ASSESSMENT OF THE INFLUENCE OF THE ELASTIC HALFSPACE ASSUMPTION ON SITE RESPONSE ESTIMATIONS

Ishika N. Chowdhury¹, Ashly Cabas²

ABSTRACT

Borehole array data provide us with the opportunity to study the effects of near-surface soil conditions on ground motions. These data are also used to validate numerical models that aim to represent the behavior of soils. In this study, ground motion data from the instrumented borehole arrays of the Garner Valley in Southern California are analyzed to assess the variability and uncertainties in site response estimations related to the elastic half-space (EHS) assumption. This site has both surface and borehole arrays of accelerometers. The soil profile consists of 18-25 m of alluvium overlying weathered granite, which transitions into granitic bedrock at 87 m depth. One-dimensional linear elastic site response analyses were performed using recordings from different depths of the borehole array as input motions. The depth of the half-space boundary assumed in the soil column being modeled is varied, according to the selected depth at which each input motion was recorded (i.e., 6 m, 22 m and 150 m). The estimated surface motions for each case are compared with the observed data from the array in terms of response spectral amplification factor. The EHS boundary, usually set at the base of the soil profile of interest to represent bedrock conditions, is expected to conform to the laws of linearity and homogeneity. Though these conditions are not met at shallow depth, the borehole record is expected to capture the effects of both upgoing and downgoing waves. Thus representing an appropriate input motion for site response analyses. Linear elastic site response analyses were conducted using low-intensity motions to avoid the effects of soil nonlinearity, and a modified damping model was used to evaluate the limitations of laboratory-based damping. Proper boundary conditions at the soil column base were investigated, and the within assumption was selected. However, comparisons between observed and computed amplification factors showed a significant misfit. The effect of the EHS assumption on the site response estimations is evident from these observations. Therefore, this study illustrates the application of direct ground motion records from borehole arrays to assess the effect of the EHS assumption.

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ABSTRACT

Borehole array data provide us with the opportunity to study the effects of near-surface soil conditions on ground motions. These data are also used to validate numerical models that aim to represent the behavior of soils. In this study, ground motion data from the instrumented borehole arrays of the Garner Valley in Southern California are analyzed to assess the variability and uncertainties in site response estimations related to the elastic half-space (EHS) assumption. This site has both surface and borehole arrays of accelerometers. The soil profile consists of 18-25 m of alluvium overlying weathered granite, which transitions into granitic bedrock at 87 m depth. One-dimensional linear elastic site response analyses were performed using recordings from different depths of the borehole array as input motions. The depth of the half-space boundary assumed in the soil column being modeled is varied, according to the selected depth at which each input motion was recorded (i.e., 6 m, 22 m and 150 m). The estimated surface motions for each case are compared with the observed data from the array in terms of response spectral amplification factor. The EHS boundary, usually set at the base of the soil profile of interest to represent bedrock conditions, is expected to conform to the laws of linearity and homogeneity. Though these conditions are not met at shallow depth, the borehole record is expected to capture the effects of both upgoing and downgoing waves. Thus representing an appropriate input motion for site response analyses. Linear elastic site response analyses were conducted using low-intensity motions to avoid the effects of soil nonlinearity, and a modified damping model was used to evaluate the limitations of laboratory-based damping. Proper boundary conditions at the soil column base were investigated, and the within assumption was selected. However, comparisons between observed and computed amplification factors showed a significant misfit. The effect of the EHS assumption on the site response estimations is evident from these observations. Therefore, this study illustrates the application of direct ground motion records from borehole arrays to assess the effect of the EHS assumption.

