Nonlinear site response from the strong ground-motion recordings in western China

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A R T I C L E   I N F O

Article history:
Received 28 March 2015
Accepted 7 December 2015
Available online 24 December 2015

Keywords:
Strong ground-motion
Horizontal-to-vertical spectral ratio (HVSR)
Site-effect
Nonlinearity
1-D equivalent-linear method

A B S T R A C T

Strong ground-motion records from the mainshocks and aftershocks of the 2008 Wenchuan (Ms 8.0) and 2013 Lushan (Ms 7.0) earthquakes, within 300 km from the faults, were used for horizontal-to-vertical spectral ratio (HVSR) analysis. The HVSRs of the S-wave show that the predominant site frequency decreases with increasing ground-motion level, a characteristic of nonlinear dynamic soil response. We applied diffuse field theory and Monte Carlo search in the model space to produce an inverted shear-wave velocity profile using the HVSRs of weak S-wave motions. The inverted velocity structures are significantly different from the initial ones derived from in-situ measurements. We also applied 1-D equivalent-linear site-response analysis to derive the spectral ratios (i.e., transfer function) for the original and inverted soil models, and compared the results with the observed HVSRs of the S-wave motions. The comparisons showed that the spectral ratios from 1-D simulation for the inverted soil models agree quite well with the observed HVRSs. In other words, this study suggests that the HVSR from observed earthquake ground motion resembles the empirical transfer function of nonlinear site-response.

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1. Introduction

It is well known that strong ground-motion can be modified in terms of its duration, frequency content, and amplitude by local geologic conditions, including near-surface soft soils. This is often called site effects, and can cause or increase damage to susceptible infrastructure during earthquakes. Classic examples of significant infrastructure damage caused by amplified ground motions induced by near-surface soft-soil include the lake sediments in Mexico City during the 1985 Michoacán earthquake (M 8.1) [1] and the bay muds in the Marina District of San Francisco during the 1989 Loma Prieta earthquake (M 6.9) [2]. These phenomena have also been observed in less seismically active areas of the central United States such as the Ohio River Valley (i.e., Maysville, Ky.) during the 1980 Sharpsburg, Kentucky, M 5.2 earthquake [3] and the Wabash River Valley during the 2008 Mt. Carmel, Illinois, earthquake [4].

Although many factors (e.g., media elasticity, incident angles, impedance contrast, soil/sediment thickness, vertical/horizontal velocity gradients, subsurface boundary geometries, and topography) influence site effects, the soil and rock shear-wave velocities and intensity of incident waves are generally two parameters used for strong-motion earthquake engineering considerations. For example, the site coefficient of peak ground acceleration (PGA) is determined by the incoming bedrock ground motion and time-weighted average of shear-wave velocity for the top 30 m of earth material in a building code such as the National Earthquake Hazard Reduction Program (NEHRP) recommended provisions for new buildings and other structures [5]. Specifically, the coefficient increases with decreasing average shear-wave velocity (i.e., amplification), but decreases with increasing input ground-motion level due to the nonlinear soil response (i.e., deamplification). The nonlinear soil response has an important role in site effects; it dampens ground motions, particularly for larger motions ( $\geq 0.3 \text{ g}$). For example, Field and others [6] found that nonlinearity of soils reduced ground-motion amplification in the greater Los
2. Strong-motion dataset

The National Strong-Motion Observation Network System of China (NSMONS) consists of more than 1700 stations and is operated by the China Strong Motion Network Center (CSMNC) (www.csmnc.net). Since 2008, NSMONS has recorded more than 200 earthquakes with M > 4.7 in western China, including the 12 May 2008 Ms 8.0 Wenchuan and 20 April 2013 Ms 7.0 Lushan earthquakes. The Ms 8.0 Wenchuan earthquake occurred along the central and northern segments of the Longmen Shan Fault in Sichuan Province, western China (Fig. 1). More than 1400 strong-motion components from the Wenchuan earthquake’s mainshock and more than 20,000 strong-motion components from aftershocks were recorded by NSMONS [21]. The Lushan earthquake occurred on the southern segment of the Longmen Shan Fault (Fig. 1). Ground motions from the mainshock of the Lushan earthquake were observed at 92 stations, and more than 1000 strong-motion components from aftershocks were recorded by NSMONS [22]. For this study, we selected strong-motion records from 21 stations that were located within 300 km of the Longmen Shan Fault (Fig. 1).

