Appendix D.2

Hanford Site-Wide SSHAC Level 3 PSHA Project
April 24, 2014
Hazard Input Document (HID)
Final GMC Model
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Overview

The GMC logic-tree is defined by two separate models, one for crustal earthquakes and another for subduction zone earthquakes. For both types of sources, the logic-tree defines alternative branches for the prediction of median spectral accelerations and for the associated standard deviations of the residuals (sigma). The model is fully defined at 20 oscillator periods: 0.01, 0.02, 0.03, 0.04, 0.05, 0.075, 0.10, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 5.0, 7.5 and 10.0 seconds. All required coefficients and factors for all 20 oscillator periods are provided in Excel spreadsheets that are submitted as supplements to the HID, for ease of transfer into the hazard code.

Median Motions from Crustal Earthquakes

Figure GMC1. Logic-tree for median motions from crustal earthquakes.
The logic-tree for median motions from crustal earthquakes is constructed from a backbone GMPE (the 2014 model of Chiou & Youngs, hereafter CY14, as pre-published in Earthquake Spectra) adjusted by 7 different $V_s$-kappa factors. These 7 new models are then transformed to 189 ($7\times9\times3$) final median models by the application of 27 scaling factors given by the product of 9 branches for inherent uncertainty in the adjustments to the backbone model (additive in natural-log space) and another 3 for host-to-target uncertainty (multiplicative on amplitudes), as illustrated in Figure GMC1.

The CY14 model for spectral accelerations is composed of two parts, the first predicting the spectral acceleration at a reference rock site, $y_{ref}$, which corresponds to a $V_{s30}$ value of 1130 m/s; this is then transformed to the target $V_{s30}$ through application of a nonlinear site adjustment factor. The equation for predicting $y_{ref}$ (in units of g) is:

$$
\ln(y_{ref}) = c_1 + \left\{c_{ia} + \frac{c_{ic}}{\cosh(2.\max(M-4.5,0))}\right\} F_{RV} + \left\{c_{ib} + \frac{c_{id}}{\cosh(2.\max(M-4.5,0))}\right\} F_{NM}
$$

$$
+ \left\{c_7 + \frac{c_{7b}}{\cosh(2.\max(M-4.5,0))}\right\} \Delta Z_{TOR} + \left\{c_{11} + \frac{c_{11b}}{\cosh(2.\max(M-4.5,0))}\right\}(\cos \delta)^2
$$

$$
+ c_2 (M-6) + \frac{c_2 - c_3}{c_n} \ln(1 + e^{c_6(c_H-M)}) + c_4 \ln(R_{rup} + c_5 \cosh(c_6.\max(m-c_{HM},0)))
$$

$$
+ (c_{a4} - c_4) \ln(\sqrt{R_{RUP}^2 + c_{RB}^2}) + \left\{c_{y1} + \frac{c_{y2}}{\cosh(\max(M-c_{y3},0))}\right\} R_{RUP}
$$

$$
+ c_8 \max\left(1 - \frac{\max(R_{RUP} - 40,0)}{30},0\right) \min\left(\frac{\max(M - 5.5,0)}{0.8},1\right) e^{-c_{a4}(M-c_{a4})^2} \Delta DPP
$$

$$
+ c_9 F_{HW} \cos(\delta) \left\{c_{9a} + (1-c_{9a}) \tanh\left(\frac{R_c}{c_{9b}}\right)\right\} \left[1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 1}\right]
$$

(1)

The median (mean log) spectral acceleration for the target site condition is then obtained from the following expression:

$$
\ln(y) = \ln(y_{ref}) + \phi_1 \min\left(\ln\left(\frac{V_{s30}}{1130}\right),0\right) + \phi_3 \left(1 - e^{-\Delta Z_{ij}/\phi_3}\right)
$$

$$
+ \phi_2 e^{\phi_2(\min(V_{s30},1130)-360)} - e^{\phi_2(1130-360)} \right\} \ln\left(\frac{y_{ref} + \phi_4\phi_5}{\phi_4}\right)
$$

