NONLINEAR SITE RESPONSE AT CALIFORNIA DOWNHOLE ARRAYS AND INTERPRETATION OF FINITE ELEMENT SIMULATION RESULTS

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Abstract

This paper summarizes the results of a recently completed project on the one-dimensional (1D) site response analysis (SRA) of five geotechnical downhole arrays in California which were subjected to both strong and weak earthquake shakings. The arrays were initially assessed in terms of the effectiveness of the 1D SRA using taxonomy classification. Then, SRA was performed utilizing finite element program LS-DYNA to study the site effects at the selected arrays. Lastly, the predictions were compared with the recorded counterparts and the uncertainties of the 1D SRA models were evaluated using two methods namely the Goodness-of-Fit (GOF) and Amplification Factor (AF) residuals. The 1D SRA results of the selected arrays were interrogated on a site-by-site basis and discussions are made on the effectiveness of the employed nonlinear SRA models.

Introduction

This study investigates the influence of local site effects and the soil nonlinear response on the amplification of recorded ground motions at five CSMIP geotechnical downhole arrays where recorded motions exceeded 0.1g. Taxonomy evaluation of the arrays was carried out to inform the expected level of accuracy of the 1D SRA models. Furthermore, LS-DYNA, an advanced Finite Element (FE) program, was utilized to develop soil column models for 1D SRA at these arrays in order to quantify the shortcomings of the 1D approximations on the computed site response. By acknowledging the limitation of the 1D SRA modeling such as: (1) all horizontal boundaries are extended infinitely, and (2) the response is dominated by vertically propagating horizontally polarized shear (SH) waves, we evaluated the accuracy of the calculated response at these arrays. Both strong and weak recorded ground motions were used to perform SRA for each downhole array and the analysis results were compared with the observations at every available downhole sensor depth in order to examine the effectiveness of SRA models in capturing the soil response. On the basis of the analyses performed, we quantified the accuracy of the 1D SRA models and the advantages of the nonlinear soil modeling using two quantitative methods namely the Goodness-of-Fit (GOF) and Amplification Factor (AF) residuals.

Selection of Geotechnical Downhole Arrays

Array Selection Criteria

We carried out a screening procedure through the CSMIP geotechnical downhole arrays with special attention to the ones recorded motions during the 2014 M_w 6.0 South Napa Earthquake to select arrays that met the following criteria:

1. Accelerometers measure bi-directional shaking (i.e. two horizontal components);
2. The array has recorded both small and moderate-to-large amplitude motions (PGA < 0.1 g and PGA > 0.10 g);
3. Recorded ground motions are regarded as free-field motions and are not affected by an adjacent structure;
4. The soil layers are not susceptible to liquefaction and liquefaction has not previously been observed at close proximity to the array;
5. The site geology is relatively simple and a soil column can reasonably represent the subsurface soil behavior (i.e. minor basin or topography effects);
6. Arrays with information on subsurface soil properties such as in-situ test data.

Selected Arrays

Ideally, the selected arrays should have met all the criteria as listed above; however, it is acknowledged that site-specific aspects of the local geology, topography, and level of site characterization will diverge from these criteria to some extent. In most cases, the constraints had to be relaxed for selecting sites. In this study, we eventually identified 5 downhole arrays including (1) Crockett - Carquinez Bridge Geotech Array #1 (CC #1), (2) Crockett – Carquinez Bridge Geotech Array #2 (CC #2), (3) Vallejo - Hwy 37/Napa River E Geo. Array (Vallejo), (4) Eureka Geotechnical Array (Eureka), (5) El Centro - Meloland Geotechnical Array (El Centro). Figure 1 presents the location of these arrays in California. At these sites, PS suspension logging was conducted by the California Department of Transportation (Caltrans) hence shear wave velocity (V_s) and compression wave velocity (V_p) were measured. The site characteristics of the selected arrays are summarized in Table 1. Detailed description of these arrays and the subsurface soil characteristics can be found in Li et al. (2017).

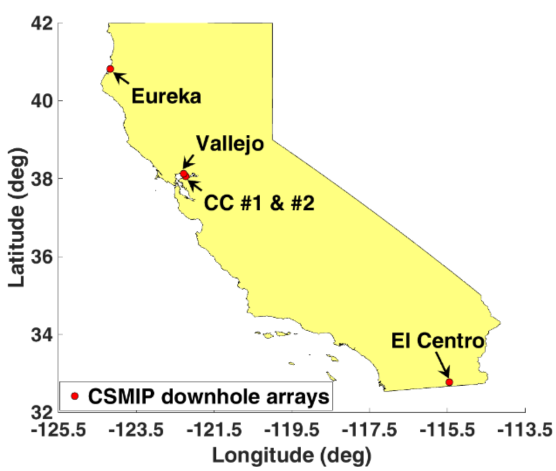


Figure 1. Location map of the selected CSMIP downhole arrays in this study

Table 1. Site characteristics of selected arrays (CESMD)

