Appendix G: Implementation of the WAACY Composite Magnitude Probability Density Function

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G.1 Introduction

The WAACY model (named for authors Wooddell, Abrahamson, Acevedo-Cabrera, and Youngs) is a recently introduced magnitude PDF that combines concepts of the characteristic earthquake and truncated exponential models. It is used to describe earthquake occurrence on fault sources that are too long for reasonable application of the characteristic earthquake model, and that could infrequently host earthquakes significantly larger than hypothesized characteristic events on shorter portions of the source. In the WAACY magnitude probability density function (PDF), characteristic earthquakes of magnitude M_{char} occur with greater frequency than would be predicted from an exponential distribution with an M_{max} value that is based on the longest multi-segment or multi-fault ruptures that could occur on the source.

The motivation for developing the WAACY magnitude PDF came from two considerations:

1. In tectonic settings such as coastal California, multi-fault or multi-segment ruptures, even if relatively unlikely, need to be considered in SSC models for PSHA (Field et al., 2013).
2. Based on paleoseismic data, the coefficient of variation (CV), or the standard deviation divided by the mean, of surface-fault displacements at single points is significantly less than predicted from faults modeled with Gutenberg-Richter-like exponential magnitude-frequency distributions (Hecker et al., 2013). The maximum slip-at-a-point CV determined from Hecker et al. (2013) is used to constrain the allowable implementations of the WAACY model.

Thus the WAACY model is proposed to satisfy a need for a magnitude PDF that permits broad aleatory variability in magnitude above characteristic magnitudes, yet remains consistent with paleoseismic data that may preclude the simpler truncated exponential magnitude distribution.

Details of the WAACY model, including its derivation, are in a draft manuscript by Wooddell et al. that is included as *Attachment G-1*. The technical justification for the use of the WAACY model in the Diablo Canyon SSC model is provided in *Chapter 10* of the main report.

G.2 WAACY Magnitude PDF Functional Form

The WAACY magnitude PDF has three components: a low-magnitude exponential portion, a characteristic portion, and a high-magnitude exponential "tail." These components and the terms introduced below are shown graphically on Figure G-1. The characteristic portion is a Gaussian distribution with a mean of M_{char}, standard deviation σ_m, and a range from M_1 to M_2, where $M_1 = M_{char} - \Delta M$ and $M_2 = M_{char} + N_{sig}\sigma_m$, with N_{sig} representing a specified number of standard deviations. The low-magnitude exponential portion is a doubly truncated exponential distribution from M_{min} to M_1 and a slope of $-b$. The high-magnitude tail is a doubly truncated exponential distribution from M_2 to M_{max} with a *b*-value of b_{tail}.

The key parameters to implement the WAACY model are M_{min}, *b*, M_{char}, ΔM, σ_m, N_{sig}, b_{tail}, M_{max}, and F1 (for the fraction of the total moment rate allocated to the low-magnitude tail). Viable combinations of these parameters are evaluated by comparing the predicted slip-at-a point CV to a threshold CV based on Hecker et al. (2013). As described in *Attachment G-1*, the predicted slip-at-a point values and corresponding CVs from a magnitude PDF depend on selection of magnitude-displacement relations. The methodology and examples of predicted slip-at-a point *CV* values from characteristic and truncated exponential magnitude PDFs are provided in Hecker et al. (2013).

Table G-1 summarizes the parameter values that the TI Team initially considered for use with the WAACY model, and lists the magnitude-displacement relations and CV constraints selected to evaluate the alternative parameter combinations. The values shown in Table G-1 do not reflect the final logic-tree values, but rather were a starting point for a parametric study.

Table G-1. Parameters for the WAACY Magnitude PDF and Values Considered in the Parametric Study

