Fourier-Based Site Response of Sedimentary Basins and Other Geomorphic Provinces in Southern California

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Abstract

We provide a site amplification model for Fourier Amplitude Spectra (FAS) inferred from earthquake ground motion recordings in southern California. The model is conditioned on the time-averaged shear wave velocity in the upper 30 m ($V_{s30}$) coupled with the depth to 1.0 km/s shear wave velocity isosurface ($Z_{1.0}$), with the $Z_{1.0}$ component further conditioned on type of geomorphic province: Basin and Basin Edges, Valleys, and Mountains/Hills. The $Z_{1.0}$-scaling is centered with respect to the $V_{s30}$-scaling and is dependent on the differential depth ($\delta z_1$), defined as the difference between a site-specific depth and a $V_{s30}$-conditioned average depth. This work closely follows the procedures set forth by Nweke et al. (2022; Nea22), which developed a $\delta z_1$-scaling model conditioned on geomorphic province in southern California for response spectral acceleration. The ground motion database and geomorphic province classifications from Nea22 are also utilized.

This report describes the $\delta z_1$-scaling component of the model and complements the $V_{s30}$-scaling model developed for the same region under SCEC Award #19097. The $V_{s30}$-scaling and $\delta z_1$-scaling components are combined to form a comprehensive FAS site amplification model specific to southern California. This site amplification model updates and regionalizes the Bayless and Abrahamson (2019; BA19) ergodic site amplification model developed for greater California.

To develop the $\delta z_1$-scaling model, we use the Nea22 ground motion database of processed ground motion recordings, calculate the FAS and smoothed FAS from the acceleration time series using methods consistent with BA19, perform residual analyses to isolate site terms, and analyze the site terms within different geomorphic provinces. The parametric models for $\delta z_1$-scaling of the site terms are developed for each frequency independently, and the coefficients of this model are smoothed. The model is applicable over the frequency range 0.1 – 24 hertz (Hz).

Nea22 found that there was not a statistically significant difference between $\delta z_1$-scaling response spectral models for basins and basin edges, and subsequently combined these provinces into one category: Basin and Basin Edge (BBE). Based on the same statistical testing, we arrive at the same conclusion for BBE for the FAS. Additionally, we find that the valley and mountain/hill $\delta z_1$-scaling models are not significantly distinct, and subsequently combine the model for these provinces into one category: Valley and Mountain/Hill (VMH). As a result, forward application of the model requires the $V_{s30}$ and $Z_{1.0}$ parameters combined with classification of the site into either of the BBE or VMH provinces.

The frequency dependence of the proposed $\delta z_1$-scaling and the BA19 $Z_{1.0}$-scaling models are broadly similar. By conditioning on geomorphic province and differential depth, the proposed model is more flexible than the BA19 $Z_{1.0}$-scaling model, resulting in a wider range of amplification factors. Additionally, the proposed models are broadly compatible with the Nea22 $\delta z_1$-scaling model, even though that model was developed for response spectra.

One potential use for this model is in future validations of simulated earthquake ground motions, such as the SCEC Broadband Platform or CyberShake (Graves et al., 2011). These validations typically use empirical models for response spectra to adjust the simulated motions from a reference condition to a site-specific condition. Directly adjusting the simulated Fourier amplitudes using this model is advantageous to response spectral methods because it more readily allows for derivation of adjusted acceleration time series, which can be used for other applications directly and from which response spectra can be calculated.
1. Introduction

We provide a site amplification model for Fourier Amplitude Spectra (FAS) inferred from earthquake ground motion recordings in southern California. This site amplification model updates and regionalizes the Bayless and Abrahamson (2019; BA19 hereinafter) ergodic site amplification model developed for greater California.

The model is conditioned on the time-averaged shear wave velocity in the upper 30 m ($V_{s30}$) coupled with the depth to the 1.0 km/s shear wave velocity isosurface ($Z_{1.0}$), with the $Z_{1.0}$ component further conditioned on type of geomorphic province: basin, valley, and mountain/hill. The $Z_{1.0}$-scaling is centered with respect to the $V_{s30}$-scaling and is dependent on the differential depth ($\delta Z_1$), defined as the difference between a site-specific depth and a $V_{s30}$-conditioned average depth.

This work closely follows the procedures set forth by Nweke et al. (2022; Nea22 hereinafter), which developed a $\delta Z_1$-scaling model in southern California for response spectra. Nea22 reformulated the depth component of the Boore et al. (2014) ergodic site response models for response spectra by considering geomorphic provinces, noting that previous models operated solely on isosurface depth without explicit consideration of whether the sites are in basins or other types of sedimentary units. The current study also utilizes the ground motion database and geomorphic province classifications from Nea22.

The site amplification model ($F_s$, in natural log units) has two coupled components as in Eq. 1:

$$F_s = F_p + F_b = F_{lin} + F_{nl} + F_b$$

Where $F_p$ is a $V_{s30}$-scaling model with linear ($F_{lin}$) and nonlinear ($F_{nl}$) components, inferred from southern California earthquake recordings, as described in SCEC Report #19097 (Bayless and Stewart, 2020). $F_b$ is the $\delta Z_1$-scaling model (also called basin depth scaling elsewhere in the literature) conditioned on the Nea22 geomorphic provinces, described in this report.

In any ground motion model, the individual model components related to physical effects of source, path, and site may be correlated. The site amplification components used to scale the ground motions with parameters $V_{s30}$ and $Z_{1.0}$ have the potential to be highly correlated, because the parameters $V_{s30}$ and $Z_{1.0}$ themselves are highly correlated. A technique to address this correlation is to first condition the site amplification on $V_{s30}$ effects, which can include basin effects to the extent they are present in the empirical data (Nea22), and to model the remaining site amplification effects with $\delta Z_1$-scaling. With this method, the $\delta Z_1$-scaling is ‘centered’ with respect to the $V_{s30}$-scaling and the two components together form the complete site amplification model. Additionally, the $\delta Z_1$-scaling is ‘centered’ in that it predicts changes in amplification for $Z_{1.0}$ depths relative to a $V_{s30}$-conditioned average depth.

