Seismic site response of shallow sites in moderate seismicity regions
Réponse du site sismique des sites peu profonds dans les régions à sismicité modérée

Menzer Pehlivan
CH2M, USA, menzer.pehlivan@ch2m.com

Duhee Park, Shamsher Sadiq
Department of Civil and Environmental Engineering, Hanyang University, Korea

Youssef M. A. Hashash
Department of Civil and Environmental Engineering, University of Illinois at Urbana-Campaign, USA

ABSTRACT: Seismic site response is highly dependent on local soil conditions that significantly influence amplification and attenuation of rock motions during a seismic event. Local site effects have been studied extensively in regions of high seismicity, low impedance contrast, and deep soil profiles. In moderate seismicity regions, rock motions with low intensity, short duration, and high frequency content might experience significant short period amplification while propagating through shallow sites with high impedance contrast. Building code-based site factors and design spectra may not accurately capture such short period amplification in moderate seismicity regions such as Korea, thus may lead to non-representative seismic site response estimates. This paper presents the results of numerical simulations of seismic site response of shallow soil sites (<30m) with high impedance contrast in moderate seismicity regions. Seismic site response is computed through series of equivalent linear and nonlinear analyses performed for four representative shallow sites from Korea for moderate seismicity events. This paper compares the computed seismic site response with building code-based design estimates and discusses potential implications of observed differences on design practice.

RéSUMÉ: L’effet sismique sur un site est fortement dépendant des conditions locales du sol qui ont une influence significative sur l’amplification et l’atténuation du mouvement de la roche au cours d’une activité sismique. Les effets locaux sur un site ont été étudiés exhaustivement en des régions de forte sismicité, faible contraste impédance, et des profonds profils du sol. Dans les régions de sismicité modérée, les mouvements du sol au niveau du rock a faible intensité, de courte durée et de haute fréquence peuvent rencontrer amplification de période courte et significative tout en se propageant à travers des sites peu profonds avec un contraste de haute impédance. Les facteurs de site basée sur le code et la conception spectrale peuvent ne pas accidentellement capturer avec précision de telle courte amplification de période dans les régions de sismicité modérée comme la Corée. Cet article présente les résultats des simulations numériques de l’impact sismique du site sur des contrastes des endroits de sol peu profonds (< 30m) avec une haute impédance dans les régions de sismicité modérée. Cet article compare la réponse calculée d’un site sismique sur quatre sites avec des estimations de conception basée sur le code et discute les implications potentielles sur la pratique de conception.

KEYWORDS: equivalent-linear and nonlinear site response analyses, moderate seismicity, shallow sites, high-impedance contrast

1 INTRODUCTION
Recent earthquakes around the world (such as 1985 Mexico City, 1994 Northridge, 1999 Kocaeli, and 2015 Nepal) demonstrated strong influence of local site conditions and seismicity on the attenuation and amplification of rock motions. The effect of local site conditions can be very significant, with the site response changing the amplitude, frequency content, and duration of shaking (Pehlivan et al., 2016). The influence of local site conditions on the seismic site response can be quantified through site-specific site response analyses or building code-based site factors.

Site-specific site response analyses use wave propagation analyses to quantify local site effects on the ground motion by considering the nonlinear soil response during ground shaking. Generally, seismic site response is evaluated through one-dimensional (1D) site response analyses, which can be performed using equivalent-linear (EQL) or nonlinear (NL) soil models. Although, EQL soil models are more commonly used in practice compared to NL soil models, NL ground response analyses provide more realistic characterization of the soil behavior (Stewart et al., 2008; Matasovic and Hashash, 2012). Alternatively, building code-based seismic site response can be obtained by scaling the rock motion using the Code-based site factors at short and long periods, which are defined based on the stiffness of the top 30 m soil and rock motion intensity. The building code-based site factors currently used to estimate the seismic site response were developed based on local site effect observations from 1994 Northridge Earthquake in California (Dobry et al., 1999). Therefore, the building code-based site factors primarily represent the amplification characteristics of regions of high seismicity, low impedance contrast, and deep soil profiles. In moderate seismicity regions, the rock motions with low intensity, short duration, and high frequency content might experience significant short period amplification while propagating through shallow sites with high impedance contrast. The building code-based site factors and design spectra may not accurately capture such short period amplification in moderate seismicity regions such as Korea and the Central and Eastern United States (CEUS) and may lead to non-representative seismic site response estimates.