Parameter	Values	Explanation
M_{min}	5.0	Standard of practice for PSHA
b	0.8, 0.9	Range is the 2008 NSHMP *b* value of 0.8 to 0.9, a range typical for standard of practice for PSHA. Preliminary analysis shows this is not a sensitive parameter.
M_{char}	6.5, 7.0, 7.5	Values rounded to the nearest half magnitude, based on range of M_{char} from 6.4 to 7.3 in the SSC logic tree (SSC Report Tables 10-4, 10-7, 10-10, and 10-13)
ΔM	0.25	Fixed to 0.25 following width of boxcar used by YC85. Preliminary analysis shows this is not a sensitive parameter.
σ_m	0.15, 0.20, 0.25	Middle value approximates the sigma of the **M**-*A* relation from WC94. Low value assumes a portion of the sigma is due to magnitude and/or area reporting errors and not true variability (cf. WGCEP, 2003). High value assumes that a larger sigma is appropriate to combine real magnitude and area variability in M_{char} approximations.
N_{sig}	1.5	Fixed to 1.5 standard deviations above the best estimate M_{char}. Preliminary analysis shows this is not a sensitive parameter.
b_{tail}	0.6 to 3	Low value represents a near-minimum *b* value that would be considered for a source and an end-member for the WAACY concept of relatively rare multi-fault ruptures. For values above 3 the large-M tail is too diminished to affect hazard at the DCPP.
M_{max}	7.5, 8.0, 8.5	Values rounded to the nearest half magnitude, based on the range of M_{max} from 7.4 to 8.5 in the SSC logic tree (SSC Report Tables 10-4, 10-7, 10-10, and 10-13)

Parameter	Values	Explanation
F1 (Fraction of total moment rate, low-magnitude portion)	3%, 6%, 12%	Middle value is from YC85. Range is half and twice the middle value. For values lower than range, low-magnitude tail does not contribute. For values higher than range, shape approximates exponential distribution and always violates *CV* constraint.
Magnitude-displacement relation	WC94, HEA13, S09,13	Available scaling relations between average surface slip and magnitude, from Wooddell et al. (*Attachment G-1*).
CV threshold	0.55	Based on Hecker et al. (2013). Their preferred *CV* is 0.40 to 0.48 for mean displacements ≥ 1.0 m.

Abbreviations: HEA13 = (Hecker et al., 2013), S09,13 = Combined Magnitude-Area relation of Shaw (2009) and Length-Displacement relation of Shaw (2013b); WC94 = Wells and Coppersmith (1994); YC85 = Youngs and Coppersmith (1995); WGCEP = Working Group on California Earthquake Probabilities.

As shown in Table G-1, three magnitude-average displacement relations were used to calculate the predicted *CV*s. The first two are log-linear magnitude-displacement regressions developed from global data for all slip types; one as published by WC94, the second as developed by Hecker et al. (2013) by fitting data in Wesnousky (2008). The third magnitude-displacement relation is derived from combining the constant stress drop magnitude-area relation of Shaw (2009) with the surface displacement-length relation of Shaw (2013b). The implementation of the magnitude-area relation of Shaw (2009) followed that used for the UCERF3 model as proposed by Shaw (2013a) and a maximum width of 15 km. The displacement-length relation of Shaw (2013b) was implemented as proposed by Shaw (2013a). Equations for the three magnitude-displacement relations are provided in Attachment G-1, and a plot showing a comparison of the three models is provided in Figure 4 of Attachment G-1.

G.3 Parametric Study and Evaluation of the WAACY Magnitude PDF

The predicted CVs from the WAACY magnitude PDF model were evaluated in a parametric study using 8 combinations of M_{char} and M_{max} in increments of 0.5 magnitude units for the range $6.5 \leq M_{char} \leq 7.5$ and $7.5 \leq M_{max} \leq 8.5$. The tests used parameters and magnitudes that spanned the ranges shown in Table G-1. An example result for the magnitude combination $M_{char} = 7.0$, $M_{max} = 8.5$ is shown on Figure G-2. The result plots predicted CV against b_{tail} for various parameter combinations. The WC94 relation results are shown as red triangles, the HEA13 relation results are green squares, and the combined S09,13 relation results are blue circles. Common features to all study results are the higher CV values using the WC94 relation compared to the other two relations, and the inverse relationship between CV and b_{tail}. Most parameter combinations with $b_{tail} \leq 1$ result in CVs that exceed the 0.55 threshold estimated by Hecker et al. (2013), whereas most parameter combinations with $b_{tail} \geq 2$ are at or below the CV threshold. Almost all combinations evaluated against the WC94 relation yielded CVs greater than the threshold.

Inspection of parametric study results across all 8 M_{char}, M_{max} combinations suggests that the parameters with the greatest impact on CV are b_{tail}, F1, and selection of magnitude scaling relation. Additional simplifications to parameters were applied to aid in selecting SSC logic tree values and weights. The simplifications are shown in Table G-2 and are represented graphically as black diamonds on Figure G-2. None of the simplifications are believed to have ground motion implications for the DCPP (*Chapter 14*).