Station Name	Site Geology	Sensor Depths (m)	$V_{s,30}$ (m/sec)	Site Class (ASCE 7-10)	GWT Depth* (m)	Taxonomy (Site Quality for 1D SRA)
Crockett - Carquinez Br #1	Shallow clay over rock	0, 20.4, 45.7	345	D	4	HP (5)
Crockett - Carquinez Br #2	Shallow clay over soft rock	0, 61, 125	173	D	0.9	LP (2)
Eureka Geotechnical Array	Deep alluvium	0, 19, 33, 56, 136	194	D	1	LG (1)
El Centro - Meloland Geotechnical Array	Deep alluvium	0, 30, 100, 195	182	D	5	LP (3)
Vallejo - Hwy 37/Napa River E	Bay mud	0, 17.9, 44.5	509	C	3	HP (4)

Note: * GWT depth is estimated as the depth where V_p reaches 1500m/sec.

Taxonomy Evaluation of Selected Arrays

In this study, we utilized the site classification scheme (i.e. taxonomy) proposed by Thompson et al. (2012) to quantify the extent of site response complexity at the selected downhole arrays and assess the validity of the 1D site response assumptions. In the proposed taxonomy classification, the sites are classified into four distinct categories, i.e. LG, LP, HP and HG sites. The first letter of the taxonomy notation indicates the inter-event variability (σ) class of empirical transfer functions (ETFs) (H for "high" and L for "low") while the second letter indicates the goodness-of-fit (r) between ETFs and theoretical transfer functions (TTFs) (G for "good" and P for "poor"). The threshold values of σ and r are 0.35 and 0.6, respectively. In order to minimize the potential for nonlinear effects and increase the statistical significance, Thompson et al. (2012) recommended to use at least 10 records with PGA < 0.1g at ground surface for the taxonomy evaluation.

We carried out the taxonomy evaluation of the selected five downhole arrays and Figure 2 illustrates two extreme examples including Eureka as an LG site (i.e. the highest quality array) and the Crockett - Carquinez Br #1 as an HP site (i.e. the least quality array) for 1D SRA studies. The taxonomy designations for all other arrays are listed in Table 1 and the details of our taxonomy evaluation can be found in Li et al. (2017). In this paper, we further discuss the correlations between the taxonomy evaluation outcome and the calculated average residuals at these arrays.

1D Site Response Analysis

Methodology

In this study, Finite Element (FE) program LS-DYNA (LSTC, 2012) was utilized to develop and run 1D SRA models. We acknowledge the constraints of the 1D SRA modeling such as (1) soil layer boundaries are horizontal and extended infinitely in lateral directions, and

(2) modeled seismic waves are limited to the vertically propagated shear waves (i.e. SH waves). Soil column models of the selected arrays were developed in LS-DYNA using solid elements constrained to move in shear and Figure 3 presents two example soil columns. The soil columns were discretized in such a way that the maximum frequency each layer could propagate was as close to 37.5 Hz as possible. The bases of the soil columns were fixed to represent the "within" profiles (Stewart et al., 2008). In the current engineering practice, soil deposits are routinely modeled with lumped mass, springs and dampers for 1D SRA (e.g., DeepSoil, Hashash et al., 2016). Alternatively, SRA modeling with advanced FE programs such as LS-DYNA are capable to represent the effects of multi-directional shaking. In this study, the recorded acceleration data at the deepest downhole sensors of each array were input in both horizontal directions (bi-directional shaking) simultaneously to study the interaction between the horizontal components of the site response.