This report describes the $\delta Z_1$-scaling component of the model. Complete model ($\delta Z_1$-scaling and $V_{s30}$-scaling) behavior is also shown and compared with other models. The remainder of this report describes the database (Section 2), the FAS residual analyses (Section 3), the model-building process (Section 4), model behavior (Section 5), and summary and conclusions (Section 6). Appendix A contains residual figures at individual frequencies spanning 0.1-24 Hz. Appendix B contains supplemental figures related to the model-building process. Appendix C provides model coefficients.
2. Database

2.1 Ground Motions

This study makes use of the Effective Amplitude Spectrum (EAS) component of the FAS. As defined by Goulet et al. (2018a), the EAS is the orientation-independent horizontal component FAS of ground acceleration. The EAS ordinates are processed following the technique outlined in Kottke et al. (2021), which includes using the Konno and Ohmachi (1998) smoothing window with smoothing parameter \( b=188.5 \). The terms FAS and EAS are used interchangeably in this report, but in all cases, it is the smoothed EAS that has been analyzed and from which the model is based.

The Nea22 ground motion recordings and metadata (including geomorphic province classifications) were used in this study with some minor modifications described below. The FAS were calculated from the acceleration time series within the database.

Nea22 performed a substantial data collection effort to supplement existing databases of ground motion recordings and applicable metadata for the southern California region. The Nea22 database consists of recordings from the NGA-West2 database (Ancheta et al., 2014) and data added as part of Nea22, Ahdi et al. (2020) and Wang (2020). In the southern California region, this database includes 1004 recording sites, 789 of which are from the NGA database, and 215 of which are newer additions.

The Nea22 database was assembled and is maintained by the UCLA geotechnical group, which includes co-PIs Nweke and Stewart, in addition to Scott Brandenberg, Tristan Buckreis, and Pengfei Wang. Calculation of the FAS and EAS, following the Kottke et al. (2021) technique, was added to the UCLA processing routine through collaboration between the PIs of this SCEC project and the UCLA geotechnical group. The UCLA geotechnical group database is available online at https://www.uclageo.com/gm_database/api/index.php.

The Nea22 database includes recordings of the 2019 Ridgecrest earthquake sequence. These acceleration time series were not available during the course of this study, so the FAS were not calculated and were not used. This represents the most significant difference between the Nea22 database and the database utilized in the current study. The other differences arise from data selection techniques. In the current study, the requirement of at least 5 earthquake recordings is imposed at a given site for the site to be used in the regression (following BA19). Nea22 required a minimum of 3 recordings per site (pers. comm.). Both the current study and Nea22 required a minimum of 5 recordings per earthquake. Additionally, minor differences in maximum allowable recording distance (cutoff distance) were used in the data selection. Nea22 used a smoothly varying magnitude-dependent cutoff distance as defined in Boore et al. (2014). The cutoff distance in the current study is a step function with magnitude, as described in Section 3.2.

2.2 Site Parameters

Nea22 describes the record processing of the newly added data, updates to metadata for the newly added data and NGA-West2 data (including source, path, and site parameters), and a method for classifying the geomorphology of sedimentary basins and non-basin regions. Nea22 utilized a consistent procedure for assigning site parameters: \( V_{s30} \) was assigned using measured shear wave velocity profiles where available, and for sites without measurements a weighted combination of the \( V_{s30} \) map derived from geologic- and topographic-based proxy relationships by Thompson et al. (2014; 2018) and the terrain-based proxy model of Yong et al. (2012; 2016) were used (Nea22; Ahdi et al., 2018). The Nea22 geomorphic categorization scheme and provinces, replicated as Figure 1 below, are adopted in the current study.
Table 1. Proposed geomorphic provinces for southern California

<table>
<thead>
<tr>
<th>Province</th>
<th>Description</th>
<th>Criteria</th>
<th>Province no.</th>
<th>No. of sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin</td>
<td>Basin interior</td>
<td>Short direction width &gt;3 km</td>
<td>3</td>
<td>429</td>
</tr>
<tr>
<td></td>
<td>Basin edge</td>
<td>Along basin margin</td>
<td>2</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Valley</td>
<td>“Small” sedimentary structure</td>
<td>1</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>Mountain/hill</td>
<td>Sites without significant sediments, generally having topographic relief</td>
<td>0</td>
<td>329</td>
</tr>
</tbody>
</table>

*Basin edge defined visually from break in slope (topographic features).

Figure 1. Table 1 from Nea22, listing the geomorphic province categorization scheme and number of available sites within each.

Nea22 used two SCEC community velocity models, CVM-S4.26.M01 (Lee et al., 2014) and CVM-H v15.1 (Shaw et al., 2015), to determine site $Z_{1.0}$ values when measured values are not available. For brevity these are referred to as CVM-S4 and CVM-H, respectively. In addition to the $Z_{1.0}$ values, Nea22 provided mean depth models for both CVMs ($\bar{Z}_{1.0}$) which are used to determine the differential depth ($\delta Z = Z_{1.0} - \bar{Z}_{1.0}$). The use of two models for determining $Z_{1.0}$ and $\delta Z$ results in two branches of the metadata database. The residual analyses described below are performed for both databases and results in two $\delta Z_{1}$-scaling models.

2.3 Summary of Database Attributes

Figure 2 maps the southern California study region and shows earthquake hypocenters (blue circles) and recording stations (triangles) utilized in the current study. Some of the earthquake hypocenters are outside of the map area. Figure 3 shows a magnitude-distance scatterplot of the database, and histograms of critical metadata (magnitudes, geomorphic province classifications, source-site rupture distances, site $V_{s30}$, and site $Z_{1.0}$ for CVM-H).
Figure 2. A map of the southern California study region, showing the Nea22 earthquake hypocenters (blue circles) and recording stations color coded by province (triangles) used in the current study.