The site information for the 21 selected strong-motion stations is listed in Table 1. As shown in Table 1, the borehole depths are all less than 23 m because the Chinese site classification is based on the average shear-wave velocity of the top 20 m (\(V_{S20}\)) [23]. According to the Code for Seismic Design of Building (CSDB), in China, rock is defined by a shear-wave velocity greater than 500 m/s [23]. However, in the United States, the NEHRP site classification is based on the average shear-wave velocity of the top 30 m (\(V_{S30}\)) and rock defined as greater than 762 m/s [5]. Fig. 2 shows the near-surface stratigraphy and shear-wave velocity profiles for stations 51SFB and 51WCW. The average shear-wave velocities of the top 30 m (\(V_{S30}\)) for the selected stations were extrapolated by assuming that the velocities at the bottom of the borehole and at a depth of 30 m are the same [24]:

\[
V_{S30\text{profile}} = 30/(t(30))
\]

(1)

\[
t(30) = \int_0^{30} \frac{dz}{V_S(z)}
\]

(2)

where \(V_S\) = shear-wave velocity at depth \(z\). The calculated NEHRP site classifications for the selected stations are listed in Table 1.

3. Horizontal-to-vertical spectral ratio analysis

The horizontal-to-vertical spectral ratio method has been widely used for estimating the dynamic site period and shear-wave velocity of near-surface soils using ambient-noise/microtremor measurements since it was introduced by Nakamura [25]. For example, several studies have derived shear-wave velocity profiles from ambient-noise/microtremor HVSR analyses [26,27]. However, it has also been found that results from the ambient-noise/microtremor HVSR method are not unique [26,28,29]. As Bonnefoy-Claudet and others [29] pointed out, ambient noise sources are (1) controlled by local surface sources and (2) caused by the ellipticity of the fundamental Rayleigh waves. In other words, ambient noise sources include not only S-wave resonance (i.e., S-wave transfer function), but also surface waves such as Rayleigh waves. The S-wave resonance of the sediments is the main concern of site effects in earthquake engineering.

The HVSR method has also been applied to weak and strong motions from earthquakes [17,18,30]. Lerme and Chavez-Garcia [30] found that the HVSR of the S-wave part of the strong-motion record can be used to estimate empirical transfer function, because site effects can be computed from a single station without need of
Nearby reference sites are cost effective. Wen et al. [17] demonstrated that nonlinear site responses can be evaluated using the HVSR of surface strong-motion recordings. Similarly, Nagashima and others [18] demonstrated the soil nonlinearity effects on the HVSRs of strong motions from earthquakes. HVSR has been used extensively for estimating site response, so many researchers tried to compare HVSR with traditional methods such as spectral ratios or generalized inversions of the S-wave spectra of the horizontal components. These comparative studies [31–35] show that estimates of the frequency of the predominant peak are similar to those obtained with traditional spectral ratios, but the amplitude level is different. Kawase and others [36] proved that HVSR can be calculated as the amplitude ratio between transfer functions for the horizontally polarized S-wave incidence and the vertically polarized P-wave incidence, both calculated at the observation point with a coefficient depending on the bedrock property. Their conclusions were based on the diffuse field theory for plane body waves. Their research provided a theoretical basis for using HVSR to detect soil nonlinearity. Therefore, we performed HVSR analyses on strong motions recorded at the 21 selected stations from mainshocks and aftershocks of the 2008 Wenchuan and 2013 Lushan earthquakes in western China (Fig. 1).

First, we applied a multiconsecutive-segment baseline correction [37] to all records in order to avoid baseline drifts caused by background noise or tilt of instruments due to strong-motion triggering. Second, we determined S-wave strong-motion windows by comparing horizontal and vertical components and visually picking the S-wave onset (Fig. 3a). Then we calculated and smoothed the S-wave Fourier spectra by using the Hanning Window (0.5-Hz window width) [38] (Fig. 3b) before deriving the final HVSR curves from the ratios between the geometric mean spectra (Fig. 4).

