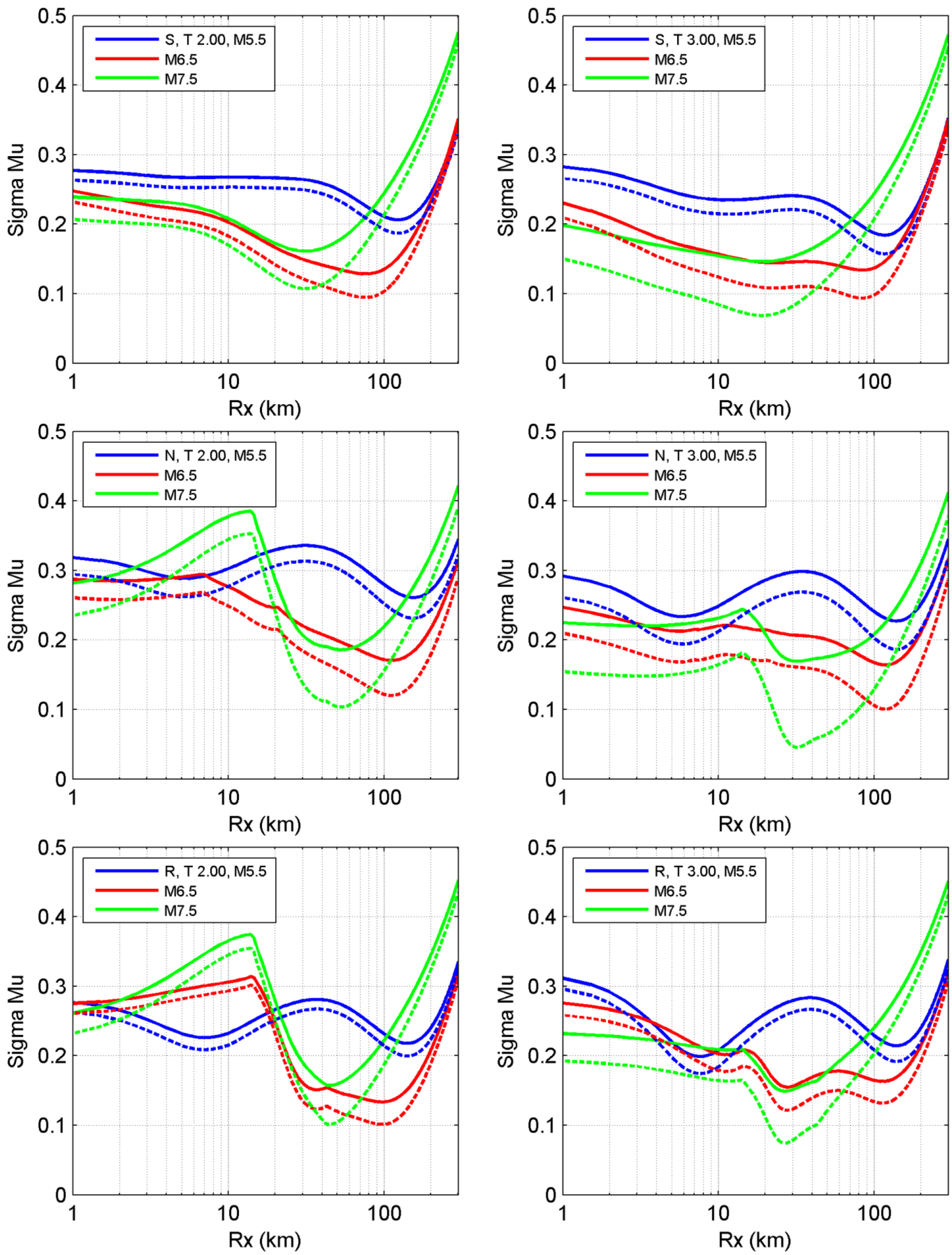

Figure 4.17 **Total epistemic uncertainty in median predictions of the NGA-West2 GMPEs using the logic tree in Figure 4.12 and the rupture geometries in Figure 1.3 at spectral periods of 2.0 and 3.0 sec. Dashed lines show the epistemic uncertainty resulting from just the differences between the 5 models.**