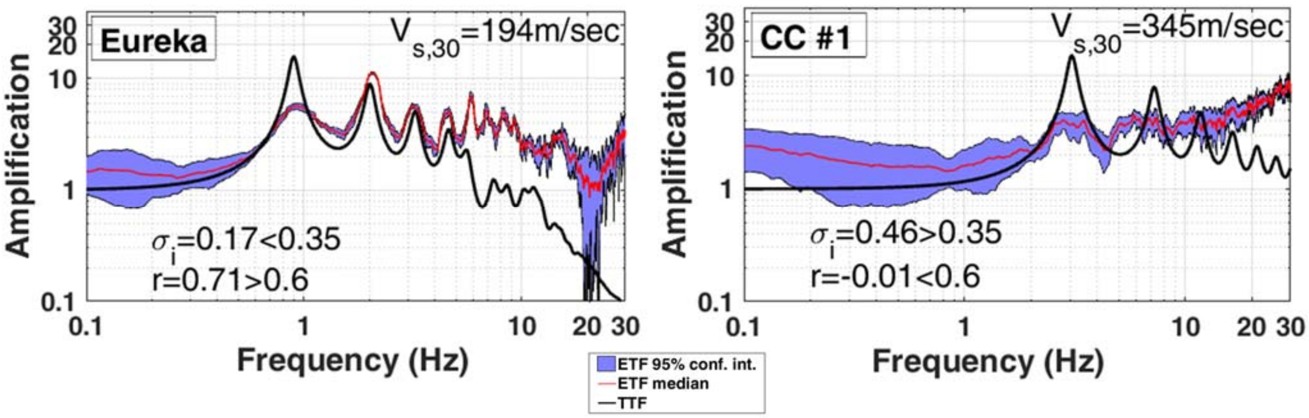


Figure 2. Taxonomy evaluation of Eureka and CC #1

The influence of dynamic stress-strain behavior on computed site response were investigated using two different soil nonlinear models, including general quadratic/hyperbolic backbone curve (Groholski et al., 2016, denoted as GQH hereafter) , modified two-staged hyperbolic backbone curve (Motamed et al., 2016, denoted as MTH hereafter). For all the nonlinear soil models, small strain damping (D_{min}) was applied using the DAMPING_FREQUENCY_RANGE_DEFORM feature in LS-DYNA which provides approximately frequency-independent damping over a range of frequencies to element deformation. D_{min} was set as 2% and 5% for strong and weak shakings in the frequency range of 1~30 Hz, respectively.

Regarding the nonlinear soil models (i.e. GQH and MTH), the MAT_HYSTERETIC_SOIL model was employed to simulate the dynamic response of the soil deposit, which includes an option to adjust soil stiffness based on the level of strain rate. Dynamic soil behavior was characterized by modified two-stage hyperbolic backbone curve for MTH model and general bivariate quadratic equation for GQH model. These two models were developed to properly account for the maximum shear stress in the constitutive model at large strain. Hysteretic damping of soil materials is governed by the loading-unloading relationship as described by Masing rule (Masing, 1926). Rate-dependent effects of clayey soils were accounted for by applying a 5% increase in stiffness per log cycle of plastic strain rate.

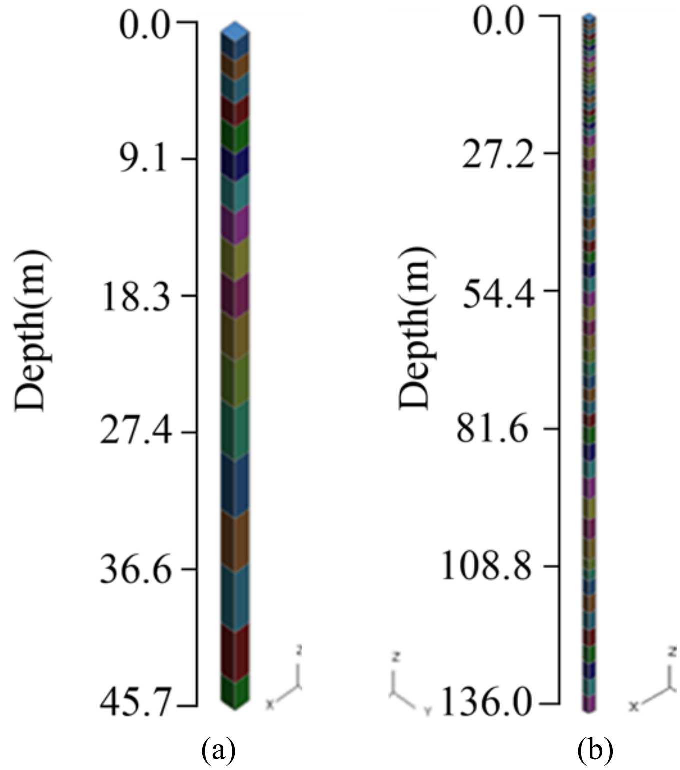


Figure 3. LS-DYNA soil column models for (a) CC #1 and (b) Eureka

Selection of Ground Motions

For each selected CSMIP downhole array, six individual analyses were performed using input motions that included one moderately strong time history (PGAsurface ≥ 0.1 g) and five low-amplitude motions (PGAsurface < 0.1 g). The processed ground motion time series were downloaded through the CESMD website. In total, 30 ground motions ranging in amplitude from PGA at the surface of 0.004g to 0.98g were utilized in this study. Figure 4 presents the distribution of recorded PGA at ground surface and the site classification of the studied arrays.

Analysis Results and Discussions

The performance of the 1D SRA models varied by site, which is attributed to the combined influence of stratigraphy and dynamic soil properties, and to aspects of the geological conditions at the sites that may not lend themselves to the 1D approximation of wave propagation. This section discusses the 1D SRA results of the two downhole arrays, Eureka and CC #1, which represent the highest and lowest quality predictions, respectively. Due to the page limitation, only the strong shaking analysis is presented for each array. For more details of our analysis results and discussions, please refer to Li et al. (2017)