(2)

The predictor variables in these equations are as follows:
M  Moment magnitude
R_{RRUP}  Closest distance to rupture plane (km)
R_{JB}  Joyner-Boore distance (km)
R_x  Perpendicular (to fault strike) distance to site from the fault line
(surface projection of top of rupture), positive in the down-dip
direction (km)
F_{HW}  Hanging-wall factor: 1 for R_x \geq 0, 0 for R_x < 0.
\delta  Fault dip angle
Z_{TOR}  Depth to top of rupture (km)
\Delta Z_{TOR}  Z_{TOR} centered on M-dependent average Z_{TOR} (see below)
F_{RV}  Flag for reverse/reverse-oblique faulting: 1 for 30^\circ \leq \lambda \leq 150^\circ, 0
otherwise
F_{NM}  Flag for normal faulting: 1 for -120^\circ \leq \lambda \leq -60^\circ, 0 otherwise;
excludes normal-oblique faulting
V_{s30}  Time-averaged shear-wave velocity over top 30 m (m/s); this is set
to 760 m/s for these calculations (assumed host value)
Z_{1.0}  Depth to shear-wave velocity of 1.0 km/s (m) (see below)
\Delta Z_{1.0}  Z_{1.0} centered on the V_{s30}-dependent average Z_{1.0} (see below)
\Delta DPP  DPP centered on site- and earthquake-specific average DPP (see below)

The parameter \Delta Z_{TOR} is calculated as the value of Z_{TOR} for the earthquake under
consideration minus the mean value for earthquakes of magnitude M, \overline{Z_{TOR}(M)}. To
account for the higher near-surface crustal strength of the basalts compared to typical
active tectonic region crust, \Delta Z_{TOR} is computed by the equation:

\[ \Delta Z_{TOR} = \max[Z_{TOR}, 3] - \overline{Z_{TOR}(M)} \]  (3)

The value of \overline{Z_{TOR}(M)} is computed from Equation (4a) for reverse and reverse-oblique
faulting or from Equation (4b) for strike-slip or normal faulting:

\[ \overline{Z_{TOR}(M)} = \max[2.704 - 1.266.\max(M - 5.849,0),0]^2 \]  (4a)

\[ \overline{Z_{TOR}(M)} = \max[2.673 - 1.136.\max(M - 4.970,0),0]^2 \]  (4b)

For the host region (California) classification, for \( V_{s30} = 760 \) m/s, the estimated value of
\( Z_{1.0} \) for all locations is 27.4 m. Since this is an estimated rather than measured value
(since it corresponds to an ideal host site profile), the term \( \Delta Z_{1.0} \) is 0.0 for all sites.
For these hazard calculations, rupture directivity effects will not be included, hence the term $\Delta DPP$ is set to zero.

The values of the coefficients of Equations (1) and (2) for the 20 response periods are given in Excel file `Hanford_GMC_Crustal_median_CY14_coefficients.xlsx`.

The values of the $V_s$-kappa adjustment factors for the 20 target oscillator periods and the five target sites are in the Excel file `Hanford_GMC_Crustal_VsKappa_factors.xlsx`.

The period-dependent adjustment factors for the inherent epistemic uncertainty in the median backbone are given by Equation (5)

$$\Delta \ln(Y) = p_1 + p_2 (M - 6.5) + p_3 \max(M - 7,0) +$$

$$F_{HW} \left[ 1 + p_4 \cos(\delta) \right] \times \ln[p_5 \cosh\left(p_6 \max(\ln(R_X/\rho_7),0)\right)] \times \exp(p_8 R_{JB}) \times \max(0, \min(M,6.5) - 5.5)$$

The term multiplying $F_{HW}$ accounts for epistemic uncertainty in hanging wall scaling. It is a maximum at sites on top of the hanging wall ($R_{JB}=0$) and decays to the footwall and neutral site epistemic uncertainty as $R_{JB}$ increases ($p_8$ is negative). The coefficients of Eq. (5) are given in Excel file: `Hanford_GMC_Crustal_Median_Scaling_Coefficients.xlsx`.