Table G-2. Simplified Parameters for Further Examination of the WAACY Magnitude PDF Model

Parameter	Values	Explanation
M_{min}	5.0	Standard of practice for PSHA
b	0.9	Selected value closest to a "typical fault" value of approximately 1.0. Model is not sensitive to this parameter.
ΔM	0.25	Model is not sensitive to this parameter.
σ_m	0.20	Middle value approximates the sigma of the **M**-*A* relation from WC94. Model is not sensitive to this parameter.
N_{sig}	1.5	Model is not sensitive to this parameter.
b_{tail}	1.0, 2.0, 3.0	Sensitive parameter. The three values sample a broad range of viable options, and often yield different CV estimates.
F1	3%, 6%, 12%	Sensitive parameter. Values commonly yield different CV estimates. Explanation of range in Table G-1
Magnitude-displacement relation	HEA13	Similar results to S09,13; More recent scaling relation fit to more recently available data in the applicable magnitude range.

The parameters *b* and σ_m were fixed as they had little influence compared to b_{tail} and F1. The values of b_{tail} were reduced to 1.0, 2.0, and 3.0 as the finer divisions did not produce meaningfully different CV estimates, and the TI Team judged the three values were adequate to sample a range of viable estimates of b_{tail} that may have ground motion significance.

Although the choice of magnitude-displacement relation clearly correlates with CV (Figure G-2), further evaluation of the results focused on the HEA13 magnitude-displacement relation to estimate *CV* values. This relation was selected for the following reasons:

1. It represents an empirical fit to the best surface-displacement data available at the time, including significant additions to the WC94 dataset.

2. It was developed to match displacements in the higher-magnitude range that includes the range of M_{char} and M_{max} combinations being evaluated for the Diablo Canyon SSC model.

3. It yields comparable results with the Shaw (S09,13) relation, and as a linear relationship it represents a simplification that the TI Team judged is appropriate

In addition, the TI Team considered it plausible that the steeper slope of the WC94 relation is influenced by data points in the lower magnitude range that may have "incompletely" ruptured the surface, thus resulting in average displacement estimates that may not properly scale with surface displacement data at greater magnitudes.

Results based on the parameterization in Table G-2 for the 8 M_{char}, M_{max} combinations showed CV values above and below the 0.55 threshold based on values or combinations of values of b_{tail} and F1. The CV results differed—in some instances significantly—based on the values of M_{char} and M_{max} and the differences in their values (i.e., $M_{max} – M_{char}$). Results of CV plotted against b_{tail} and F1 are shown on Figures G-3 and G-4, respectively. The plots show three groupings of M_{char}, M_{max} combinations, with slight offsets on the horizontal (x) axes to better visualize the similarities and differences among the groups. We note here that the three groupings shown on Figure G-3 and G-4 were selected based on an earlier version of the parametric study results. The results shown here became available after finalization of the SSC model logic tree, and are identical to the results used by Wooddell et al. for their manuscript in *Attachment G-1*. We make note below of instances where differences between the earlier and this more recent set of results would impact decisions about logic tree weights. However, we emphasize that the differences between the earlier and the current parametric study results are minor, such that changes in logic tree branch weights to better match the current results would have negligible effects on the overall hazard results, as shown in the Diablo Canyon SSC report, *Chapter 14*.

The first group, referred to as Group (A), contains three members (Figures G-3a and G-4a). This group includes the two combinations with the smallest difference between M_{char} and M_{max} (0.5 magnitude units) and the combination of the lowest M_{char} and M_{max} values (6.5 and 7.5, respectively). Group (B) has two members, with differences between M_{char} and M_{max} of 1 magnitude unit (Figures G-3b and G-4b). The remaining three M_{char}, M_{max} combinations belong to Group (C). Combinations in this group have $M_{char} – M_{max}$ differences greater than 1 magnitude unit (Figures G-3c and G-4c).

Inspection of the plots suggests similarities among groups and differences between groups that are useful for characterizing parameter values and combinations that are favorable, permissible, or can be rejected. For example, Group (A) combinations show CV values less than the threshold value across all combinations of b_{tail} and F1 considered (Figures G-3a and G-4a). Within Group (A), there is a visible but slight preference for higher b_{tail} values than for the lowest value, and a preference for lower F1s than the maximum F1.

Group (B) combinations show a preference for higher b_{tail} values and lower F1 values, with some combinations of low b_{tail} and high F1 values exceeding the threshold *CV* value of 0.55 (Specifically, for M_{char} = 7.5, M_{max} = 8.5, combinations of b_{tail} = 1 and CV = 0.06 or 0.12 and b_{tail} = 2 and CV = 0.12 exceed the CV threshold of 0.55). We note here that the biggest difference between the previous parametric study results and the more recent ones is in the CVs for Group (B) combinations. Previously, only combinations of b_{tail} = 1 and CV = 0.12 yielded CV > 0.55, and there were similar Group (B) characteristics that distinguished them from the other groups. In light of current results, the groups could be further simplified into two, with M_{char} = 7.0, M_{max} = 8.0 having similarities with Group (A) and M_{char} = 7.5, M_{max} = 8.5 having similarities with Group (C).