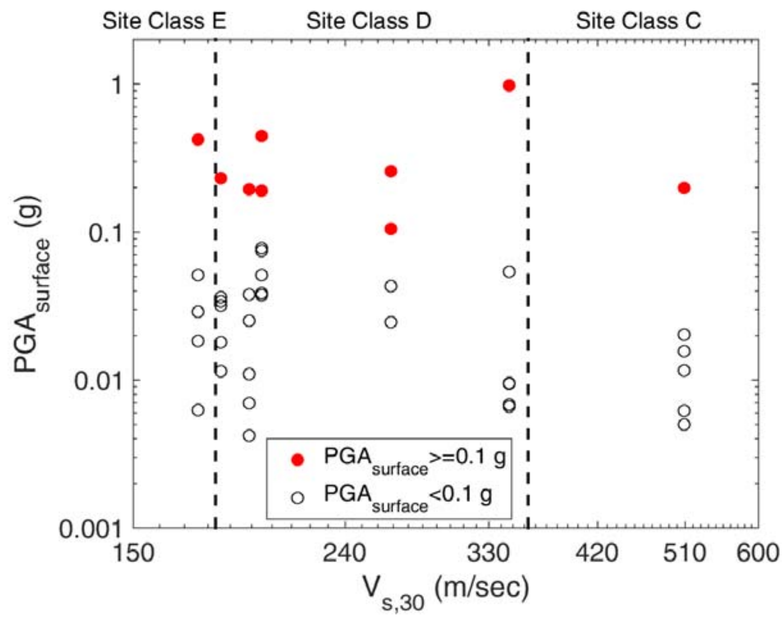


Figure 4. Distributions of PGA at the ground surface versus $V_{S,30}$ for the ground motion records used in this study and the site classes.

Eureka

The 1D SRA analysis results of Eureka subjected to the Ferndale Earthquake (Mw 6.5, 01/09/2010) are presented in Figures 5 and 6. As can be seen in Figure 5, GQH and MTH models fairly well reproduced the soil response for all components at various depths with regard to the 5% damped spectral acceleration (Sa). However, they slightly underestimated the peaks of Sa at surface and 19 m depth for both EW and NS components. Conversely, general overestimation was noticed at all depths (EW and NS components) for the linear elastic model. In addition, Figure 6(a) illustrates that the two nonlinear models underestimated the PGA at all depths while the linear model overestimated PGA at all depths. Figure 6(b) shows that the shear strain level in the soil profile reached as high as about 0.3%, indicating that the soil likely exhibited some nonlinear behavior in response to this strong shaking.

CC #1

The 1D SRA analysis results of CC #1 subjected to the main shock (M_w 6.0, 08/24/2014) of the South Napa Earthquake are plotted in Figures 7 and 8. It is shown in Figures 7 and 8(a) that the 5% damped spectral acceleration (S_a) and PGA predictions of GQH and MTH models reach fairly good agreement with the observations at mid-depth of 20.4 m. However, these two nonlinear models underpredicted 5% damped spectral acceleration (S_a) at period less than 0.4 sec and PGA at surface. In contrast, the linear elastic model overpredicted the soil response at 20.4 m depth while it surprisingly performed much better in capturing the large amplification at surface, especially in the EW direction. The nonlinear soil behavior was not dominant in the soil profile as shown in Figure 8(b) with peak shear strain smaller than 0.1%.