The host-to-target scaling factors are independent of the oscillator period and the three values are indicated in Figure GMC1. The weights on all branches of the logic-tree for median ground motions from crustal earthquakes are also indicated in the figure.

**Median Motions from Subduction Earthquakes**

The preliminary GMC logic-tree for median spectral accelerations due to subduction earthquakes uses a new GMPE, adapted from the BCHydro GMPE as a backbone. The full logic tree has 72 branches, as can be inferred from Figure GMC2, below.

The backbone model is adjusted to the local site conditions ($V_s$ profile), but this is done as the final step since the adjustment depends on the predicted median spectra for a specific scenario. No kappa correction is applied. For the backbone GMPE, branching is applied to model the epistemic uncertainty, with branches for different magnitudes at which the magnitude scaling changes ($\Delta C1$), for uncertainty in the anelastic attenuation over large distances ($\theta_6$), and for alternative median values. The branches for
alternative median values reflect the composite effect of uncertainty in the median and host-to-target adjustments.

\[ y = \theta_1 + \theta_4 \Delta C_1 + (\theta_2 + \theta_{14} F_{\text{event}} + \theta_3 (M - 7.8)) \ln(R + C_4 e^{(M-6)\theta_9}) + \theta_6 R + \theta_{10} F_{\text{event}} + f_{\text{Mag}}(M) + f_{\text{depth}}(Z_h) + f_{\text{FABA}}(R) + f_{\text{site}}(PGA_{1000}, V_{s30}) \]  

(6)

The model for magnitude scaling is:

\[ f_{\text{Mag}}(M) = \theta_4 [M - (C_1 + \Delta C_1)] + \theta_{13} (10 - M)^2 \quad M \leq C_1 + \Delta C_1 \]  

(7a)

\[ f_{\text{Mag}}(M) = \theta_5 [M - (C_1 + \Delta C_1)] + \theta_{13} (10 - M)^2 \quad M > C_1 + \Delta C_1 \]  

(7b)

The model for depth scaling is:

*The Vs adjustment factors are conditioned on both \( \Delta C_1 \) and \( \theta_6 \)

*Figure GMC2. Logic-tree for median motions from subduction earthquakes.*
$$f_{\text{depth}}(Z_h) = \theta_1(Z_h - 60)F_{\text{event}} \quad \text{(8)}$$

The model for forearc/backarc scaling is:

$$f_{\text{FABA}}(R) = \begin{cases} 
\theta_8 \ln\left(\frac{\max[R,40]}{40}\right)F_{\text{FABA}} & F_{\text{event}} = 1 \\
\theta_{16} \ln\left(\frac{\max[R,40]}{40}\right)F_{\text{FABA}} & F_{\text{event}} = 0
\end{cases} \quad \text{(9a)}$$

$$f_{\text{FABA}}(R) = \begin{cases} 
\theta_8 \ln\left(\frac{\max[R,40]}{40}\right)F_{\text{FABA}} & F_{\text{event}} = 1 \\
\theta_{16} \ln\left(\frac{\max[R,40]}{40}\right)F_{\text{FABA}} & F_{\text{event}} = 0
\end{cases} \quad \text{(9b)}$$

where $F_{\text{FABA}}$ is 0 for forearc (or unknown) and 1 for backarc sites.