Group (C) combinations show the strongest correlation between CV and b_{tail} value, with all b_{tail} = 1 cases being essentially at or above the threshold *CV* value (Figure G-3c). Prior versions of the parametric study results showed all b_{tail} = 1 cases above the threshold *CV* value. There is likewise a preference in Group (C) for low F1 values, which is comparable to, though perhaps slightly less than, the preference in Group (B) for lower F1 values (Figure G-4). A summary of observations within each Group are presented in Table G-3

Table G-3. Summary of WAACY Magnitude PDF Parametric Study Results by Group

Group	M_{char} – M_{max} Combinations	Notes
A	6.5–7.5, 7.0–7.5, 7.5–8.0	All parameter combinations below threshold CV; preference for higher b_{tail} and lower F1 values
B*	7.0–8.0, 7.5–8.5	Many parameter combinations with b_{tail} = 1 are above threshold CV; b_{tail} = 2, F1 = 0.12 also is above threshold CV. Preference for higher b_{tail} values; preference for lower F1 values.
C	6.5–8.0, 6.5–8.5, 7.0–8.5	Most parameter combinations with b_{tail} = 1 are above threshold CV. Strong preference for higher b_{tail} values; moderate preference for lower F1 values.

*Characteristics of Group B are less distinct with the current parametric study results than indicated by prior results upon which the groupings (and logic tree) were initially based.

G.4 Logic Tree Implementation of WAACY Model for Diablo Canyon SSC

The SSC logic tree implementation of the WAACY magnitude PDF follows the results in Figures G-2 to G-4 and Tables G-2 and G-3. The logic tree for non-fixed parameters is shown graphically on Figure G-5. Fixed parameter values for use in the SSC model are shown in Table G-4. The results are identical to those in Table G-2 with the minor exception of *b*. For the parametric study, the authors of *Attachment G-1* selected *b*-values of 0.8 and 0.9 for testing. The TI Team separately decided to use a *b* = 1.0 following review of typical fault *b* values shown in Stirling et al. (1996) and Page et al. (2011), and making the assumption that removal of dependent earthquakes (aftershocks or foreshocks) occurring on or near those faults would not significantly reduce the *b*-value.

Table G-4. Fixed Parameters for the WAACY Magnitude PDF Model and Their Assigned Values for the Diablo Canyon SSC Logic Tree

Parameter	Value
M_{min}	5.0
b	1.0
ΔM	0.25
σ_m	0.20
N_{sig}	1.5

The logic tree branch weights for b_{tail} and F1 are correlated with specific SSC logic tree M_{char}, M_{max} combinations based on the proximity of the M_{char} and M_{max} values to one of the 8 combinations tested in the parametric study (Figure G-5). The logic trees for F1 and b_{tail} include asymmetric weighting across all groups, with progressively higher weights for lower F1 values (shown on the logic tree as *percent* moment allocation to the low-magnitude tail), and generally higher weights to greater b_{tail} values. Weighting schemes between groups for F1 show the stronger preference for lower F1s for Group (B) M_{char}, M_{max} combinations (e.g., a weight of only [0.10] for the 12% moment) compared with Groups (A) and (C) (a weight of [0.20] for the same 12% moment). This difference in weighting is less justified given the current parametric study results (Figures G-3 and G-4) compared to past results, but the TI Team judges that the difference between the Group (B) and the other Groups' weighting schemes has negligible hazard consequences. Weighting schemes between Groups for b_{tail} values show a progressively greater preference for higher values, with the limit of a zero weight for b_{tail} = 1 for Group C, and a weight of [0.30] for the same value in Group (A). We note that there are specific instances of branch combinations that have non-zero weight but resulted in CV values greater than the 0.55 threshold. For example, the Group (B) case for F1 = 0.12 and b_{tail} = 1 yields CV > 0.55 for all cases, but the combination has a weight of [0.1]*[0.2] = 0.02. The TI judges that the low combined weight is adequate, keeping in mind the other simplifications made to the parametric study (e.g., Table G-2).