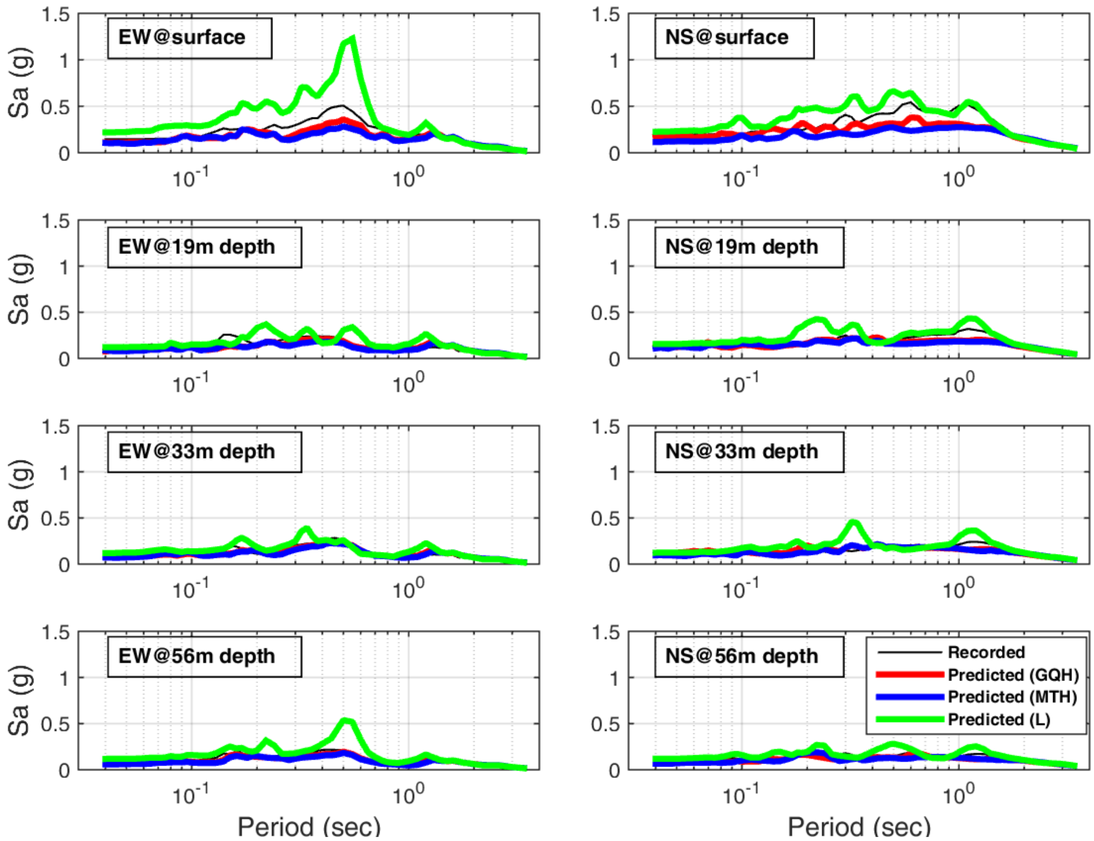
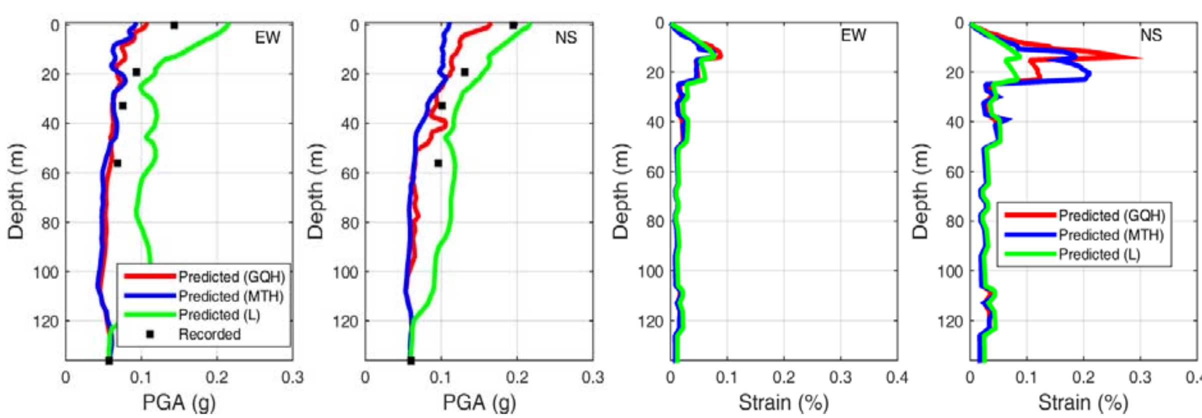


Figure 5. Comparison of measured and predicted 5% damped spectral accelerations at the Eureka array under the shaking of Ferndale Earthquake at different depths.



(a) (b)

Figure 6. (a) PGA and (b) max shear strain profiles of Eureka under the shaking of the Ferndale Earthquake.

Quantitative Assessment of 1D SRA Results

In this study, we quantified the accuracy of the different 1D SRA models using two different approaches namely the Goodness-of-Fit methodology proposed by Anderson (2004) and the amplification factor residuals described by Zalachoris and Rathje (2015). These two measures are described briefly hereafter and the results are presented.

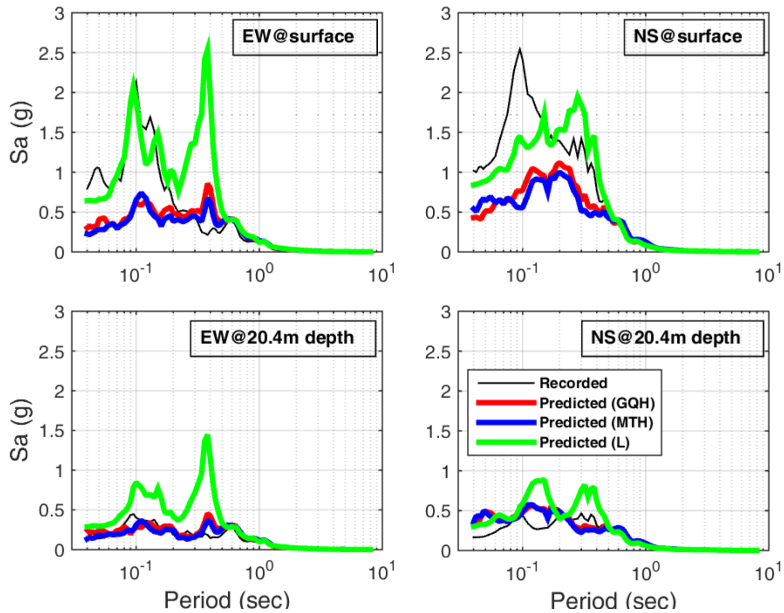
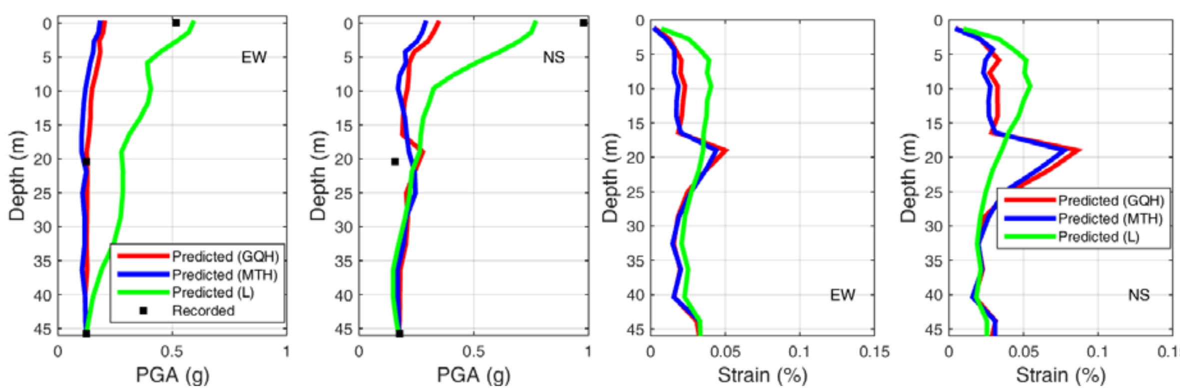