Figure 3. A magnitude-distance scatterplot of the database, and histograms of the earthquake magnitudes, site basin classifications, source-site rupture distances, site $V_{s30}$, and site $Z_{1.0}$ for CVM-H.
3. Residual Analyses

3.1 Overview of Procedure

Ground motion residual analyses are performed to isolate and study the site response effects using the BA19 EAS ground motion model for California as the reference model. Following Villani and Abrahamson (2015) and Bayless and Abrahamson (2019), the residuals take the form of Eq. 2:

\[
\delta_{\text{total,es}}(f) = Y(f) - g(X_{\text{es}}, \theta, f) = \delta B_e(f) + \delta S2S_s(f) + \delta WS_{\text{es}}(f) + C(f)
\]

(2)

where \(Y(f)\) is the natural log of the EAS of the ground motion recording at frequency \(f\), \(g(X_{\text{es}}, \theta, f)\) is the median BA19 GMM, \(X_{\text{es}}\) is the vector of explanatory seismological parameters (moment magnitude, distance, site conditions, etc.), \(\theta\) is the vector of GMM coefficients, and \(\delta_{\text{total,es}}(f)\) is the total residual for earthquake \(e\) and site \(s\). The residual components \(\delta B_e(f)\), \(\delta S2S_s(f)\), and \(\delta WS_{\text{es}}(f)\) represent the between-event, site-to-site, and single station within-site residuals, respectively. The residual components \(\delta B_e\), \(\delta S2S_s\), and \(\delta WS_{\text{es}}\) are well represented as zero mean, independent, normally distributed random variables with standard deviations \(\tau\), \(\phi_{S2S}\), and \(\phi_{SS}\), respectively. \(C(f)\) represents the mean total residual, or the mean bias. The mean bias exists because the median EAS from the southern California database is different from the BA19 database.

The residual analysis involves the following stages. Each stage is performed independently at select log-spaced frequencies ranging between 0.1 – 24 Hz:

Stage 1

Database screening for moment magnitude (M), rupture distance (\(R_{\text{rup}}\)), \(V_{330}\), recording usable frequency range, and minimum number of recordings per earthquake and per site.

Stage 2

A nonlinear mixed effects residual analysis to partition the residuals into \(C(f)\), \(\delta B_e(f)\), \(\delta S2S_s(f)\), and \(\delta WS_{\text{es}}(f)\). At this stage, the BA19 GMM is modified to include the southern California \(V_{330}\)-scaling model (Bayless and Stewart, 2020) and the BA19 \(Z_{1.0}\)-scaling to obtain the mean bias and event terms, \(C(f)\) and \(\delta B_e(f)\). No consideration for geomorphic province is taken at this stage.

Stage 3

The data are corrected for \(C(f)\) and \(\delta B_e(f)\) from stage 2, and a second mixed effects residual analysis is performed. At this stage, the BA19 GMM with the southern California \(V_{330}\)-scaling model and without \(Z_{1.0}\)-scaling is used. This isolates the \(Z_{1.0}\)-scaling effects in the site terms. Stage 3 is performed separately from stage 2 so that the \(\delta S2S_s\) residuals without \(Z_{1.0}\)-scaling (stage 3) are not mapped into the mean bias or event terms (\(C\) or \(\delta B_e\)).

Stage 4

Examination of the residual terms \(\delta B_e(f)\), \(\delta S2S_s(f)\), and \(\delta WS_{\text{es}}(f)\) by plotting them against the predictive parameters \(M\), \(R_{\text{rup}}\), \(V_{330}\), and depth to the top of the rupture plane (\(Z_{\text{rup}}\)) to confirm that the model components do not contain significant biases or trends. The site terms have an expected trend with \(Z_{1.0}\) because the \(Z_{1.0}\)-scaling was fixed to zero.

Stage 5

Modeling: Investigation and modeling of trends of \(\delta S2S_s(f)\) with differential depth for each of the Nea22 geomorphic provinces. Model coefficients are smoothed to ensure the model
amplification factors to not have abrupt transitions between frequencies. Finally, investigation of the aleatory variability of residual components $\delta S^2 S^c$ for the Nea22 geomorphic provinces.

The remainder of Section 3 (Residual Analyses) summarizes Stages 1-4. Section 4 (Model Building) summarizes Stage 5. All five stages were performed independently for the CVM-H and CVM-S4 datasets, and for each frequency independently.

### 3.2 Stage 1: Data Screening

At each frequency, the database is screened to select the data which fits the following criteria: recordings with $R_{rup} \leq 150$ km for events with $3 \leq M < 4$, recordings with $R_{rup} \leq 200$ km for events with $4 \leq M < 6.5$, recordings with $R_{rup} \leq 300$ km for events with $M \geq 6.5$, sites with $V_{s30} > 160$ m/s, earthquakes with at least five recordings, sites with at least five earthquakes recorded, and that the given frequency is with the usable frequency range for a recording. This step function of cutoff distance with magnitude is used as an approximation to the smoothly varying magnitude-dependent cutoff distance of Boore et al. (2014). The usable frequency range is determined from the lower and upper corner filter frequencies. The usable range is between $1.25^*\text{HPF}$ and $\text{LPF}/1.25$, where HPF and LPF are the high-pass and low-pass corner frequencies used in the ground motion processing, respectively. This definition of the usable frequency range was selected by BA19 for consistency with the NGA-West2 spectral acceleration models and was retained in this study. Figure 4 shows the number of earthquake recordings, earthquakes, and unique sites used versus frequency.

![Figure 4. The number of earthquake recordings, earthquakes, and unique sites used in the analysis versus frequency after performing the data screening.](image)

### 3.3 Stages 2-4: Residual Analyses

First, a nonlinear mixed effects residual analysis is performed to partition the residuals into $C(f)$, $\delta B_c(f)$, $\delta S^2 S^c(f)$, and $\delta W S^c S^w(f)$. At this stage, the BA19 GMM is modified to include the southern California $V_{s30}$-scaling model (Bayless and Stewart, 2020) and the BA19 $Z_{1.0}$-scaling. No consideration for geomorphic province is taken at this stage. The purpose of this step is to calculate $C(f)$ and $\delta B_c(f)$ for this dataset, from the complete median GMM.
Then, the data are corrected for $C(f)$ and $\delta B_e(f)$ determined from the previous step, and a second mixed effects residual analysis is performed to determine $\delta S2S_s(f)$, and $\delta WS_{es}(f)$. At this stage, the BA19 GMM with the southern California $V_{s30}$-scaling model is used, and the $Z_{1.0}$-scaling is fixed to zero. This isolates the $Z_{1.0}$-scaling effects in the site terms. The data are corrected for $C(f)$ and $\delta B_e(f)$ prior to this residual analysis so that the $\delta S2S_s$ residuals without $Z_{1.0}$-scaling are not mapped into the mean bias or event terms ($C$ or $\delta B_e$). Figure 5 shows $C(f)$ for both CVM-H and CVM-S4.

![Graph](image)

Figure 5. The frequency dependence of the mean bias term, $C$, for the CVM-H and CVM-S4 datasets.