Several previous studies showed higher short period amplification predicted for shallow sites with high impedance contrast in moderate seismicity regions, when compared to building code-based seismic site response estimates (Kim et al., 2016). This paper presents the results of numerical simulations of seismic site response at four representative shallow soil sites (<30m) with high impedance contrast in Korea. Seismic site response at each site is computed through series of equivalent linear and nonlinear analyses and performed for spatially varied dynamic soil profiles. Seismic site response and site amplification estimates at each of the four sites is compared with building code-based design estimates and site factors. The potential implications of observed seismic site response of shallow sites in moderate seismicity regions are discussed.
2 SITE RESPONSE ANALYSES

One-dimensional (1D) site response analysis is the most common approach used to assess the effect of local soil conditions on seismic site response. EQL or NL analysis methods can be used for 1D site response analysis. EQL analyses use nonlinear modulus reduction and damping curves to approximate nonlinear, inelastic stress-strain behavior for cyclically loaded soils, whereas NL analyses are capable of representing the actual nonlinear stress-strain behavior through incrementally-linear model (Kramer, 1996).

Equivalent-linear and nonlinear site response analyses were performed for four Korea sites that are representative of the moderate seismicity of the region. Rock motions that are consistent with the moderate seismicity of the region were used for the analyses. Multiple 1D site profile realizations are generated by randomizing the shear wave velocity (Vs) profiles using Monte Carlo simulation. Median seismic site response obtained from EQL and NL analyses of spatially varied four shallow site profiles for moderate seismicity levels are compared.

2.1 Site Characteristics

To study the influence of shallow site response in Korea, four sites representative of local soil conditions were: Joongbu Naeryuk (P1), Gamcheong (P2), Kyungjeon Seon (P3), and Jihacheol (P4). The subsurface profile of selected sites consists of alluvial/residual soils followed by weathered rock sitting above the bedrock. Table 1 summarizes the characteristics of the four selected sites and Figure 1a plots the Vs profile of each site. The surface shear wave velocity of selected sites varies from 140 m/s to 300 m/s. The depth to rock ranges from 5.3 m to 23 m, with rock shear wave velocity of ranging from 744 m/s to 1673 m/s for the analyses. The small strain natural period, Tp, of the selected sites ranges from about 0.11 s to 0.38 s based on the quarter-wavelength method.

The variability of the subsurface conditions is accounted for by generating twenty (20) realizations for each of the four sites using Monte Carlo Simulation with the baseline Vs profiles given in Figure 1a. The parametric uncertainty introduced through the Monte Carlo simulation technique represents the aleatory variability in the site properties, in addition to some epistemic uncertainty in the baseline Vs profiles. The 1D shear wave velocity realizations are generated through the randomization tool implemented in the site response program DEEPSOIL v7 (Hashash et al., 2016).

Table 1. Summary of site characteristics of selected four sites

<table>
<thead>
<tr>
<th>Site</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth to Bedrock (m)</td>
<td>5.3</td>
<td>14.5</td>
<td>20.8</td>
<td>23</td>
</tr>
<tr>
<td>Vs30 (m/s)</td>
<td>611</td>
<td>456</td>
<td>356</td>
<td>290</td>
</tr>
<tr>
<td>Tp (s)</td>
<td>0.11</td>
<td>0.22</td>
<td>0.29</td>
<td>0.38</td>
</tr>
<tr>
<td>Surface Vs (m/s)</td>
<td>140</td>
<td>300</td>
<td>248</td>
<td>190</td>
</tr>
<tr>
<td>Rock Vs (m/s)</td>
<td>1150</td>
<td>1389</td>
<td>744</td>
<td>1090</td>
</tr>
<tr>
<td>KBC Site Class</td>
<td>Sc</td>
<td>Sc</td>
<td>Sd</td>
<td>Sd</td>
</tr>
<tr>
<td>IBC Site Class</td>
<td>C</td>
<td>C</td>
<td>D</td>
<td>D</td>
</tr>
</tbody>
</table>

The EQL and NL site response analyses were performed using Monte Carlo simulation technique represents the aleatory variability in the site properties, in addition to some epistemic uncertainty in the baseline Vs profiles. The 1D shear wave velocity realizations are generated through the randomization tool implemented in the site response program DEEPSOIL v7 (Hashash et al., 2016).