G.5 References

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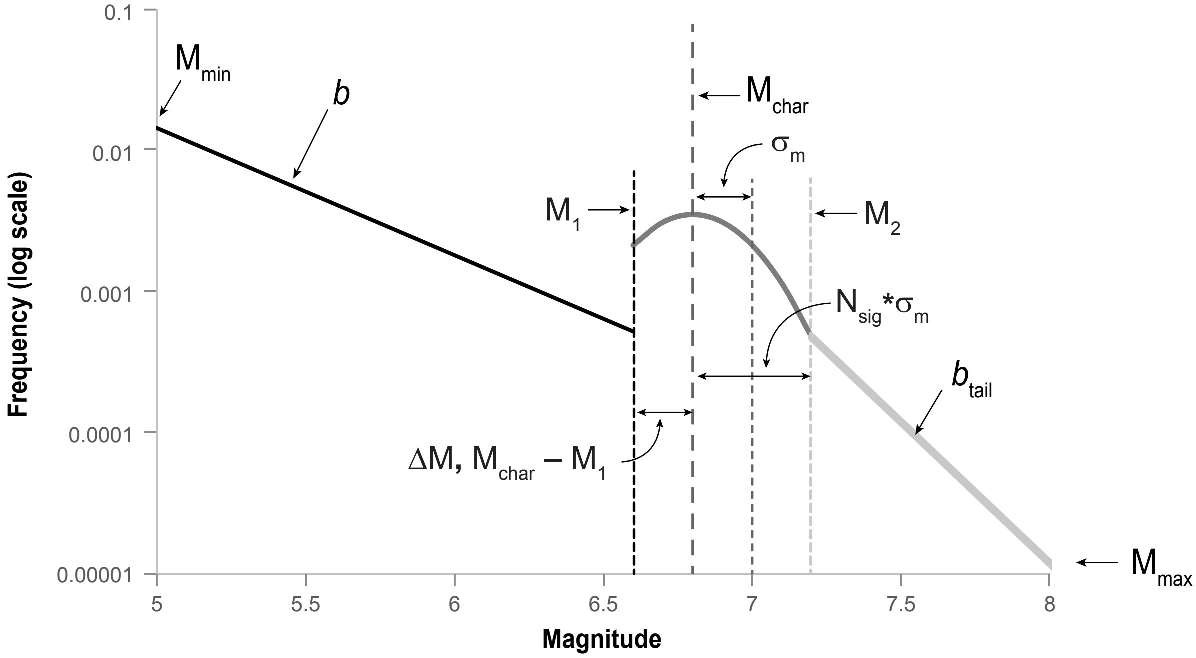

EXPLANATION

- Low-magnitude exponential portion
- Characteristic portion
- High-magnitude tail

Functional Form and Definition of Parameters of the WAACY Magnitude PDF

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Figure **G-1**

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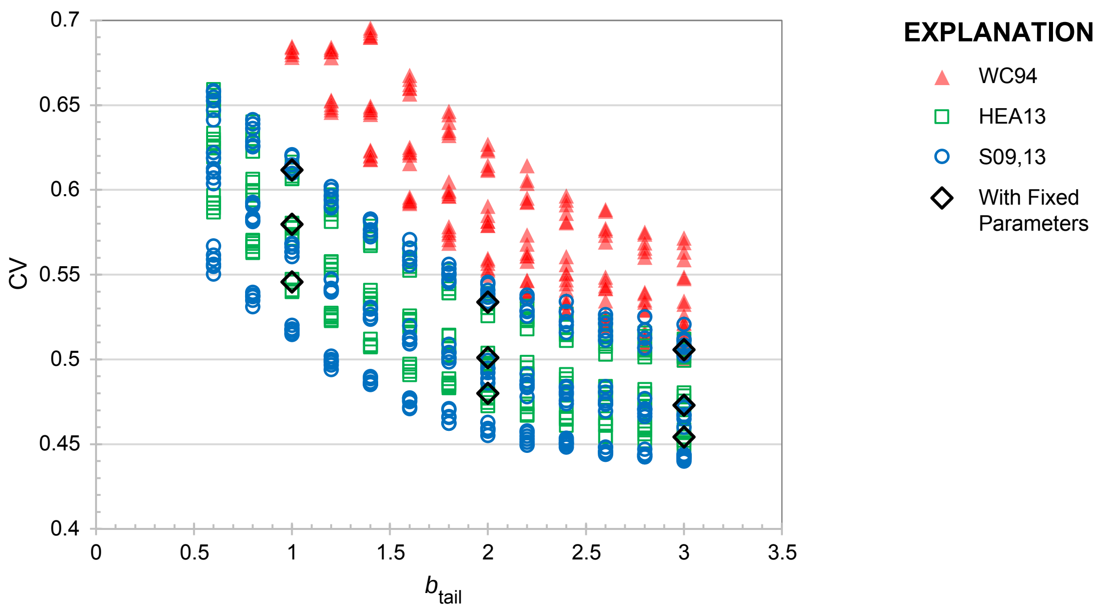