The residuals from the regression analysis are examined as functions of the main model parameters to check for biases or strong trends. The presence of obvious strong trends in the residuals versus predictor variables would indicate that the southern California data do not agree with the BA19 model. In general, the residuals indicate agreement with BA19. Figure 6 shows residuals for $f=1.0$ Hz. In Figure 6a, the event terms ($\delta B_e$) are plotted versus $M$ and $Z_{40r}$ and site terms ($\delta S2S_s$) are plotted against $V_{s30}$, and $Z_{1.0}$. At this frequency the $\delta B_e$ are negatively biased for $M$ greater than about 6.0, representing model over-prediction on average. All the earthquakes with $M>6.0$ are from the NGA-W2 database (Figure 3), and therefore were utilized in development of BA19. This bias is the result of using only southern California data instead of data from all of California. In Figure 6a there are no apparent trends or biases in $\delta B_e$ with $Z_{40r}$ or in $\delta S2S_s$ with $V_{s30}$. $\delta S2S_s$ residuals have an expected trend with $Z_{1.0}$ because the $Z_{1.0}$-scaling was set to zero. In Figure 6b, the within-site residuals ($\delta WS_{es}$) are plotted versus $M$, $R_{rup}$, $V_{s30}$, and $Z_{1.0}$. There are no apparent trends in $\delta WS_{es}$ at $f=1.0$ Hz. The lack of trend with $R_{rup}$ is especially important because it indicates the path model is effective for the dataset.

Appendix A contains residual figures for the other frequencies analyzed.
Figure 6. CVM-H EAS residuals at f=1.0 Hz versus various predictor variables. (a) Event and Site terms. (b) Within-site residuals. Black diamonds represent binned means.
4. Model-Building

This section describes the development of parametric models for $\delta z_1$-scaling in geomorphic provinces, based on the residuals developed in the previous section. This section primarily focuses on the CVM-H depth model, and Appendix B contains the complete set of figures related to both CVMs.

First, the site terms are investigated by geomorphic province. The selected $\delta z_1$-scaling model form is described, and statistical tests are performed to evaluate if the models for the provinces are similar enough to be combined. Then, model coefficient smoothing is described. This section concludes with an evaluation of the aleatory variability of residual components $\delta S/\delta_s$.

4.1 Site Terms by Province

The Nea22 mean depth models are used to determine the differential depth ($\delta z_1$) for each site based on the site's $V_{s30}$. Figure 7 shows the $\delta S/\delta_s$ for all sites (ignoring geomorphic province) plotted versus $\delta z_1$ for frequencies of $f=0.52$ Hz and $f=5.25$ Hz. Figure 7a shows that, at low frequencies the binned mean site terms (red diamonds) scale with $\delta z_1$, and that this scaling is very similar to the Boore et al. (2014) model created for response spectra (black dashed line). At higher frequencies, such as 5.25 Hz in Figure 7b, the site terms do not scale with $\delta z_1$ on average.

Figure 8 shows the variation of $\delta S/\delta_s$ with $\delta z_1$ for sites categorized by geomorphic province for (a) $f=0.52$ Hz and (b) $f=5.25$ Hz. In each panel, the grey circles show site terms for all sites. The four rows highlight the site terms by geomorphic province: Basin (blue), Basin Edge (yellow), Valley (green), and Mountain/Hill (purple), respectively. In each panel the dashed line indicates the mean $\delta S/\delta_s$ for that province, and red diamonds are binned means.

Nea22 highlighted the following three important elements of these plots for model development:

- Mean offset from zero, which indicates the average amplification in the data relative to the $V_{s30}$-scaling model for the defined geomorphic provinces.
- Slope of the data with respect to $\delta z_1$, which if present, indicates scaling of site response with differential depth.
- For ground motion parameters and provinces that produce scaling with $\delta z_1$, limits at low and/or high $\delta z_1$ beyond which depth scaling is not supported by the data.

At $f=0.52$ Hz (Figure 8a), basin sites have positive mean offset of approximately 0.25 natural log units, representing amplification relative to the $V_{s30}$-scaling, and there is a positive slope of the site terms with $\delta z_1$. The basin edge province has relatively fewer sites and is subject to larger uncertainty but appears to exhibit some scaling with $\delta z_1$. Both the valley and mountain/hill provinces have negative mean offset, representing de-amplification, and have a positive slope of the site terms with $\delta z_1$. The provinces are generally well populated between $\delta z_1 = -0.5$ to 0.5 km.

At $f=5.25$ Hz (Figure 8b), all four provinces have mean offset nearly equal to zero, representing little or no additional amplification on average relative to the $V_{s30}$-scaling model. The site terms generally do not exhibit scaling with $\delta z_1$. 
Figure 7. Variation of $\delta S_2$ with $\delta z_1$ for all sites (grey circles), showing binned means (diamonds) and the Boore et al. (2014) model, developed for response spectral acceleration (dashed line) at (a) $f = 0.52$ Hz and (b) $f = 5.25$ Hz.

Figure 8. Variations of $\delta S_2 S_3$ with $\delta z_1$ by province at (a) $f = 0.52$ Hz and (b) $f = 5.25$ Hz.

As Nea22 highlighted, the mean offsets represent the mean site amplification for a province relative to the $V_{30}$-scaling, without taking into consideration $\delta z_1$ (it is the mean over all sites and therefore all $\delta z_1$). Figure 9a shows the frequency dependence of the mean offset for each geomorphic province, for the CVM-H model. The mean of all sites (black line) is zero because the $\delta S_2 S_3$ for all sites is centered in the mixed effects regression, by definition. In Figure 9, the solid, colored lines represent the mean offsets for individual provinces. Shaded zones around the mean for Basin (blue) and Mountain/Hill (purple) provinces show the 95% confidence intervals for these two provinces; the confidence intervals are shown only for these two provinces to maintain figure legibility. Figure 9b shows the same information for the CVM-S4 model and is very similar to Figure 9a.
Figure 9a shows that, on average, Basin sites exhibit amplification and Mountain/Hill sites exhibit de-amplification of the low frequency ground motions. This is consistent with site response physics as the deeper basins have low resonant frequencies expected to produce a large site response at low frequencies, and the Mountain/Hill sites are associated with relatively limited soil cover (Nea22, Figure 9c). At very low frequencies, less than about 0.25 Hz in this case, the uncertainties are very large due to usable data limitations, as indicated by the wide 95% confidence interval bands. At approximately 5 Hz, the Basin and Mountain/Hill mean offset cross the zero line and switch to de-amplify and amplify the higher frequency ground motions, respectively. At approximately 3 Hz and larger, the 95% confidence intervals for the Basin and Mountain/Hill provinces overlap. When the confidence intervals do not overlap, the difference in mean offset of these two provinces is statistically significant at the 95% confidence level.