Introduction

One of the critical aspects that must be considered when conducting one-dimensional site response analyses (SRA) is the selection of the elastic half-space (EHS) depth and characteristics. The hypotheses associated with an EHS are assumed to be satisfied by a linear and homogeneous material of assumed infinite depth. Hence, this boundary is usually defined at a horizon sufficiently stiff such that the assumption of linear behavior will likely hold and no subsequent strong impedance contrast is expected below this depth [1]. These conditions are mostly satisfied by the bedrock material (i.e., hard rock with high shear wave velocity). Selecting the top of the bedrock layer as the EHS boundary implies that the bedrock is fully elastic and homogeneous and no strong impedance contrast will take place below this depth (so it will absorb a portion of the downgoing seismic waves). However, if these conditions are not met, a part of the energy of downgoing waves

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at depth will be reflected upward due to the presence of deeper impedance contrast boundaries. Therefore, selecting a reasonable EHS boundary to minimize this effect is a relevant task for engineers. Additionally, engineers often face challenges to properly identify a layer that meets the EHS assumption due to budgetary and/or technological constraints.

Borehole array data can provide us with an excellent opportunity to assess the effect of EHS assumption. Borehole array data are usually used to study the effects of near-surface soil conditions on ground motions and thus, they can help to identify the variability and uncertainties involved in SRA. The borehole record includes the effect of both upgoing and downgoing waves. Therefore, the input of this record in SRA at the corresponding depth is expected to represent an appropriate input motion for the truncated site response model under consideration. Though the use of borehole data as input motion in 1D SRA requires the assumption of a rigid base (i.e., known as the within assumption), the variable depth of the selected reference horizon or assumed truncation depth can provide us with a good approximation of the effect of EHS assumption. In this study, the borehole records are used as input motions at different depths, and that lead to different estimations of site response at the surface. This misfit can be associated with the effect of EHS assumption. The objective of this study is to investigate the effects of the EHS assumption on site response estimations when using input motions from a downhole array.

The later sections of this paper describe the characteristics of the selected site, and the methodology followed. The results of SRA are evaluated, and the potential sources of the observed mismatch with empirical observations are investigated. Finally, the effects of EHS assumption on SRA are investigated.

**Study Site**

The Garner Valley Downhole Array (GVDA) site, which belongs to the George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES), is located in southern California in a narrow valley within the Peninsular Ranges Batholith. This instrumented site is located within 7 km of the main trace of San Jacinto fault system and within 35 km of the San Andreas fault. San Jacinto is historically the most active strike-slip fault system in southern California with a fault slip rate of 10 mm/yr. The absence of large earthquakes in this fault since 1890 may lead to a relatively high probability of a magnitude 6.0 or larger earthquake in the near future. The GVDA consists of 18-25 m of lake-bed soft alluvium overlying a thick weathered granite layer. The latter transitions into unweathered granitic bedrock with a boundary at 87 m depth. More specifically, the upper 18-25 m of soil consist of alternating layers of sand, silty sand, clayey sand, and silty gravel. The alluvium gradually transitions into decomposed granite consisting of gravelly sand between 18 m to 25 m. This layer extends to about 87 m where the hard bedrock is located. The groundwater table at the GVDA site varies from 0-3m below the ground surface depending on the season and rainfall rate. Figure 1(a) shows the corresponding soil profile at the GVDA site. The site has both, a surface array and a downhole array of accelerometers. Instrumentation of this site began in 1989 and the NEES project began in 2002. After major improvements in 1995 and 2004, the GVDA site currently has seven accelerometers located at the ground surface level and six downhole accelerometers at depths of 6 m, 15 m, 22 m, 50 m, 150 m and 501 m below the ground surface. Accelerometers at the site record acceleration data at a rate of 200 samples per second using continuous data acquisition system. In this study, we have analyzed data from accelerometers at three depths (i.e., 6 m, 22 m and 150 m) and used those as input motions to conduct one-
dimensional site response analyses at the site. We have subsequently compared our estimated surface motions with observed records at 0 m.

Borehole suspension logging was conducted at the GVDA site by Agbabian Associates in 1994 and 1996 up to 50 m and 100 m depth, respectively. Considering that two of the downhole accelerometers are located below 100 m depth, the velocity and density models need to be extended in order to have sufficient information to conduct one-dimensional site response analyses. In this study, the velocity model presented in Bonilla et al. [3] is used. These authors computed synthetic accelerograms at different depths using the discrete wavenumber technique and compared those with observations. Then a trial-and-error procedure was applied to determine the best-fit model in terms of both time and amplitude. The relationship between shear wave velocity and density adapted by Boore [4] is used in the study presented herein to define the corresponding density model. Site response estimates were computed using this density model and using the density data from borehole logging, separately. The results from both analyses provided a good agreement. The velocity and density model used in this study are shown in Figure 1(b).