Note: The plot shows predicted CV vs. *b*-value of high-magnitude exponential tail (b_{tail}) for b_{tail} values between 0.6 and 3.0. Symbols represent alternative combinations of WAACY model variables explored in the parametric study* for the case of M_{char} = 7.0 and M_{max} = 8.5. The three colored symbols represent alternative magnitude-displacement relations considered. WC94 = Wells and Coppersmith (1994), HEA13 = Hecker et al. (2013), S09,13 = combined equations from Shaw (2009) and Shaw (2013). Equations for the three relations are presented in the draft manuscript by Wooddell et al. included as *Attachment G-1*. Variable parameters represented in the plot include low-magnitude exponential *b*-value (values of 0.8 and 0.9), standard deviation of the characteristic portion (σ_{char}; values of 0.15, 0.2, 0.25), and fraction of the total moment rate allocated to the low-magnitude exponential portion (F1; values of 0.03, 0.06, 0.12). Black diamond shows the simplification of the parametric study performed by the TI Team for purposes of implementing the WAACY model in the Diablo Canyon SSC logic tree. The diamonds show CV values for the HEA13 relation, b = 0.9, σ_{char} = 0.2, alternative values of b_{tail} of 1.0, 2.0, and 3.0, and alternative values of F1 of 0.03, 0.06, and 0.12.

*The SSC model logic tree on Figure G-5 that provides instructions to implement the WAACY magnitude PDF was constructed based on an earlier version of the parametric study results shown here. The parametric study results shown here are the latest available and are consistent with the version of the manuscript by Wooddell et al. that is included as *Attachment G-1*. Differences between the current and earlier results are minor such that changes in magnitude pair groupings and logic tree branch weights to better match the current results would have negligible effects on the overall results.

CV Versus b_{tail} for M_{char} = 7.0 and M_{max} = 8.5, Grouped by Magnitude-Displacement Relation and Showing WAACY Model Variables Examined in the Parametric Study

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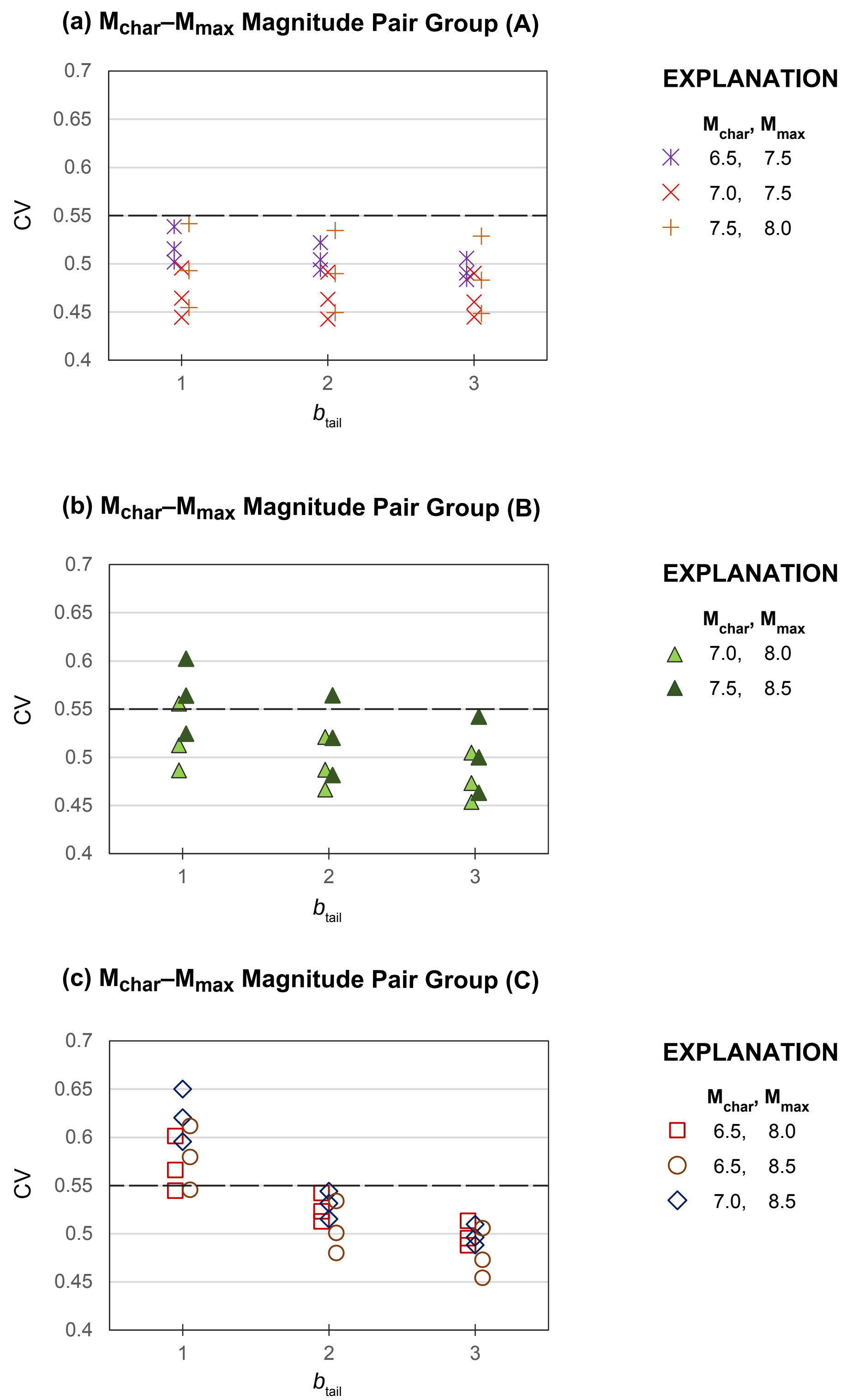