The Basin Edge province has the fewest sites, and therefore the largest uncertainty (not shown in Figure 9 for clarity). An assessment of the similarity of this province relative to basins is provided in Section 4.3. The Valley province mean offsets follow similar patterns to the Mountain/Hill provinces, de-amplification of low frequencies and a reversal to amplification of the higher frequencies. An assessment of the similarity of this province relative to the Mountain/Hill province is also provided in Section 4.3.

Figure 9. Mean $\delta S^2_S$ versus frequency by geomorphic province, for (a) CVM-H and (b) CVM-S4. Colored fills for Basin (blue) and Mountain/Hill (purple) provinces show the 95% confidence intervals for these provinces. (c) From Nea22, mean $\delta S^2_S$ versus period (based on response spectra) with color scheme as identified in the legend.
4.2 Model Form

Nea22 proposed a trilinear form for the basin term, $F_b$ (Nea22, Equation 12). This form is adopted based on visual inspection of the differential depth-dependence of $\delta S2S_2$ as described in the previous section. The trilinear form for $F_b$, in natural log units, is given by Eq. 3:

$$F_b = \begin{cases} 
  f_7 + f_6\delta z_1 & \text{for } \delta z_1 < f_8 \\
  f_7 + f_6\delta z_1 & \text{otherwise} \\
  f_7 + f_6\delta z_1 & \text{for } \delta z_1 > f_9
\end{cases}$$

(3)

Where $f_7$ is the offset (value of $F_b$ at $\delta z_1 = 0$), $f_6$ is the slope of the $\delta z_1$-scaling, and $f_8$ and $f_9$ are the lower and upper limiting values of $\delta z_1$, between which $F_b$ scales with $\delta z_1$, and outside of which $F_b$ is constant. Use of this model form limits the $\delta z_1$-scaling to the ranges of $\delta z_1$ and $F_b$ supported by the data and prevents unconstrained extrapolation. Figure 10 shows an example of the Eq. 3 trilinear form with the four example coefficients identified in red.

![Figure 10. An example of the trilinear form of $F_b$ given in Eq. 3.](image)

4.3 Grouping of Province Models

The four Nea22 geomorphic provinces are Basins, Basin Edges, Valleys, and Mountain/Hills. In this study and in Nea22, the residuals analyses were performed, as described above, and differential depth trends from each province were evaluated. The Basin Edge and Valley provinces have the smallest number of sites (Figure 3), leading to the least confident models. Nea22 performed statistical testing to guide modeling decisions on whether regressed models from combined categories (e.g., Basin combined with Basin Edge; BBE) are significantly different from alternate models fit to individual sub-categories (e.g., Basin and Basin Edge).

Nea22 found that the sparsely populated basin edge data does not reject the basin model, and as a result these provinces were grouped together into BBE. Nea22 also noted that the boundary between basin and basin edge sites is somewhat arbitrary and keeping these as separate entities would produce a step of site amplification that would be difficult to justify given the arbitrariness of the boundary (Nea22).

We consider the same statistical tests as Nea22 to evaluate the following potential groupings: Basin and Basin Edge grouped (BBE) and Valley and Mountain/Hill grouped (VMH). The process for determining if sub-groups are statistically distinct is described in Nea22 and Parker et al. (2017); an F-test (Snedecor and Cochran, 1989) compares the statistical performance of submodels with that of a full model for a common data set. The F-statistic is compared with the
F-distribution to get a significance level (p-value), and if the p-value is below a certain threshold (alpha), then the sub-groups are considered distinct at the alpha confidence level. Nea22 selected the 0.05 confidence level for the threshold, below which the sub-groups were considered distinct.

Figure 11 shows p-values as a function of frequency using this method, for (a) the CVM-H and (b) the CVM-S4 depth models. In Figure 11, the blue lines are p-values for testing the BBE group. At almost all the frequencies tested, the BBE p-value is above the 0.05 confidence level threshold (dashed line), indicating that the subgroups Basin and Basin Edge are not distinct. This is consistent for both CVM depth models and therefore supports the grouping of BBE.

In Figure 11, the red lines are p-values for testing the VMH group. For the CVM-S4 depth model, the p-values are above the 0.05 confidence level threshold at all frequencies. For the CVM-H depth model, p-values are above the threshold for frequencies greater than about 1 Hz but are below the threshold for lower frequencies.

Based on these p-values and on the residuals using the BBE and VMH groups, both groups are adopted for model development. An additional advantage, besides the increase in data quantity with fewer groups, is in forward application of the model. The reduction from four geomorphic provinces to BBE and VMH effectively reduces the model to ‘within basin’ or ‘outside basin’ categories. This will be easier for future users of the model and eliminates the need for the user to determine (potentially arbitrarily) if their site should be considered a valley versus a hill site, for example.

Finally, it is noted that the combination of provinces into groups for modeling does not imply that the site response in one category matches the other. Each of these provinces can have distinct physical wave propagation features, for example basin edge generated surface waves (e.g., Graves, 1993; Graves et al. 1998; Kawase, 1996; Pitarka et al., 1998), or topographic amplification at slope crests (e.g., Boore, 1972; Davis and West, 1973; Çelebi, 1987; Meunier et al., 2008). By combining the groups for modeling, we imply that the site amplification conditioned on $V_{s30}$ and $\delta z_1$ are not statistically distinct for sub-groups and can therefore be modeled together. The differences in geology, and site response, will be reflected by differences in the independent variables ($V_{s30}$ and $Z_{1.0}$), and we are only looking at differences in the model after conditioning on those variables.

![Figure 11](image-url)
4.4 Model Development and Coefficient Smoothing

Models are developed from the $\delta S 2 S_v$ residuals categorized by province groups BBE and VMH. The modeling procedure for a given frequency follows the Nea22 procedure: set coefficients $f_4$ and $f_6$ based on visual inspection, determine $f_5$ and $f_7$ from a least squares regression using data between $f_6$ and $f_9$, and smooth coefficients in frequency space to ensure the model amplification factors to not have abrupt transitions between frequencies.