Table 1 lists information on 37 events with PGA greater than 5 cm/s/s recorded at station 51SFB from the mainshocks and aftershocks of the Wenchuan and Lushan earthquakes. Fig. 5 shows the average HVSRs for all 37 events at station 51SFB based on the PGA bins of 5–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–150, and > 150 cm/s/s, respectively. We can see that the HVSRs are similar in each PGA bin. It has been clearly demonstrated that the predominant frequencies (commonly defined as the frequency corresponding to the response peak, but sometimes determined through comparison with transfer function analysis) in each PGA bin are similar.

**Table 1** Site information of selected strong-motion stations.

<table>
<thead>
<tr>
<th>Site name</th>
<th>Station code</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Borehole depth H (m)</th>
<th>CSDB in China</th>
<th>NEHRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anxian-T</td>
<td>51AXT</td>
<td>104.4</td>
<td>31.5</td>
<td>11.8</td>
<td>191</td>
<td>II</td>
</tr>
<tr>
<td>Baoxing-D</td>
<td>51BXD</td>
<td>102.8</td>
<td>30.4</td>
<td>22.2</td>
<td>312</td>
<td>II</td>
</tr>
<tr>
<td>Baoxing-Y</td>
<td>51BXY</td>
<td>102.9</td>
<td>30.5</td>
<td>19.8</td>
<td>252</td>
<td>II</td>
</tr>
<tr>
<td>Baoxing-Z</td>
<td>51BZX</td>
<td>102.9</td>
<td>30.5</td>
<td>18.2</td>
<td>220</td>
<td>II</td>
</tr>
<tr>
<td>Chengdu-Z</td>
<td>51CDZ</td>
<td>104.1</td>
<td>30.6</td>
<td>/</td>
<td>&gt; 500</td>
<td>I</td>
</tr>
<tr>
<td>Changxi-Q</td>
<td>51CXQ</td>
<td>105.9</td>
<td>31.7</td>
<td>4.9</td>
<td>321</td>
<td>II</td>
</tr>
<tr>
<td>Guangyan-Z</td>
<td>51GYZ</td>
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<td>32.6</td>
<td>20.1</td>
<td>355</td>
<td>II</td>
</tr>
<tr>
<td>Jiangyou-C</td>
<td>51JYC</td>
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<td>32.0</td>
<td>15.0</td>
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</tr>
<tr>
<td>Jiangyou-H</td>
<td>51JYH</td>
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<td>31.8</td>
<td>22.0</td>
<td>241</td>
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<tr>
<td>Lushan-F</td>
<td>51LSF</td>
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<td>30.0</td>
<td>9.8</td>
<td>261</td>
<td>II</td>
</tr>
<tr>
<td>Lixian-M</td>
<td>51LXM</td>
<td>102.8</td>
<td>31.7</td>
<td>21.0</td>
<td>339</td>
<td>II</td>
</tr>
<tr>
<td>Mianzhu-Q</td>
<td>51MZQ</td>
<td>104.1</td>
<td>31.5</td>
<td>9.1</td>
<td>318</td>
<td>II</td>
</tr>
<tr>
<td>Pujian-D</td>
<td>51PJY</td>
<td>103.4</td>
<td>30.2</td>
<td>22.0</td>
<td>318</td>
<td>II</td>
</tr>
<tr>
<td>Pujian-W</td>
<td>51PJW</td>
<td>103.7</td>
<td>30.3</td>
<td>22.0</td>
<td>290</td>
<td>II</td>
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<tr>
<td>Pixian-Z</td>
<td>51PXZ</td>
<td>103.8</td>
<td>30.9</td>
<td>/</td>
<td>&gt; 500</td>
<td>I</td>
</tr>
<tr>
<td>Qionglai-Y</td>
<td>51QLY</td>
<td>103.3</td>
<td>30.4</td>
<td>22.0</td>
<td>216</td>
<td>II</td>
</tr>
<tr>
<td>Shifang-B</td>
<td>51SFB</td>
<td>104.0</td>
<td>31.3</td>
<td>15.2</td>
<td>232</td>
<td>II</td>
</tr>
<tr>
<td>Songpan-A</td>
<td>51SPA</td>
<td>103.6</td>
<td>32.5</td>
<td>21.0</td>
<td>282</td>
<td>II</td>
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<tr>
<td>Wenchuan-W</td>
<td>51WCC</td>
<td>103.2</td>
<td>31.0</td>
<td>22.0</td>
<td>295</td>
<td>II</td>
</tr>
<tr>
<td>Xiaojin-D</td>
<td>51XJD</td>
<td>102.4</td>
<td>31.0</td>
<td>21.0</td>
<td>306</td>
<td>II</td>
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<tr>
<td>Yaan-M</td>
<td>51YAM</td>
<td>103.1</td>
<td>30.1</td>
<td>22.0</td>
<td>377</td>
<td>II</td>
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</table>