Figure 7. Comparison of measured and predicted 5% damped spectral acceleration of <u>CC #1</u> under the shaking of South Napa Earthquake mainshock at different depths.



(a) (b)

Figure 8. (a) PGA and (b) max shear strain profiles of <u>CC #1</u> under the shaking of South Napa Earthquake mainshock.

Goodness-of-fit

Anderson (2004) proposed the Goodness-of-Fit (denoted as GOF hereafter) scoring system to characterize how well synthetic seismographs match the statistical characteristics of observed records using ten different parameters including the peak acceleration, Arias intensity, Fourier spectrum, acceleration response spectrum, etc. A GOF score below 4 is a poor fit, a score of 4-6 is a fair fit, a score of 6-8 is a good fit, and a score over 8 is an excellent fit. In this study, the GOF for an individual site subjected to a specific shaking is calculated by averaging the GOF at different depths and shaking directions.

We utilized the GOF matrix to evaluate the overall accuracy of the nonlinear (i.e. GQH, MTH) and linear (i.e. L) models across all sites and the results are summarized in Figure 9 which are the mean GOF of the site response models, computed by averaging the GOF across all sites and ground motions. The GOF were also computed using subsets of the pooled GOF corresponding to records with binned γ_{max} (0.01% =<γ_{max} < 0.02%, 0.02% <= γ_{max} < 0.05%, 0.05% ≤ γ_{max}< 0.1% and γ_{max} ≥ 0.1%) and measured $PGA_{surface}$ ($PGA_{surface}$ < 0.05 g, 0.05 g ≤ $PGA_{surface}$ < 0.1 g, 0.1 g ≤ $PGA_{surface}$ < 0.15 g and $PGA_{surface}$ ≥ 0.15 g). As illustrated in Figure 9, the overall quality of the nonlinear SRA models was higher than the linear models (i.e. higher GOF score) and this improvement was more substantial in stronger shakings. We further investigated the correlations between the GOF score and the taxonomy classification which is elaborated hereafter.

Figure 10 presents a summary plot to correlate taxonomy designations with GOF of the nonlinear models for all sites. Each plot was divided by dashed red lines into four subareas representing the taxonomy classification the sites fell under. Besides, the size of the circles in Figure 10 is linearly proportional to the magnitude of the GOF score. The texts adjacent to the circles indicate the actual values of GOF score.

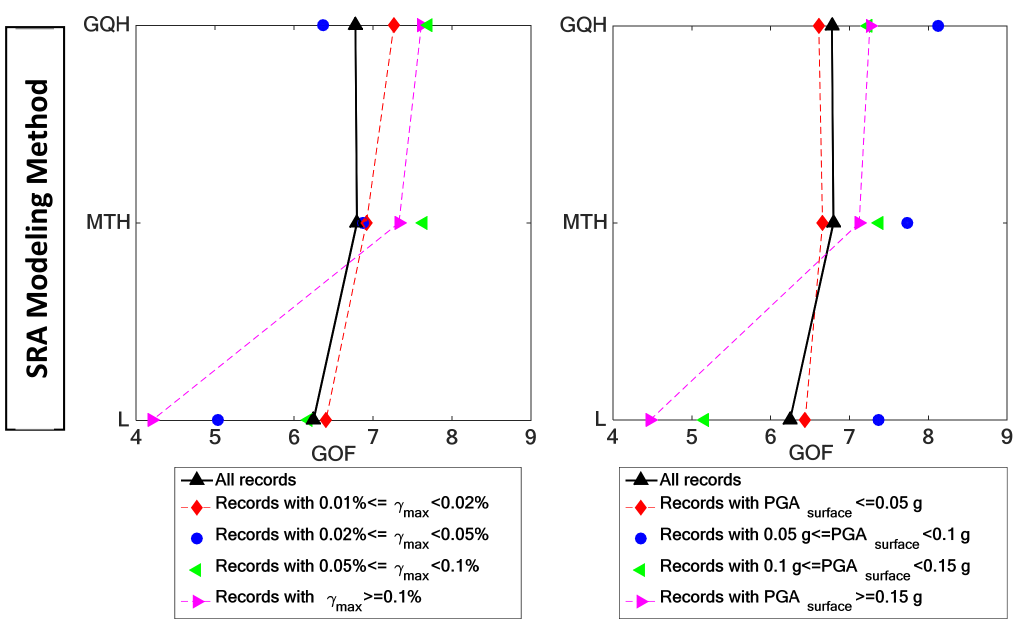


Figure 9. GOF of the 1D SRA models binned for different levels of γ_{max} and PGA at surface.