Figure 12 shows the result of this procedure at frequencies 0.52, 5.25, and 15.85 Hz for BBE sites (blue) and VMH sites (green). The solid black lines within each panel represent the model for $F_q$ (Eq. 3) with the values of coefficients $f_6$, $f_7$, $f_8$, and $f_9$ before performing smoothing. At $f=0.52$ Hz (Figure 12a), the BBE model has positive $f_7$ (intercept or $F_q$ at $\delta z_1 = 0$) and relatively weaker $\delta z_1$-scaling, and the VMH model has negative $f_7$ and stronger $\delta z_1$-scaling. This behavior is generally representative of the other frequencies less than about 5 Hz.

At $f=5.25$ Hz (Figure 12b), both the BBE and VMH models have $f_7$ values of approximately zero and weak or no $\delta z_1$-scaling. At frequencies higher than about 5 Hz, (e.g., $f=15.85$ Hz, Figure 12c), both BBE and VMH groups similarly have near-zero $f_7$, and have $\delta z_1$-scaling with negative slope (coefficient $f_6$). Negative $f_6$ corresponds to ground motion amplification for shallower than expected basin depths and de-amplification for deeper than expected basin depths. This feature, and a comparison with Nea22, is discussed further in Section 5. Appendix B provides the model-development figures for additional frequencies.

Figure 13 shows the frequency dependence of $f_6$ and $f_7$ for the BBE and VMH models for CVM-H depths. The symbols with bands represent coefficient values from the least squares regression with 95% confidence intervals. The solid lines represent smoothed, final model values. Smoothed values of $f_6$ are set by visual inspection for both models, with the following considerations. For frequencies less than about 0.2 Hz uncertainties are very large due to usable data limitations and the coefficients from the regression are not reliable. For BBE, smoothed coefficients less than about 0.2 Hz are set by extrapolating the curvature of the regressed $f_6$ values between 0.2 Hz and higher. A moving average in log-frequency space is used to set the smoothed $f_6$ values for frequencies higher than about 3 Hz. Smoothed values of $f_7$ are set by visual inspection for both the BBE and VMH models.

Coefficients $f_6$ and $f_9$, initially set based on visual inspection of the residuals, are smoothed to avoid abrupt transitions in amplification factors between frequencies (Figure 14). For the BBE model and at frequencies below 5 Hz, $f_6$ and $f_9$ are set to -0.3 and 0.35 km, respectively. Between 5 Hz and 24 Hz, both models use interpolation in log-frequency space to taper $f_6$ and $f_9$ to -0.15 and 0.25 km, respectively. The intention of this transition is to model the observation that the $\delta z_1$-scaling occurs over a narrower range of $\delta z_1$ at the higher frequencies for both provinces. For the VMH model, $f_6$ and $f_9$ are set to two-thirds of the BBE model values to model the observation that the VMH sites $z_1$-scaling also occurs over a narrower range of $\delta z_1$ than BBE sites, and with relatively stronger $z_1$-scaling over that limited range (larger values of $f_6$). The smoothed model coefficients are provided in Appendix C.
Figure 12. CVM-H modeling variations of $\delta S_2 S_2$ with $\delta z_2$ by BBE and VMH provinces at (a) $f = 0.52$ Hz, (b) $f = 5.25$ Hz, and (c) $f = 15.85$ Hz.
Figure 13. Smoothing of coefficients $f_6$ (left column) and $f_7$ (right column) for BBE (a) and VMH (b) province models, developed from the CVM-H depth model dataset.

Figure 14. Frequency dependence of coefficients $f_6$ and $f_7$ for the BBE and VMH province models, CVM-H depth model.
Figures 15 and 16 show the frequency dependence of $f_6$, $f_7$, $f_8$ and $f_9$ resulting from the modeling of residuals using the CVM-S4 depths. For both the BBE and VMH models and at frequencies below 5 Hz, $f_8$ and $f_9$ are set to -0.2 and 0.3 km, respectively. Between 5 Hz and 24 Hz, both models use interpolation in log-frequency space to taper $f_8$ and $f_9$ to -0.15 and 0.2 km, respectively. For the CVM-S4 residuals, the $\delta z_1$-scaling occurs over narrower ranges of $\delta z_1$ than for the CVM-H residuals, and with steeper slope, resulting in larger peak values of coefficient $f_6$ for this depth model (Figure 15). The CVM-S4 coefficients $f_6$ and $f_7$ also have generally larger uncertainty. These parameters are determined from least squares regression and the larger uncertainties reflect having generally fewer sites for the regression (due to the narrower range of $\delta z_1$-scaling) and to less defined linear trends in $\delta S_2 S_3$.

Figure 17 compares the coefficients $f_6$ and $f_7$ for both BBE and VMH provinces, and for both CVMs. The proposed model coefficients are provided in Appendix C.

Residual analyses are performed using the final models to confirm that they remove the trends in site terms with basin depth (e.g. Figure 6) and do not introduce any additional biases or trends with other independent variables. Residual figures like those from Section 3 are provided in Appendix A.
Figure 15. Smoothing of coefficients \( f_6 \) (left column) and \( f_7 \) (right column) for BBE (a) and VMH (b) province models, developed from the CVM-S4 depth model dataset.

Figure 16. Frequency dependence of coefficients \( f_6 \) and \( f_9 \), CVM-S4 depth model.
4.5 Aleatory Variability

The residual components $\delta B_e$, $\delta S2S$, and $\delta WS_e$ have standard deviations $\tau$, $\phi_{S2S}$, and $\phi_{SS}$, respectively. The site-to-site variability ($\phi_{S2S}$) is investigated for magnitude dependence and for differences between geomorphic provinces. Models for the magnitude- and geomorphic province-dependence of $\phi_{S2S}$ will be provided in the published version of this report.

Goulet et al. (2018b) refined the Al Atik (2015) analyses for response spectra and provided a global magnitude-dependent $\phi_{S2S}$ model, with higher variability for oscillator periods $<$1.0 s for $M<5.5$ events than for $M>5.5$ events. At periods $>$1.0 s, the reverse was true (higher $\phi_{S2S}$ for larger $M$ events). Nea22 identified similar features for the southern California dataset, with regional standard deviations lower than the global model (Goulet et al., 2018b) and the California model (Boore et al., 2014). The Nea22 $\phi_{S2S}$ model decreases with $M$ at short periods and increases with $M$ at long periods.