Note: The plots show predicted CV vs. b_{tail} for b_{tail} values of 1.0, 2.0, and 3.0. Symbols differentiate pairs of M_{char} and M_{max}, and are offset slightly from the precise b_{tail} values to more clearly visualize the results*. The vertical stacks of three symbols at each b_{tail} represent the three values of F1; systematically, from higher to lower CV, these are 0.12, 0.06, and 0.03. The dashed line at CV = 0.55 represents the threshold CV of Hecker et al. (2013); values less than 0.55 are consistent with CVs calculated from global paleoseismic data on repeated displacement per event at a point.

*See note on Figure G-2

CV Versus b_{tail} for HEA13 Relation, Evaluating Logic Tree Groupings of M_{char}–M_{max} Pairs for Implementiation of the WAACY Model

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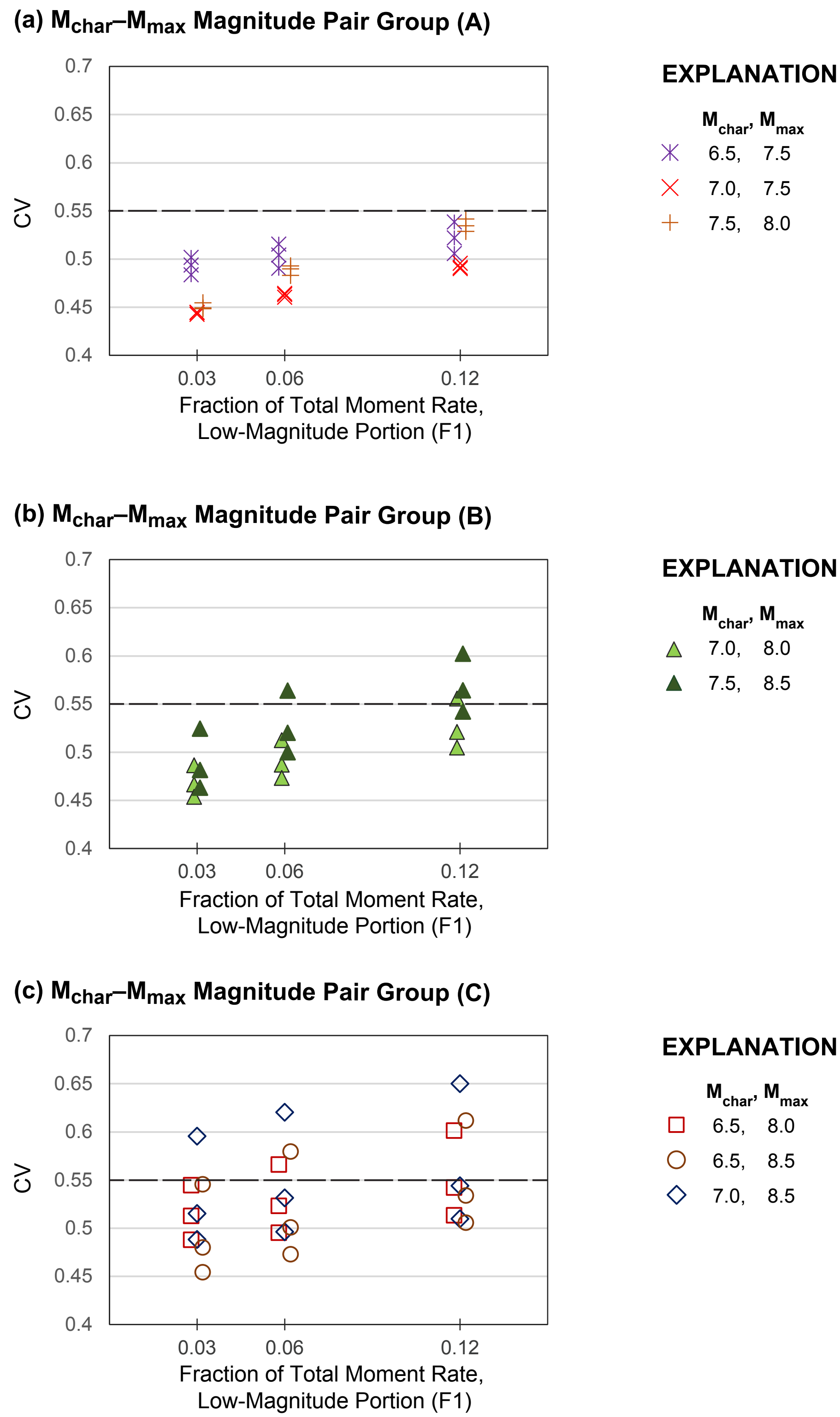