* No profile data; inferred from Vs20.
or traditional spectral ratio) decrease with increasing PGA: from 7–8 Hz at 5–20 cm/s/s to 2–3 Hz at 556 cm/s/s. Fig. 5 also shows that the ratios corresponding to the predominant frequencies decrease slightly with increasing PGA.

Table 3 lists information on 48 events with PGA greater than 5 cm/s/s recorded at station 51WCW from the mainshock and aftershocks of the Wenchuan and Lushan earthquakes. Fig. 6 shows the average HVSRs for all 48 events at station 51WCW based on the PGA bins of 5–20, 20–40, 40–60, 60–80, 80–100, 100–200, 200–300, and > 300 cm/s/s, respectively. When we put all the HVSRs together, it is clear that they are similar in each PGA bin. Fig. 6 clearly demonstrates that the predominant frequencies decrease with increasing PGA: from about 9 Hz at 5–20 cm/s/s to about 2.3 Hz at 958 cm/s/s. It also shows that the ratios corresponding to the predominant frequencies decrease slightly with increasing PGA.

Fig. 7 shows the average HVSRs for stations 51CDZ, 51GYZ, 51JYC, 51JYH, 51PXZ, and 51QLY. Stations 51CDZ and 51PXZ are on rock, and 51GYZ, 51JYC, 51JYH, and 51QLY are on soil. As shown in Fig. 7, the predominant frequencies decrease with increasing PGA for the stations on soils. However, the predominant frequencies vary only slightly variations regardless of PGA at the rock stations (51CDZ and 51PXZ). These systematic observations suggest that the difference in HVSR in relation to high PGA ground motions and weak motions may be caused by soil nonlinearity. Similar phenomena had been observed and analyzed by Kawase [39] at a K-NET site and by Nagashima and others [18] at several K-NET sites in Japan in recent years. In Fig. 7, class C sites such as 51JYC, 51GYZ, 51QLY have great fundamental frequency difference. Class D site such as 51JYH even has bigger fundamental frequency than class C sites such as 51JYC, 51GYZ, 51QLY. Since observation showed strong discreteness and limited sites in our study, we did not conclude the correlation between site classes and predominant frequencies, more data is required for a robust conclusion in this area.

4. Analysis of 1-D site response

Our study demonstrated that the HVSRs from earthquake S-wave motions show a nonlinear site response: the predominant frequency decreases with increasing PGA. This nonlinear characteristic has also been observed in other strong-motion data [17–18,30]. For example, Nagashima and others [18] found similar HVSR characteristics for strong motions recorded at station MYG004 in Japan. The Japanese K-NET and KiK-net (www.kyoshin.bosai.go.jp) have compiled a large strong-motion database. For
station MYG004, more than 700 records are available. Fig. 8 shows the HVSRs of selected S-wave motions recorded at station MYG004 (www.kyoshin.bosai.go.jp). As shown in Fig. 8, the predominant frequencies decrease with increasing PGA.

In order to explain such nonlinear characteristics, we compared the HVSR of S-wave motion with the theoretical transfer function obtained from the most commonly used 1-D equivalent-linear site-response analysis: SHAKE [40]. The theoretical transfer
function is defined as the spectral ratio between the surface and the input motion at top of rock. Several modified versions of this algorithm are available, such as SHAKE91 [41], SHAKE04 [42], and LSSRLI [43]. LSSRLI was used in this study. Input parameters for LSSRLI include soil shear-wave velocity, thickness, density, shear modulus, and damping reduction curves. The shear-wave velocities, thicknesses, and densities were available from the stations’ initial site investigations (Table 1, Fig. 2). The nonlinear characteristics of soils and rocks recommended for use in Sichuan Province (Fig. 9) [44] was used in this study.