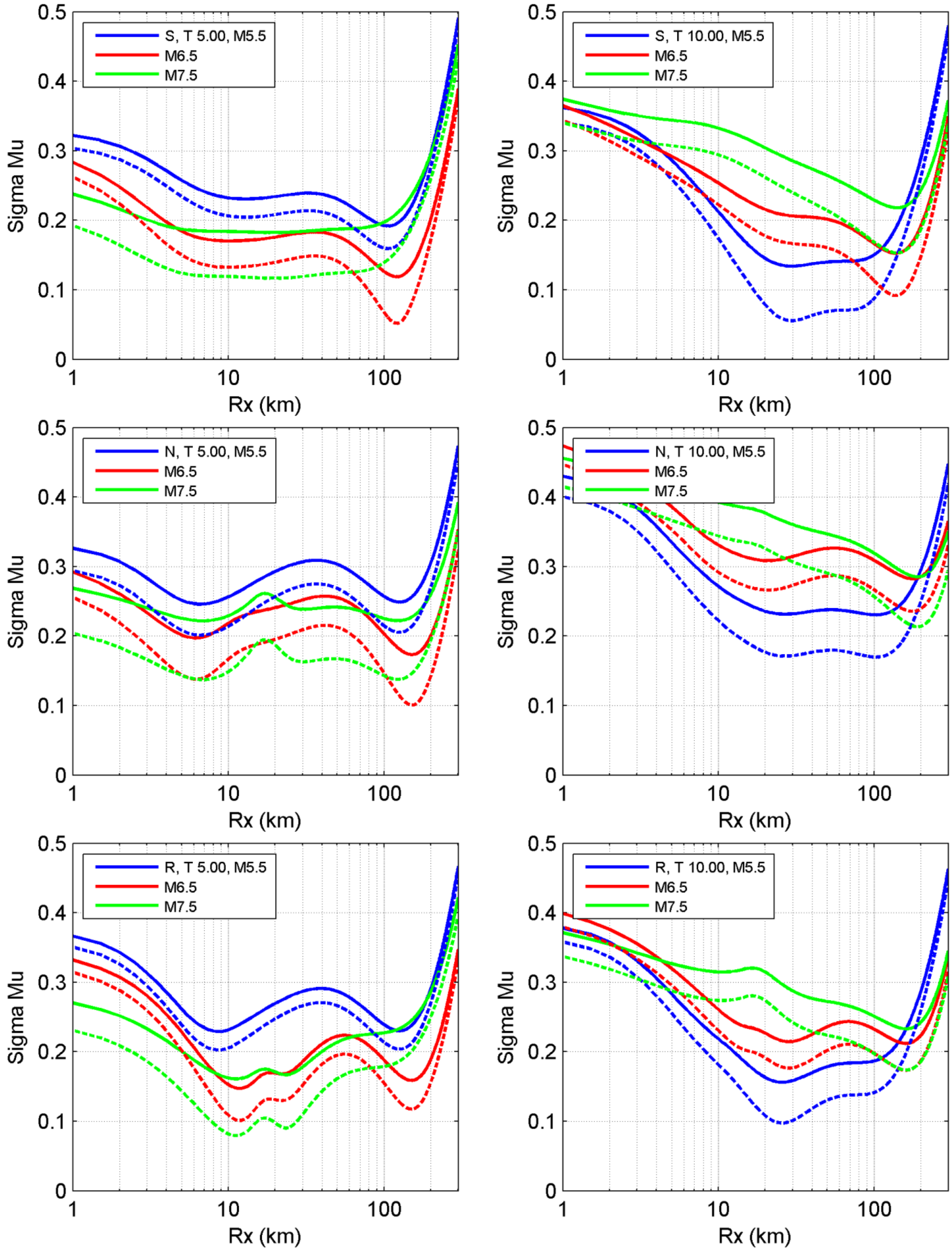

Figure 4.18 **Total epistemic uncertainty in median predictions of the NGA-West2 GMPEs using the logic tree in Figure 4.12 and the rupture geometries in Figure 1.3 at spectral periods of 5.0 and 10.0 sec. Dashed lines show the epistemic uncertainty resulting from just the differences between the 5 models.**

5 Summary

We presented a simple model to assign additional epistemic uncertainty to the median predictions of each of the 5 NGA-West2 GMPEs in a logic tree framework. The epistemic uncertainty was evaluated based on the model-to-model differences and the statistics of the model fits and empirical data distributions while accounting for imposed model constraints. The proposed additional epistemic uncertainty is distance-independent but depends on magnitude, style-of-faulting, and spectral period. The 5 NGA-West2 models are given equal weights and the epistemic uncertainty in the median predictions is modeled using a three-point discrete approximation to a normal distribution. This additional epistemic uncertainty represents the minimum uncertainty to be used with the NGA-West2 models.

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