Note: The plots show predicted CV vs. F1 for the F1 values of 0.03, 0.06, and 0.12. Symbols differentiate pairs of M_{char} and M_{max}, and are offset slightly from the precise F1 values to more clearly visualize the results*. The vertical stacks of three symbols at each F1 represent the three b_{tail} values; systematically, from higher to lower CV, these are 1.0, 2.0, and 3.0. The dashed line at CV = 0.55 represents the threshold CV of Hecker et al. (2013); values less than 0.55 are consistent with CVs calculated from global paleoseismic data on repeated displacement per event at a point.

*See note on Figure G-2

CV Versus F1 for HEA13 Relation, Evaluating Logic Tree Groupings of M_{char}–M_{max} Pairs for Implementiation of the WAACY Model

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Magnitude Range	Group	Percent Moment Rate, Low-Magnitude Exponential Portion	*b*-Value, High-Magnitude Tail
M_{char} = 6.5 ± 0.2, M_{max} = 7.5 ± 0.2 or M_{char} = 7.0 ± 0.2, M_{max} = 7.5 ± 0.2 or M_{char} = 7.3, M_{max} = 8.0 ± 0.2	GROUP (A)	12% [0.2]	3 [0.35]
		6% [0.35]	2 [0.35]
		3% [0.45]	1 [0.30]
M_{char} = 7.0 ± 0.2, M_{max} = 8.0 ± 0.2 or M_{char} = 7.3, M_{max} = 8.3–8.5	GROUP (B)	12% [0.1]	3 [0.45]
		6% [0.4]	2 [0.35]
		3% [0.5]	1 [0.2]
M_{char} = 6.5 ± 0.2, M_{max} = 8.0 ± 0.2 or M_{char} = 6.5 ± 0.2, M_{max} = 8.3–8.5 or M_{char} = 7.0 ± 0.2, M_{max} = 8.3–8.5	GROUP (C)	12% [0.2]	3 [0.7]
		6% [0.35]	2 [0.3]
		3% [0.45]	1 [0.0]

Note: WAACY magnitude PDF parameters are shown on Figure G-1 and defined in the text. The logic trees specify values and weights for the two non-fixed WAACY parameters to be used with specific M_{char}, M_{max} combinations based on their proximity to one of 8 combinations tested in the parametric studies. The magnitude pair groups and associated logic tree parameter weights shown on this figure were constructed based on an earlier version of the parametric study results shown on Figures G-2 to G-4 and in *Attachment G-1*. Differences between the current and earlier results are minor such that changes in group assignments or logic tree branch weights to better match the current results would have negligible effects on the overall results.

Logic Trees for the Non-Fixed Parameters in the WAACY Magnitude PDF Model

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