To investigate the magnitude dependence of $\phi_{S2S}$, the residual analyses are repeated using the final $\delta z_s$-scaling models and by selecting data within four magnitude bins: $3 < M < 5$, $4 < M < 6$, $M > 5$, and all $M$. Figure 18a shows the frequency dependence of $\phi_{S2S}$ from each analysis (CVM-H model) and the BA19 model for $\phi_{S2S}$. The two lowest magnitude bins have very similar $\phi_{S2S}$. The bin with $M > 5$ earthquakes has substantially higher $\phi_{S2S}$ at low frequencies, and lower $\phi_{S2S}$ at high frequencies. This is behavior is generally consistent with the Nea22 model; decreasing with $M$ at short periods and increasing with $M$ at long periods.

To investigate the differences in $\phi_{S2S}$ between geomorphic provinces, the residuals from the regression analysis are partitioned by province. In this analysis all magnitudes are used in order to have sufficient data within each province. Figure 18b shows the $\phi_{S2S}$ by geomorphic province, and by the provinces grouped into $\delta z_s$-scaling models (BBE and VMH). For frequencies larger than 0.4 Hz, the BBE $\phi_{S2S}$ hare systematically lower than VMH. At frequencies lower than 0.4 Hz, where the uncertainties are largest due to limited data, that is reversed.
Figure 18. $\phi_{s2S}$ versus frequency (a) for regressions performed using data within various magnitude bins and (b) for all M events and by geomorphic province.
5. Model Behavior and Comparisons

This section summarizes the proposed model performance and compares amplifications factors with other models.

The $\delta z_1$-scaling model described in this report is conditioned on the southern California $V_{s30}$-scaling from Bayless and Stewart (2020) and models the remaining site amplification effects. Amplification factors for the CVM-S4 $\delta z_1$-scaling model are demonstrated in Figure 19, which shows the range of amplifications for the BBE (blue) and VMH (green) models. The three different line types represent the amplification for the maximum case ($\delta z_1 = f_4$; thin solid lines), minimum case ($\delta z_1 = f_3$; dashed lines) and for the case of $\delta z_1 = 0$ (thick solid lines).

The BBE amplification factors peak at 0.3 Hz (factor of 1.69) and are lowest at 24 Hz (factor of 0.81). For the minimum $\delta z_1$ case ($\delta z_1$), the BBE amplification factors range from 0.78 to 0.97 between 0.1-1 Hz and are approximately 0.91 for higher frequencies. The $\delta z_1 = 0$ case for BBE has peak amplification of 1.19 and peak de-amplification of 0.86. In forward application, most sites classified as BBE will be modeled with amplification at frequencies less than 5 Hz, and de-amplification at frequencies higher than 5 Hz.

For the VMH model and for the $\delta z_1 = f_9$ case, the amplification factors peak over a broader low frequency range than the BBE model, with peak factor of 1.33, and lowest factor of 0.80 at 24 Hz. For the minimum $\delta z_1$ case ($\delta z_1 = f_3$), the VMH sites are de-amplified significantly (factor of 0.59) at 0.5 Hz, and transition to a peak amplification of 1.34 at 24 Hz. The median ($\delta z_1 = 0$) case de-amplifies the VMH sites in a similar fashion, with peak de-amplification of 0.81 and peak amplification of 1.07 at 24 Hz.

Figure 20 shows the analogous amplification factors for the CVM-H depth model.

![Amplification factors for the proposed $\delta z_1$-scaling model, CVM-S4 depth model.](image)
Figures 21-23 show model amplification factors in natural log units for three model components: $V_{s30}$-scaling (Bayless and Stewart, 2020), $\delta z_1$-scaling (this study, CVM-H model), and total amplification (the sum of the two components). Each figure depicts a different $V_{s30}$ condition and within that $V_{s30}$ condition, three different basin depth conditions. The amplification factors do not include nonlinear effects in the $V_{s30}$-scaling. In each figure, the top panel corresponds to the $\delta z_1 > f_9$ case, the middle corresponds to the $\delta z_1 = 0$ case, and the bottom corresponds to the $\delta z_1 < f_9$ case. These three cases represent the range of possible amplification factors of the $\delta z_1$-scaling model. Dashed lines represent the proposed model, and the solid lines represent the BA19 model with southern California $V_{s30}$-scaling and ergodic $Z_1$-scaling. In each figure, the Nea22 $\delta z_1$-scaling amplification factors for response spectra are shown with the dotted black lines.

Figure 21 shows amplification factors for the $V_{s30} = 300$ m/s condition. Figure 21 shows that the BBE $\delta z_1$-scaling from this study (yellow dashed line, CVM-H model) has similar frequency dependence as the Nea22 model, with amplification of the low frequencies for the neutral and positive $\delta z_1$ conditions. For the same $\delta z_1$ conditions, this model features de-amplification of the high frequencies, whereas the Nea22 amplification factors are one (zero log units). For the negative $\delta z_1$ condition, representing shallower than expected basins, there is minimal amplification in both Nea22 and this model. That is a significant departure from the BA19 model (solid yellow lines), which applies de-amplification based on the low value of $Z_1$ and no consideration of geomorphic province.

Overall, the agreement with Nea22 is strong in Figure 21, especially at low frequencies and up to about $f=5$ Hz. The differences at frequencies higher than about $f=5$ Hz are expected, due to the fundamental differences between response spectra and FAS. The response spectrum is the peak response from a single-degree-of-freedom (SDOF) system. The SDOF response is influenced by a range of frequencies, and the breadth of that range is dependent on the oscillator period. For short oscillator periods (high frequencies), where there is little energy left...
to resonate the oscillator, the ordinates are influenced by a very wide frequency band of the ground motion; meaning the predominant period of the ground motion (approximately \( f = 2-6 \) Hz, Rathje et al, 2004) dominates the short-period response. For this reason, it is encouraging that the two models, one for response spectra and the other for FAS, are compatible at frequencies around \( f = 5 \) Hz.