Figure 1. (a) Soil profile (adapted from Chandra et al. [2]) and (b) Shear wave velocity and density profile at the Garner Valley site

Methodology

To assess the impact of the EHS assumption, this study uses data from accelerometers at three different depths. The first one is close to ground surface at a depth of 6 m, the second one at an impedance contrast boundary, which is located at 22 m from the ground surface, and lastly, a depth of 150 m at granite bedrock is considered. The comparison between observed and predicted motions can be biased by the model selected to address soil nonlinearity. To isolate the effects of
the EHS assumed properties from other modeling assumptions on site response results, only linear-
elastic soil behavior is considered. Hence, only low-intensity input ground motions (PGA<0.05g) 
are used in this study. A suite of 20 motions (i.e., 20 recorded horizontal components from ten 
different seismic events) is used, and the corresponding characteristics are presented in Table 1. 
One-dimensional linear elastic SRA are performed using the site response program Strata [5]. 
Minimum shear strain damping values are obtained from Darendeli and Stokoe [6] model. The 
motions recorded at the downhole accelerometers located at 6 m, 22 m and 150 m are used as input 
motions at the corresponding depths. The half-space boundary is assumed to be located at the 
aforementioned depths, where the input motions are applied. Accordingly, soil profiles used to 
conduct the one-dimensional SRA are truncated at such depths. For example, when using the 
motion recorded at 6 m as input motion, only 6 m of the soil profile is modeled in SRA, and the 
soil below this depth is not considered (i.e., the half-space boundary is assumed to be located at 6 
m). Similarly, when using records from 22 m and 150 m depth, the modeled soil profile is truncated 
at 22 m and 150 m depth, respectively.

Table 1. Characteristics of seismic events selected for this study

<table>
<thead>
<tr>
<th>Date</th>
<th>Magnitude</th>
<th>Depth (km)</th>
<th>Epicentral Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/09/17</td>
<td>2.71</td>
<td>13.7</td>
<td>6.2</td>
</tr>
<tr>
<td>06/03/08</td>
<td>3.04</td>
<td>16.2</td>
<td>5.48</td>
</tr>
<tr>
<td>01/09/16</td>
<td>3.3</td>
<td>13.6</td>
<td>9.32</td>
</tr>
<tr>
<td>07/26/09</td>
<td>3.53</td>
<td>14</td>
<td>5.84</td>
</tr>
<tr>
<td>11/17/08</td>
<td>4.11</td>
<td>12.2</td>
<td>25.64</td>
</tr>
<tr>
<td>01/16/10</td>
<td>4.28</td>
<td>13.9</td>
<td>43.67</td>
</tr>
<tr>
<td>01/06/16</td>
<td>4.39</td>
<td>16.7</td>
<td>37.87</td>
</tr>
<tr>
<td>03/11/13</td>
<td>4.7</td>
<td>13.1</td>
<td>27.31</td>
</tr>
<tr>
<td>04/04/10</td>
<td>6.6</td>
<td>6</td>
<td>131.03</td>
</tr>
<tr>
<td>04/04/10</td>
<td>7.2</td>
<td>10</td>
<td>206.41</td>
</tr>
</tbody>
</table>