The input motion for 1-D equivalent-linear site-response analysis is ideally selected from strong motions recorded at a nearby
rock station. In our study, the S-wave motions recorded by station 51PXZ (bedrock site) during the mainshock and aftershocks of the Wenchuan and Lushan earthquakes were used and scaled to appropriate levels as basement excitation. Fig. 10 shows the horizontal components (East–West) of the ground motions recorded at station 51PXZ from the mainshocks of the Wenchuan and Lushan earthquakes, and one aftershock of the Wenchuan earthquake (Ms 6.4). Fig. 11 shows the spectral ratios from LSSRLI analysis for stations 51SFB and 51WCW. To get results in Fig. 11, we used different basement excitations, for example, for input PGA equal to 10 cm/s², the S-wave part of the EW time-history of the Qingchuan earthquake was adopted and scaled to 10 gal as basement excitation, for input PGA 50 cm/s², the S-wave part of the EW time-history of the Lushan mainshock was adopted and scaled to 50 gal, and for input PGA greater than 100 cm/s², the S-wave part of the EW time-history of the Wenchuan mainshock were scaled as basement excitation. The response showed that the predominant frequencies decrease with increasing PGA of input motions, but the peak spectral ratios do not change with the input motion levels.

Fig. 12 compares the observed HVSRs of S-wave and spectral ratios of the 1-D equivalent-linear method at stations 51SFB and 51WCW for three levels of PGA. The differences between the observed HVSRs and spectral ratios are obvious in terms of peak values and frequencies. For example, the fundamental peak frequency of the observed HVSR at station 51SFB is 7 Hz for small seismic events with PGA 5–20 cm/s², whereas that of the theory is 6 Hz for input of about 10 cm/s². The fundamental peak frequency of the observed small seismic events at 51WCW is about 9 Hz, whereas that of the theory is about 5.5 Hz. At station 51SFB, considering the linear situation, the transfer function curve has
two peaks, whereas only one peak was observed. At station 51WCW, there are clearly two peaks for small seismic events, whereas the transfer function curve is not so clear.

The discrepancies between the observed HVSRs and the spectral ratios of the 1-D equivalent-linear method could be caused by many factors. One of the factors is the accuracy of 1-D approximation based on the in-situ dynamic soil properties, S-wave velocity profile in particular. As shown by Kawase and others [36], the observed HVSRs of weak motions can be used for the inversion of a layered structure. In this paper, we utilized the HVSRs of weak motions to invert S-wave velocity and density structure. The algorithm proposed by Herak [45], based on a combination of the simple and the guided Monte Carlo search in the model space, was used in the inversion. This algorithm can achieve the smallest misfit as defined in Eq. (3):

$$ \text{misfit} = \sum_i \left[ \left( |HVSR_{\text{obs}}(f_i) - HVSR_{\text{the}}(f_i)| \right) W_i \right]^2, $$

where indices OBS and THE stand for the observed and theoretical HVSR, and $W_i$ is the weight defined by:

$$ W_i = |HVSR_{\text{obs}}(f_i)|^E, \quad E \geq 0. $$

Depending on $W_i$, larger weights (for $E > 0$) are given to data around the frequencies where the observed HVSR is large.

Fifteen small seismic events with PGA less than 5 cm/s$^2$ were recorded at station 51SFB and 12 events with PGA less than 7 cm/s$^2$ at station 51WCW in our data set. At such a small PGA level, the site responses can be considered linear, so all of these events were chosen to get the logarithmic average of observed HVSRs and the 95% confidence limits of the mean. We chose the density, S-wave velocity, and thickness of each layer down to the bedrock as model variables. We used the in-situ measurements (Fig. 2) as the initial model of the subsurface structure, and performed the inversions on the east–west component and north–south component separately. As shown in Fig. 13, there were significant differences between HVSRs of the initial model and observation, especially in the amplitude. At station 51SFB, the HVSR of the initial model has a peak at 6 Hz, and amplitude of about 2, whereas the observed HVSR of the east–west component has a peak at 6.5 Hz and amplitude of about 8, similar to the east–west component, the north–south component has a peak at 6.5 Hz and amplitude of about 9. At station 51WCW, the situation is more complicated. HVSR of the initial model has a peak at 6 Hz and amplitude less than 2, whereas two peaks were observed. The major peak is at