It is shown that the GOFs of all sites are in between 6 and 8, which implies that a "good fit" was achieved by either GQH or MTH model for the arrays, and illustrates the GOFs of GQH and MTH models for the same site are in good agreement.

In general, as shown on Figure 10, the GOF score becomes larger with low σ or high r for both models. For example, Eureka is classified as a LG site according to the taxonomy scheme with the lowest σ and the highest r among all arrays and thus it yields the highest GOF for both models. Contrarily, CC #1 is designated as a HP site and achieves the lowest GOF with the combined effects of the highest σ and the second lowest r among all sites. This observation indicates that taxonomy designation is in general agreement with the calculated GOF scores for the studied arrays.

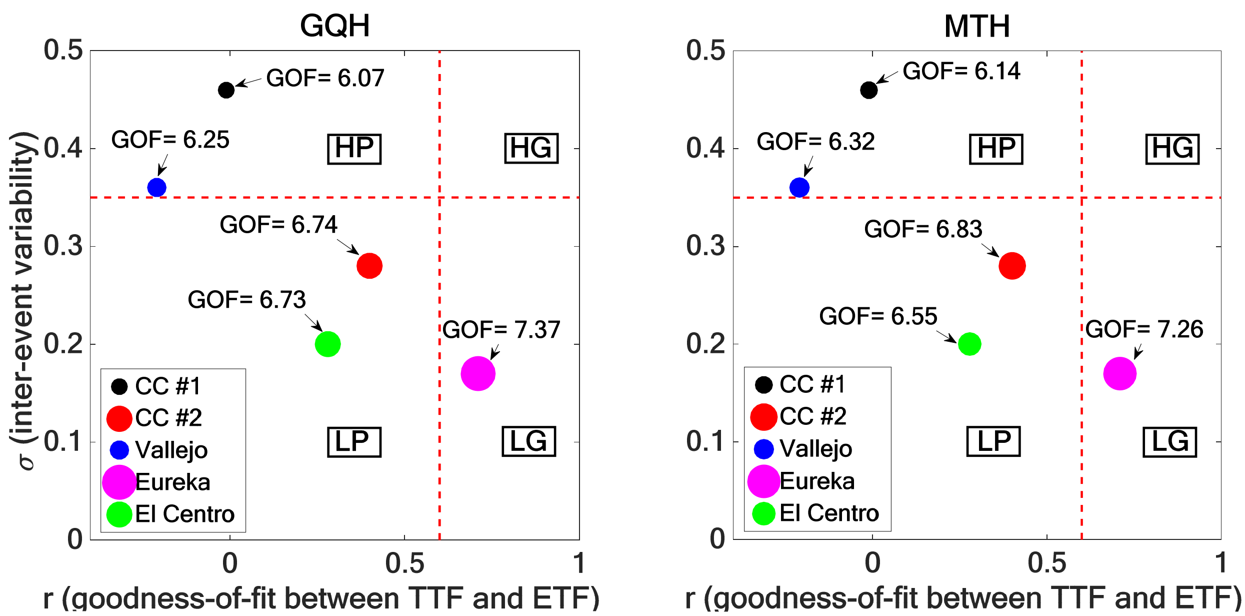


Figure 10. Correlation of taxonomy classification with mean GOF of GQH and MTH models for the CSMIP downhole arrays.

Residual of Amplification Factor

In this study, similar to Zalachoris and Rathje (2015), we quantify the misfit (or bias) as the difference between the natural log of the measured and computed amplification factors (AF) at each period. For the *i*th site and *j*th recording, the residual (R) at period T between the observed amplification factor (AF^{obs}) and the calculated amplification factor (AF^{calc}) is given by Equation 1.

$$R_{i,j}(T) = \ln AF_{i,j}^{obs}(T) - \ln AF_{i,j}^{calc}(T) \tag{1}$$

A positive residual indicates underprediction by the model while a negative residual implies overprediction. A consistent period range (0.04 – 3.0 sec), which was the commonly shared period range of response spectra of all sites and events provided by CSMIP, was utilized to compute the AF residual hereafter.