A key model assumption when using downhole accelerometer records as input motion in 
site response analysis is the selected boundary conditions at the depth of application of such input 
motions. As the recorded motion at the borehole depth includes both the upgoing and downgoing 
wave effects, the current standard practice is to use the within boundary condition assumption. The 
latter basically assumes a rigid base where all the downgoing waves get reflected back up to the 
profile as they reach the half-space boundary. However, this downgoing wave effect may decrease 
at greater depths of borehole accelerometer. Bonilla et al. [3] have investigated the effect of 
downgoing waves at the GVDA site and shown that it is significant for 6 m, 15 m, 22 m and 50 m 
records. However, for records at 220 m and 500 m depth, this effect is less significant, and outcrop 
boundary conditions provide a better match to observations. Records from 150 m depth were not 
analyzed in their paper as the corresponding sensor was placed later in 2004. Before using the 
records of 150 m in this study, the proper boundary condition was investigated. Figure 2 shows 
the median observed and median computed response spectral amplification factor using both, 
within and outcrop boundary condition assumptions separately. The within boundary condition 
provides a better agreement with the observation. It should be noted that Bonilla et al. [3] illustrated 
this comparison in Fourier spectral domain and Figure 2 is presented in response spectral domain.
The GVDA site has a strong impedance contrast (increase in shear wave velocity from 650 m/s to over 1600 m/s) at 87 m depth. Bonilla et al. [3] indicated that this boundary could trap most of the seismic energy. However, from Figure 2, with the better match between within assumption and observed amplification, it is evident that the downgoing wave effect is significantly present even below 87 m depth. After this initial assessment of the proper boundary condition at all three selected depths (6 m, 22 m and 150 m), the within boundary condition assumption was used in this study for further analyses.

Figure 2. Observed and Computed Response Spectral Amplification Factors for 150 m borehole records using within and outcrop assumption

Comparisons between observed and computed motions using SRA are made in the frequency domain. Response spectra with 5% damping are calculated because of their significance in engineering applications. A period range of 0.01-10 sec is considered in the analysis with 512 logarithmically spaced periods. Comparisons are made in terms of response spectral ratios calculated as the response spectra at surface divided by the response spectra at the borehole depth under study.

Results

The assessment of the effects of the EHS assumption in the study presented herein involves the comparison of computed site response analyses results with observed values using borehole records at selected depths. The linear elastic site response analysis results for records at different depths are shown in terms of response spectral amplification factors in Figure 3(a). The median observed amplification factor corresponding to the selected suite of motions presented in Table 1 is also shown in Figure 3(a) along with the median predicted amplification factor plus one standard deviation. It is evident from the plots that one-dimensional linear elastic SRA overpredicts the response especially at lower periods (i.e., Period<1 second). This disagreement can be due to an inaccurate model of the soil profile, inaccurate damping model or the effect of the EHS assumption. The GVDA soil profile has been well characterized with numerous in situ tests over the years. Moreover, the location of the computed amplification factor peaks has a good agreement with those of observed amplification. This indicates that the soil profile used in the analyses is
Figure 3. Computed and Observed Response Spectral Amplification Factors for different depths (a) using minimum damping (b) using best-fit damping
representing the actual site conditions reasonably well. Therefore, the overprediction is most probably due to an inaccurate damping model and/or the effects of the EHS assumption. In this study, an effort is made to correct the damping model to focus on the effects of EHS assumption only.

Initially, the minimum shear strain damping values obtained from Darendeli and Stokoe [6] damping model are used in the analyses. This model predicts the damping values as a function of soil parameters such as effective confining stress, soil plasticity and over consolidation ratio. This results in a gradual decrease of damping values from the ground surface to greater depths. The small strain damping which is the minimum damping obtained from Darendeli and Stokoe [6] model is used in the initial linear elastic SRA. However, this damping value is coming from the viscous damping measured in the laboratory, which may not always be representative of the in-situ conditions. Because the in-situ conditions include other mechanisms of energy dissipation (such as scattering of the wave) that can not be captured by a laboratory test, the minimum damping values obtained from Darendeli and Stokoe [6] need to be adjusted. A grid search procedure proposed by Zalachoris and Rathje [7] is adapted in this study to carry out such modification. Thus, linear elastic SRA are performed using records from selected depths using minimum shear strain damping values from Darendeli and Stokoe [6] model multiplied by a factor of 1-10 with a step of 0.5. The difference between the computed and observed amplification factors is quantified using the root-mean-square error (RMSE). The damping profile that resulted in the smallest value of RMSE was taken as the best-fit damping model. For all three selected depths, the minimum damping multiplied by a factor of 3.5 resulted in the smallest RMSE. The initial minimum shear strain damping and the best-fit damping model are shown in Figure 4.