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![Fig. 11. Spectral ratios simulated using the 1-D equivalent-linear method for stations 51SFB and 51WCW.](image1)

![Fig. 12. Comparisons between the observed HVSRs of S-wave and spectral ratios of the 1-D equivalent-linear method for stations 51SFB (a) and 51WCW (b).](image2)
9 Hz and amplitude of 5–6, the lower one at 2.5 Hz has amplitude of ~3. The mismatch of HVSRs of the initial model and observation may be produced by the difference between the real velocity structure and the in-situ measurement. The mismatch also demonstrates why the velocity structure must be reconstructed to reproduce the observed HVSRs. Theoretical HVSRs of inverted models can fit observation very well. In Fig. 13, the best-fit HVSRs were almost located in the 95% confidence limits of observation. But we have to noticed that at station 51WCW, the best-fit also omitted the lower peak, the difference between averaged observed HVSR and theoretical HVSR of inverted model is obvious in the comparison diagram of east–west component from 2 to 3 Hz. For stations with multiple response peaks, our inversion method can fit the major peak very well, but will sometimes ignore lower peaks.

As shown in Fig. 13, the east–west and north–south components were respectively used to conduct inversion. Averaged HVSRs of weak motions derived from different horizontal components were almost the same. So, in order to obtain a consistent soil profile, ratios between geometric mean spectra of the horizontal and vertical components, also averaged HVSRs of weak motions, were adopted as target HVSRs to conduct inversion.

<table>
<thead>
<tr>
<th>No.</th>
<th>Soil type</th>
<th>Th (m)</th>
<th>(V_s) (m/s)</th>
<th>(\rho) (t/m³)</th>
<th>Inverted Model</th>
<th>Th (m)</th>
<th>(V_s) (m/s)</th>
<th>(\rho) (t/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Miscellaneous fill</td>
<td>3.3</td>
<td>136</td>
<td>1.8</td>
<td>1.4</td>
<td>42</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Pebble</td>
<td>5.1</td>
<td>263</td>
<td>2.3</td>
<td>6.4</td>
<td>283</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sandy shale</td>
<td>0.6</td>
<td>150</td>
<td>2.0</td>
<td>0.4</td>
<td>124</td>
<td>2.0</td>
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<tr>
<td>4</td>
<td>Sandstone</td>
<td>3.0</td>
<td>452</td>
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<td>0.9</td>
<td>521</td>
<td>2.4</td>
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<td>5</td>
<td>Sandstone</td>
<td>3.2</td>
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<td>2.6</td>
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<td>548</td>
<td>2.6</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4**

Thickness, density, and S-wave velocity \(V_s\) of the initial and inverted soil structures at station 51SFB.
analysis. Initial models and inverted models are shown in Tables 4 and 5. Fig. 14 compares the spectral ratios from 1-D equivalent-linear analysis based on inverted models to the HVSRs for stations 51SFB and 51WCW at several PGA levels. As shown in Fig. 14, the spectral ratios from 1-D equivalent-linear analysis agree quite well with the HVSRs in terms of the predominant frequency and amplitude at similar PGA levels at station 51SFB and 51WCW. We also compared the predominant frequencies obtained from the S-wave HVRSs and 1-D equivalent-linear analysis at stations 51SFB and 51WCW for all levels of PGA (Fig. 15). As shown in Fig. 15, the predominant frequencies derived from 1-D analysis for the inverted velocity models (triangles) are more consistent with the observed ones from HVRSs of S-wave motions (squares) than those from 1-D analyses for the initial models (circles). These comparisons show that the inverted soil models produced much better nonlinear responses than the initial in-situ models.