The goal of the site response analyses is to generate site-specific amplification factors for a range of input intensities that are representative of moderate seismicity observed in Korea. For this study, input motions were selected from the NGA strong motion database (peer.berkeley.edu/nga). Input motions are selected from sites with an average shear wave velocity in the top 30 m (Vs30) greater than 760 m/s. Using this criterion, 10 recorded ground motions were identified for use in the EQL and NL site response analyses.

Selected ten (10) rock input motions represents earthquakes with Moment Magnitudes (Mw) ranging from 5.7 to 6.9 and recorded at Distances (R) ranging from 9.6 km to 40.4 km. The response spectra of the 10 rock input motions are shown in Figure 2. The input intensity (PGA) of the rock motions range from about 0.1 g to 0.41 g. For the site response analyses, the rock input motions were scaled to 0.2 g and 0.4 g following the procedure outlines in ASCE 7-10 design guidelines. Figure 2 also plots the Korean Building Code (KBC) design spectrum developed for Site Class B (Sd) (760 – 1500 m/s) conditions (MOLIT, 2016) for 0.2 g and 0.4 g input intensities for comparison.

2.2 Ground Motions

The goal of the site response analyses is to generate site-specific amplification factors for a range of input intensities that are representative of moderate seismicity observed in Korea. For this study, input motions were selected from the NGA strong motion database (peer.berkeley.edu/nga). Input motions are selected from sites with an average shear wave velocity in

Figure 1. (a) Baseline Vs profiles of four representative sites in Korea, (b) 20 realizations of Vs profiles generated for P-2.

Figure 2. Ten unscaled rock input ground motions selected for the site-specific site response study plotted with KBC design spectra for Sd.
curves proposed by Darendeli (2001) were used. For the nonlinear analyses, the Modified Kondner-Zelasko (MKZ) model (Matasovic, 1993) was used. The modulus reduction and damping curve fitting procedure, termed MRDF, was used to match the target nonlinear curves (Phillips and Hashash, 2009).

Recent studies showed that the nonlinear curves cannot accurately simulate the stress-strain response at high levels of shear strain. Modified constitutive models have been developed to better capture such behavior. Yee et al. (2013) proposed a composite hyperbolic curve to asymptotically approach the shear strength at large strains. Groholski et al. (2015) developed a General Quadratic/Hyperbolic (GQH) strength-controlled constitutive model for enhanced modeling of nonlinear behavior at large strains. In this study, the strength correction was not initially applied considering the moderate level of intensities of input ground motions. However, given the computed strain levels a future study is warranted to investigate the impact of use of strength correction even for shallow profiles in moderate seismicity regions.

3 ANALYSIS RESULTS

For each rock input motion, surface response spectra and the associated amplification factor at each period were computed for 20 realizations of the four selected sites. Figure 3a and 3b presents the surface spectral acceleration (Sa) estimates from EQL and NL site response analyses, respectively, performed with 0.2 g scaled rock input motion propagated through 20 Vs realization generated for P2 site profile. The median Sa calculated for P2 site conditions using both models are also shown in Figure 3a and 3b, together with the Sa estimated using baseline P2 Vs profile. Introducing spatial variability in the soil properties via Monte Carlo simulations resulted in lower Sa predictions around the natural period of the site, 0.22 g, which is consistent with the observations from previous studies (Pehlivan et al., 2016). While the EQL linear analyses are shown to predict higher levels of surface spectral acceleration than NL analyses at short periods (T < ~0.5 s), the variance observed across the median Sa is similar for both analyses types.

Figure 3c plots the median Sa predictions for P2 under 0.2 g and 0.4 g scaled input motions. At T = 0.27 s EQL analyses performed with 0.2 g scaled input motions predict approximately 20 % higher median surface ground motion compared to NL analyses, the difference in the median seismic site response predictions between two methods is approximately 40 % when analyses are performed with 0.4 g scaled input motions. Figure 3d, which plots the ratio of median seismic site response predicted by EL and NL models for P2 site conditions using 0.2 g and 0.4 g scaled rock input motions, better illustrate the difference in the median predictions of two methods for different intensity levels.