![Figure 4. Minimum shear strain damping values used in one-dimensional linear-elastic SRA.](image)

The RMSE between computed and observed amplification factors obtained from these two damping models for records at selected depths are presented in Table 2. It should be noted that
there is a significant decrease in error after using modified (best-fit) damping model. Moreover, the errors are showing a trend of increase with depth in both cases.

Table 2. RMSE between computed and observed amplification factors using minimum damping and best-fit damping

<table>
<thead>
<tr>
<th>Accelerometer Depth (m)</th>
<th>RMSE- Minimum damping</th>
<th>RMSE- Best-Fit damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.31</td>
<td>0.15</td>
</tr>
<tr>
<td>22</td>
<td>0.61</td>
<td>0.27</td>
</tr>
<tr>
<td>150</td>
<td>1.90</td>
<td>0.79</td>
</tr>
</tbody>
</table>

The linear elastic SRA results using the best-fit damping model (i.e., the Darendeli and Stokoe [6] model multiplied by a factor of 3.5), are shown in Figure 3(b). The computed and observed amplification factors have a better agreement compared to that of the initial minimum shear strain damping (Figure 3(a)). The modified damping model has helped reduce the overall overprediction but at the cost of underprediction especially for 22 m and 150 m records. After modifying the damping model, now the disagreement between computed and observed amplification factor is primarily a function of the effect of EHS assumption. From the plots, it is evident that the disagreement between computed and observed amplification factors is increasing with greater depth of borehole records. To better quantify this misfit or bias, the mean residual between the natural log of computed amplification factor (AF$_{pred}$) and observed amplification factors (AF$_{obs}$) at each period is calculated. Figure 5 shows these residuals for three selected borehole depths.

Figure 5. Computed mean residuals for records at different depths

A positive residual indicates underprediction and a negative residual indicates overprediction. For periods less than 1 sec, the residuals from records of three borehole depths did not follow any specific trend. And, for the periods greater than 1 second, we can observe mostly higher values of absolute residual with greater depth of borehole record. However, largest values of absolute residual for all three selected depths are observed at lower periods (< 1 second). The
increase of misfit with increased depth of borehole records observed from Table 2 and Figure 5 (for periods > 1 second) may be due to the fact that with greater depth, more uncertainties related to the soil profile are adding up. Even though the borehole records capture the energy of both upgoing and downgoing waves at the corresponding depths, the misfits between the observed and estimated amplification factors are different for three different depths used in this study (Figure 5). This implies that the depth of the half-space assumption has a significant effect in SRA. This phenomenon should be further investigated to quantify the uncertainties involved and how much the EHS assumption is contributing to them.

Conclusions

This paper presents the assessment of the effects of the EHS assumption on 1D site response analyses when using input data from borehole arrays at different depths. Linear elastic SRA were conducted using low-intensity motions to avoid the uncertainties in SRA coming from the selected model to address soil nonlinearity. Initially, the proper boundary condition for the analyses at different depths was investigated, and it was found that the downgoing wave effect is significant even at 150 m depth. Therefore, within boundary conditions were assumed for further analyses. The initial analyses showed significant overprediction of response spectral amplification factors at lower periods (0.01-1.0 second), when comparing computed and observed amplifications. One potential cause was the inadequacy of the minimum shear strain damping values used from laboratory-based models. Therefore, the damping model was modified in a trial-and-error process. A multiplicative factor of 3.5 applied to the initial minimum damping values was found to provide the lowest errors when compared to observed amplifications. This was selected as the best-fit damping model and was used for further analysis. Comparisons between observed and computed amplification factors showed significant misfit and the misfits were different for three different depths used in this study. The effect of the EHS assumption on the site response estimations is evident from these observations. The results of this study support recent research efforts (Cabas et al. [8]) to assess the effect of the EHS assumption on SRA. Further research is deemed necessary to formally quantify the contribution of this key model assumption to the overall uncertainty and variability in SRA results. The implications of this study include improvements to the assessment of site-specific seismic hazards, ground motion prediction equation (GMPE)s development, ground motion simulations, etc.

References