The predictor variables in these equations are as follows:

- $M$: Moment magnitude
- $C_1 + \Delta C_1$: Magnitude at which magnitude scaling changes; ($C_1$ is always equal to 7.8)
- $Z_h$: Focal depth (km)
- $F_{\text{event}}$: 0 for interface events, 1 for intraslab events
- $R$: $R_{\text{RUP}}$ for $F_{\text{event}} = 0$, $R_{\text{hyp}}$ for $F_{\text{event}} = 1$
- $V_{s30}$: A value of 760 m/s is used

The site-response scaling model, for sites with $V_{s30}$ less than $V_{\text{lin}}$ is:

$$f_{\text{site}}(PGA_{1000},V_{s30}) = \theta_{12} \ln\left(\frac{V^*_s}{V_{\text{lin}}}\right) - b \ln(PGA_{1000} + c) + b \ln\left(PGA_{1000} + c\left(\frac{V^*_s}{V_{\text{lin}}}\right)^n\right) \quad \text{(10a)}$$

and for sites with $V_{s30} \geq V_{\text{lin}}$ is:

$$f_{\text{site}}(PGA_{1000},V_{s30}) = \theta_{12} \ln\left(\frac{V^*_s}{V_{\text{lin}}}\right) + b n \ln\left(\frac{V^*_s}{V_{\text{lin}}}\right) \quad \text{(10b)}$$

The predictor variables in Eq.(10) are the following:

- $PGA_{1000}$: Median PGA for $V_{s30} = 1,000$ m/s
- $V^*_s$: 1,000 m/s if $V_{s30} > 1,000$ m/s; $V_{s30}$ for $V_{s30} \leq 1,000$ m/s
The values of the coefficients of Equations (6) through (10) for the 20 response periods are given in Excel file *Hanford_GMC_Subduction_Median_Coefficients.xlsx*.

The values of the $V_s$ adjustment factors, which are specific to each combination of $\Delta C_1$ and $\theta_6$ (hence there are six sets of values for each of the 5 hazard calculation sites) are listed in Excel file *Hanford_GMC_Subduction_Vsfactors.xlsx*.

**Sigma Model for Crustal Earthquakes**

The structure of the sigma logic-tree for crustal earthquakes consists of 2 branches representing different assumptions on the distribution shape, and 3 branches representing different values of the standard deviation (sigma), as illustrated in Figure GMC3 below.

![Figure GMC3](image)

**Figure GMC3.** Logic-tree for sigmas associated with medians from crustal earthquakes.

Tables in Excel File *Hanford_GMC_sigma_model.xlsx* contain the values for sigma corresponding to the logic tree shown above. The values on tab “Crustal_Normal” contain the values for the model where the distribution is modelled as a single lognormal distribution. For the mixture model, the conditional probability of exceeding a specific ground motion value $z$ is given by the equation:

$$P(Z > z) = w_{Mix1} \left[ 1 - \Phi \left( \frac{z - \mu}{\sigma_{Mix1}} \right) \right] + w_{Mix2} \left[ 1 - \Phi \left( \frac{z - \mu}{\sigma_{Mix2}} \right) \right]$$

(11)
In Equation (11) \( w_{Mix1} \) and \( w_{Mix2} \) are the mixing proportions, which are both equal to 0.5. The values of \( \sigma_{Mix1} \) and \( \sigma_{Mix2} \) are listed on tabs “Crustal_Mixture_1” and “Crustal_Mixture_2”, respectively.

For the crustal model, the values of \( \sigma \) are magnitude dependent for both the normal and mixture models. The value of \( \sigma \) for any specific magnitude is computed from the relationship:

\[
\sigma = \sigma_1 + \frac{\sigma_2 - \sigma_1}{2} \left[ \min(\max(M, 5), 7) - 5 \right]
\]  

(12)

where \( \sigma_1 \) and \( \sigma_2 \) are either the normal values or the mixture values.

**Sigma Model for Subduction Earthquakes**

The structure of the sigma logic-tree for subduction earthquakes is identical to that for crustal earthquakes. The only difference is that the values of \( \sigma \) are magnitude and period independent. The values of \( \sigma \) for the normal model are listed on tab “Subduction” in Excel File *Hanford_GMC_sigmamodel.xlsx* and the values for the mixture model are listed on tab “Subduction” in Excel File *Hanford_GMC_sigmamodel.xlsx*. The mixture model is implemented using Equation (11).