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**Figure 21. Amplification factors (In units) for the proposed \( V_{s30} \)-scaling and \( \delta z_t \)-scaling model components. All amplification factors are for hypothetical sites with \( V_{s30} = 300 \) m/s using the BBE model. The top, middle, and bottom panels are for sites with \( Z_1 = 1.5 \) km, 0.84 km, and 0.20 km, respectively. The black dotted lines are amplification factors from Nea22.**
Figure 22 shows amplification factors for the $V_{s30} = 500$ m/s condition. The top panel ($\delta z_1 > f_9$) uses the BBE province model because it represents a deep site, and the lower two panels ($\delta z_1 = 0$, $\delta z_1 < f_9$) use the VMH model because they represent shallower sites. In the top panel, the BBE $\delta z_1$-scaling from this study has similar frequency dependence as the Nea22 and BA19 models, and features stronger amplification by about 0.1 ln units (~10%) of the low frequencies. For the VMH model, the proposed model is compared with the Nea22 Mountain/Hill $\delta z_1$-scaling model as identified in the figure legend. For the median depth case ($\delta z_1 = 0$; middle panel), both Nea22 and this model feature $\delta z_1$-scaling de-amplification of the low frequencies by relatively modest factors (less than 0.13 ln units), whereas the BA19 model features modest amplification because the geomorphic province has not been accounted for. For the very shallow basin depth case ($\delta z_1 < f_B$; bottom panel), all three models de-amplify the low frequency ground motions within the range of about -0.24 to -0.4 ln units.

Figure 23 shows amplification factors for the $V_{s30} = 760$ m/s condition. All three panels ($\delta z_1$ conditions) use the VMH province model and the Nea22 Mountain/Hill model. For the deepest depth case ($\delta z_1 > f_9$; top panel), all three $\delta z_1$-scaling models amplify the low frequencies and de-amplify the high frequencies. Compared with both Nea22 and BA19, the amplification factors of the proposed model are smaller at low to moderate frequencies; the largest difference is approximately 0.3 ln units at $f=0.5$ Hz. For the median depth case ($\delta z_1 = 0$; middle panel), the behavior is like that from Figure 22; low-frequency amplification in BA19 compared with de-amplification in Nea22 and this model. For the very shallow basin depth case ($\delta z_1 < 0$; bottom panel), the behavior is also like that from Figure 22; all three models de-amplify the low frequency ground motions and BA19 and this model amplify the high frequency ground motions.
Figure 22. Amplification factors (in units) for the proposed $V_{s30}$-scaling and $\delta z_1$-scaling model components. All amplification factors are for hypothetical sites with $V_{s30} = 500$ m/s. The top, middle, and bottom panels are for sites with $Z_{1.0} = 0.80$ km (BBE model), 0.31 km (VMH model), and 0.05 km (VMH model), respectively. The black dotted lines are amplification factors from Nea22.
Figure 23. Amplification factors (in units) for the proposed $V_{s30}$-scaling and $\delta z_1$-scaling model components. All amplification factors are for hypothetical sites with $V_{s30} = 760$ m/s using the VMH model. The top, middle, and bottom panels are for sites with $Z_{1.0} = 0.80$ km, 0.07 km, and 0.01 km, respectively. The black dotted lines are amplification factors from Nea22.
6. Summary, Conclusions, and Future Steps

This report describes the $\delta z_1$-scaling component of a site amplification model for Fourier Amplitude Spectra (FAS) inferred from earthquake ground motion recordings in southern California. The $\delta z_1$-scaling model is developed by closely following the procedures set forth by Nweke et al. (2022) and by utilizing the ground motion database and geomorphic province classifications of Nweke et al. (2022). Models of median $\delta z_1$-scaling are provided for two geomorphic provinces: Basin and Basin Edge (BBE) and Valley and Mountain/Hill (VMH). Median $\delta z_1$-scaling models are also provided for two SCEC CVMs from which basin depth parameters were utilized: CVM-S4.26.M01 (Lee et al., 2014) and CVM-H v15.1 (Shaw et al., 2015). The model coefficients are provided in Appendix C.

For sites located in southern California, the proposed $\delta z_1$-scaling models supersede the BA19 $Z_{1,0}$-scaling model. The California-wide BA19 $Z_{1,0}$-scaling model is conditioned only on $Z_{1,0}$, not the differential depth $\delta z_1$, and has no consideration of geomorphic province. Because of this, the BA19 model is more generic and applies ground motion amplification to relatively deep sites regardless of their geomorphic province categorization and expected depth, whereas the proposed models are conditioned on the province and the difference between the site-specific depth and a mean depth. The frequency dependence of the proposed and BA19 $\delta z_1$-scaling models are similar.

Additionally, the proposed models are broadly compatible with the Nea22 $\delta z_1$-scaling model, even though that model was developed for response spectra. The agreement with Nea22 is strongest at low frequencies and up to about $f=5$ Hz. The differences at frequencies higher than about $f=5$ Hz are expected, due to the fundamental differences between response spectra and FAS. The response spectrum is the peak response from a single-degree-of-freedom (SDOF) system. The SDOF response is influenced by a range of frequencies, and the breadth of that range is dependent on the oscillator period. For short oscillator periods (high frequencies), where there is little energy left to resonate the oscillator, the ordinates are influenced by a very wide frequency band of the ground motion; meaning the predominant period of the ground motion (approximately $f=2$-6 Hz, Rathje et al, 2004) dominates the short-period response. For this reason, it is encouraging that the two models, one for response spectra and the other for FAS, are compatible at frequencies around $f=5$ Hz.

This report complements the $V_{s30}$-scaling model developed for the same region under SCEC Award #19097. The $V_{s30}$-scaling and $\delta z_1$-scaling components are combined to form a comprehensive FAS site amplification model specific to southern California. A journal paper describing the complete model is in preparation and will include models for the site-to-site residual aleatory variability ($\phi_{S2S}$).
7. References


Wang P (2020) Predictability and repeatability of non-ergodic site response for diverse geological conditions. PhD Dissertation, Department of Civil and Environmental Engineering, University of California, Los Angeles (UCLA), Los Angeles, CA.
Appendix A: Residual Figures
Please access the Appendix at this URL:
https://drive.google.com/drive/u/0/folders/1tgkoj4TZv7q_6gsLvTRo9qxFkEzH4waP

Appendix B: Model-Building Figures
Please access the Appendix at this URL:
https://drive.google.com/drive/u/0/folders/1tgkoj4TZv7q_6gsLvTRo9qxFkEzH4waP

Appendix C: Model Coefficients
Please access the Appendix at this URL:
https://drive.google.com/drive/u/0/folders/1tgkoj4TZv7q_6gsLvTRo9qxFkEzH4waP