The results of seismic site response analyses are used to calculate the amplification factor at each period that better illustrates the influence of the local soil conditions on observed seismic site response. The amplification factor (AF) is defined as the ratio of the surface response spectra to the rock response spectra at a given period and damping. Figure 4 plots the AF predictions of EQL and NL analyses for P2 and P4 sites for 0.2 g and 0.4 g scaled rock input motions, allowing observation of the effects of soil nonlinearity on site amplification. If the plots were normalized by the post-shaking predominant period of the each site, the difference between the median AF predictions that indicates the influence of different site conditions can be observed more clearly, which need further investigation in a future study. However, visual inspection of Figure 4 indicates that the peak AF predictions of the EQL and NL site response analyses correspond to similar post-shaking predominant period and although at different periods, the peak AF observed around the predominant site period are comparable for P2 and P4 sites, slightly higher response predicted in stiffer and shallower P2 site as compared to the softer and deeper P4 site under lower intensity input motions (i.e. 0.2 g scaled input motions).

![Figure 3](image1.png)

![Figure 4](image2.png)

![Figure 5](image3.png)
4 COMPARISON OF OBSERVED SHALLOW SITE RESPONSE WITH BUILDING CODE-BASED DESIGN

The median seismic site response and amplification factors estimated at four sites form Korea using the 0.2 g and 0.4 g scaled input motions through EQL and NL analyses are compared with building code-based design estimates for each site. Figure 6 compares the amplification factors obtained at SC and SD classified sites with estimated site-specific site amplification from site response analyses. Figure 6 shows that the AF estimated through site-specific site response analyses are higher than the building code-based site factor at short periods ($F_s$) for shallow sites with high impedance contrast under moderate intensity ground motions, which exemplifies site and seismicity conditions in Korea.

In Figure 6 the median AF estimated based on site-specific EQL and NL analysis across short period range ($0.1 \text{s} < T < 0.5\text{s}$) decreases as depth to bedrock increases or the input intensity level increases. The AF predicted based on site response analyses is higher than the building code-based site factor at long periods ($F_s$) for P2 site under 0.4 g scaled input motion (Figure 6b). Figure 6 also presents comparison for predicted AF from EQL and NL site response analyses. Note that the lower amplification observed around the natural period of sites might be related to the unrealistic higher implied strength associated with the MKZ constitutive model used for the current study.

Figure 6. Comparison of site-specifics median AF estimated through EQL and NL analyses with building code-based site factors for (a) Sc site conditions (P1 and P2 sites) and 0.2 g scaled rock motion, (b) Sc site conditions (P1 and P2 sites) and 0.4 g scaled rock motion, (c) Ss site conditions (P3 and P4 sites) and 0.2 g scaled rock motion, and (d) Ss site conditions (P1 and P2 sites) and 0.4 g scaled rock motion.

5 CONCLUSION

Seismic site response is highly dependent on the local soil conditions, which can significantly influence the amplification and attenuation of the rock motion during a seismic event. In moderate seismicity regions, the rock-level ground motions with low intensity, short duration, and high frequency content might experience significant short period amplification while propagating through the shallow sites with high impedance contrast. The building code-based site factors that are developed for deep soil and high seismicity conditions may not accurately capture such short period amplification in moderate seismicity regions such as Korea leading to non-representative seismic site response estimates.

This study presents seismic site response of shallow soil sites (<30m) with high impedance contrast in moderate seismicity regions. Seismic site response is computed through series of EQL and NL analyses performed for four representative shallow sites from Korea for two different intensity levels. The spatial variability at each site is modeled through Monte Carlo simulations. Predicted seismic site response and amplification factor from EQL and NL site response analyses are compared, seismic site response obtained from EQL analyses are higher than the NL analyses performed using MKZ constitutive model. The amplification factor obtained from EQL and NL site-specific seismic site response analyses were shown to be higher than the building code-based site factors for shallow sites with moderate seismicity at short periods. Close inspection of the NL analysis results indicated higher implied strengths at shallow depths that might lead to lower surface response around the shorter periods. Further studies are currently underway to address this limitation.

6 REFERENCES

American Society of Civil Engineers (ASCE) (2010), Minimum Design Load for Buildings and Other Structures. ASCE/SEI 7-10