5. Summary and conclusion

The strong ground-motion records from the mainshocks and aftershocks of the 2008 Wenchuan (Ms 8.0) and 2013 Lushan (Ms 7.0) earthquakes, within 300 km distance from the faults, were used for horizontal-to-vertical spectral ratio (HVSR) site-response analysis. Although the ground-motion data used in this study are limited, in particular, there are very few strong-motion records with PGA greater than 200 cm/s/s, the results show that at most stations, the HVSRs of the S-wave ground motions from earthquakes demonstrate the characteristics of the nonlinear dynamic response: the predominant frequency decreases with increasing ground-motion level. Although soil nonlinearity has also been reported to make the amplitude decrease with increasing ground-motion level [16], this characteristic is not clear in this study because of limited data, especially for high levels of ground motion.

The 1-D equivalent-linear site response analysis of SHAKE [40] was used for nonlinear site-response simulation. The preliminary comparisons between the observed HVSRs of S-waves and spectral ratios of the 1-D equivalent-linear method based on the in-situ soil models at stations 51SFB and 51WCW showed that there are significant differences between the observed HVSRs and spectral ratios. As shown by Kawase and others [36], the observed HVSRs of weak S-wave motions can be used to invert soil structure. We applied the diffuse field theory [36] and Monte Carlo search in the model space [45] to invert the S-wave velocity profile using the HVSRs of weak S-wave motions at stations 51SFB and 51WCW. To obtain inverted models, 15 small seismic events with PGA less than 5 cm/s² recorded at station 51SFB and 12 events with PGA less than 7 cm/s² recorded at 51WCW were used, averaged HVSRs of weak motions were taken as target HVSRs of the linear regime, and the in-situ measurements were used as the initial model of the subsurface structure.

The inverted soil models for both stations are quite different from the initial ones: shear-wave velocities were significantly lower, the top layer in particular. These inverted soil models were also used for the nonlinear site response simulations with 1-D equivalent-linear site-response analysis. The results showed that the spectral ratios (i.e., transfer functions) from 1-D analysis agree quite well with the HVSRs in terms of the predominant frequency and amplitude at similar PGA levels. These comparisons suggest that the HVSRs of weak S-wave motions can be used to improve or constrain the soil profile that was derived from in-situ measurement. In other words, our study shows that the HVSR from observed earthquake ground motion resembles the transfer function for horizontal motion and nonlinear site response. This suggests that the HVSR from observed earthquake ground motion

<table>
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<th>No.</th>
<th>Soil type</th>
<th>Th (m)</th>
<th>Vs (m/s)</th>
<th>ρ (t/m³)</th>
<th>No.</th>
<th>Soil type</th>
<th>Th (m)</th>
<th>Vs (m/s)</th>
<th>ρ (t/m³)</th>
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<td>212</td>
<td>2.0</td>
<td>1</td>
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<td>0.8</td>
<td>212</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>Silt with pebble</td>
<td>2.8</td>
<td>210</td>
<td>2.0</td>
<td>2</td>
<td>Silt with pebble</td>
<td>2.8</td>
<td>210</td>
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</tr>
<tr>
<td>3</td>
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<td>3.4</td>
<td>240</td>
<td>2.1</td>
<td>3</td>
<td>Pebble</td>
<td>3.4</td>
<td>240</td>
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</tr>
<tr>
<td>4</td>
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<td>2.2</td>
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<tr>
<td>5</td>
<td>Pebble</td>
<td>2.8</td>
<td>424</td>
<td>2.3</td>
<td>5</td>
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<td>424</td>
<td>2.3</td>
</tr>
<tr>
<td>6</td>
<td>Pebble</td>
<td>3.1</td>
<td>394</td>
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</tr>
<tr>
<td>7</td>
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<td>443</td>
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<td>Phyllite</td>
<td>6.2</td>
<td>443</td>
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</table>
could be used to provide an empirical transfer function for a site of engineering interest.

Acknowledgments

We would like to thank the three anonymous reviewers for their very valuable and helpful suggestions on improving the manuscript. This study was partially supported by the National Natural Science Foundation of China (No. 51208474, No. 91215301 and No. 51208108), the National Program on Key Basic Research Project of China (973 Program, 2011CB103601), a research Grant from the Institute of Crustal Dynamics, China Earthquake Administration (No. ZDJ2014-07) and the China Scholarship Council. We would like to thank the CSMNC for providing the strong ground motion records used in this study. We also thank Meg Smath for editorial help.

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Fig. 15. Comparison of predominant frequency between the HVRs and the 1-D equivalent-linear analyses for stations 51SF and 51WCW.