The analysis results were initially grouped based on their corresponding level of shaking, as depicted by the measured peak acceleration of the surface motions ($PGA_{surface}$). Since the recorded peak ground acceleration at the surface ranges from low (0.004 g) to high (0.98 g), the effect of shaking intensity on the accuracy of the predictions was investigated. Four different ranges of $PGA_{surface}$ were considered: $PGA_{surface} \leq 0.05$ g, 0.05 g < $PGA_{surface} \leq 0.1$ g, 0.1 g < $PGA_{surface} \leq 0.15$ g and $PGA_{surface} > 0.15$ g.

As seen in Figure 11, the performance of the GQH, MTH and L models strongly depended on the level of shaking, and thus implicitly on the magnitude of the induced shear strains. At low intensity levels, namely for $PGA_{surface}$ less than 0.05 g, there is strong agreement between the observations and the prediction results at all frequencies. A slight underprediction occurs at periods less than 0.2 sec and a slight overprediction at periods greater than 0.2 sec, but still the agreement is fairly good. As the shaking intensity increases, the calculated amplification factor residuals of the site response models deviate from each other, as well as from the observations. In general, the GQH and MTH models moderately underpredicted the amplification at shorter periods while L model strongly overpredicted the amplification over a wide range of periods at high intensity shakings.

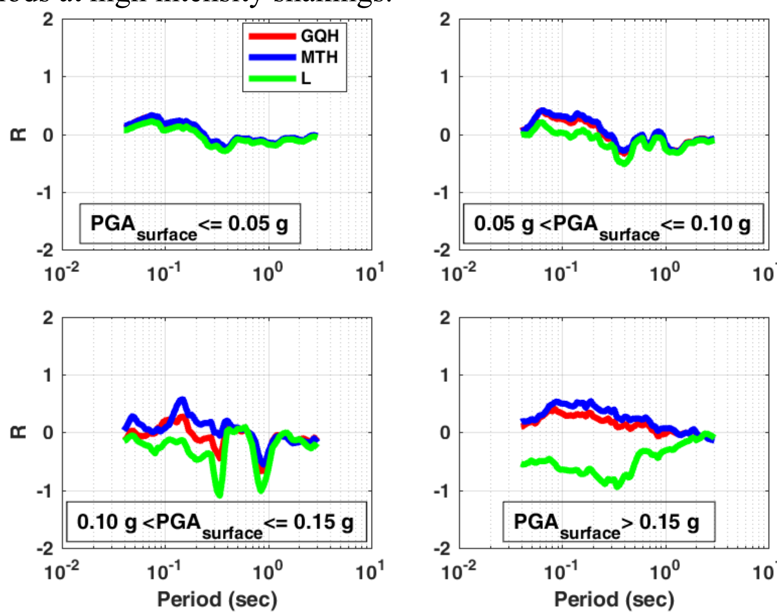


Figure 11. Computed mean residual of amplification factor for all sites at different ranges of measured PGAsurface.

Conclusions

This paper evaluated the taxonomy classification of the five selected CSMIP downhole arrays, hence their quality for 1D SRA studies is ranked. The 1D SRA modeling was performed in LS-DYNA for these arrays to study the effects of subsoil conditions on the amplification of ground motions. Both strong and weak shakings were analyzed for each array and the analysis results were presented.

Overall, nonlinear finite element models for all arrays were capable of reproducing the ground motions fairly well over low frequency range (< 1 Hz) but failed to capture (in most cases underestimated) the components of the motions at intermediate and high frequencies (> 1 Hz). Besides, linear elastic models of arrays in general overestimated the soil response (especially for strong shaking case) and tended to yield intermediate period spectral acceleration peaks caused by resonance of soil profiles. In addition, the nonlinear SRA models typically resulted in better quality predictions compared to the linear models and this improvement was more significant under strong shakings (PGA > 0.1g).

The outcome of the taxonomy evaluation informed us of the expected level of accuracy at the five studied arrays and our observations were in good agreement with the taxonomy site classification. Among the five arrays studied in detail, Eureka was identified as an LG site (i.e. highest 1D SRA quality rank suggested by the taxonomy scheme) which was consistent with the calculated average GOF and amplification residual at this site. On the other hand, CC#1 was identified as an HP site (i.e. lowest 1D SRA quality rank suggested by the taxonomy scheme) which was again in good agreement with the calculated average GOF and amplification residuals at this site.

We employed two methods to quantify the extent of accuracy of the 1D SRA models using (1) GOF scoring system, and (2) amplification factor residuals and both techniques were found to be useful in comparing the results. The strengths and limitations inherent in the practical application of 1D SRA model demonstrated the following: (i) 1D SRA is applicable for sites where the 1D SRA assumptions are valid, (ii) 1D SRA fails to account for 2D and 3D effects including spatial heterogeneity, nonvertical incidence, basin effects and topographic effects. Considering the presence of complex geologic and topographic conditions at some sites was found to be significant, 1D SRA was not quite effective or accurate in estimating site amplifications. As a means to understand the complexity of site response and the validity of 1D SRA assumptions, it is recommended to evaluate taxonomy class of a specific site prior to performing 1D SRA in engineering practice, if weak ground shakings were recorded at that site.

Acknowledgements

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