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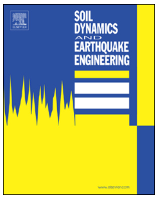

Nonlinear site response from the strong ground-motion recordings in western China

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ABSTRACT

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 HVRSs 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 HVRSs 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.

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 (≥ 0.3 g). For example, Field and others [6] found that nonlinearity of soils reduced ground-motion amplification in the greater Los

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Angeles region during the 1994 Northridge earthquake. Nonlinear soil behavior (i.e., the soil shear modulus is decreasing while its damping is increasing with increasing shear strain under cyclic loading) was first described and measured by Hardin and Drnevich [7,8]. This relationship between shear modulus and shear strain, as well as the relationship between damping and shear strain, has traditionally been determined in a laboratory using either cyclic triaxial or resonant column tests [7–11]. More recently, these properties have also been determined insitu using large-scale seismic S-wave vibratory tests [12,13] and downhole arrays [14,15].

The effects of soil nonlinearity on observed ground motions at free-surface have also been reported [6,16–18]. For example, Wen and others [17] and Nagashima and others [18] showed the effects of soil nonlinearity on the horizontal-to-vertical spectral ratio (HVSR) of the observed ground motions. Even quantitative simulation of waveforms based on strong and weak motions has been studied by some researchers [19,20]. For example, Satoh and others [19] quantitatively studied the nonlinear behavior of soil sediments in the Ashigara Valley, Japan, using both strong- and weak- motion records observed at the surface and in the borehole. The results showed that the S-wave velocity and the damping factor in surface layer for the main part of strong motion are about 10% smaller and 50% greater, respectively, than those for weak motions. Aguirre and Irikura [20] analyzed the nonlinear behavior from the acceleration records at Port Island, Kobe, Japan, using a spectral ratio technique and a nonlinear inversion method, their results also showed the change of the S-wave velocity structure before and after the mainshock, and that the reduction of the surface horizontal peak acceleration was about 25% of the peak acceleration from the linear theory, due to nonlinearity. However, as shown by Satoh and others [19], more study is needed to determine such quantitative relationships.

We explored characteristics of soil nonlinearity by performing HVSR analysis on the observed ground motions at free-surface from recent earthquakes in western China. We also compared the HVSRs with the theoretical transfer-function derived from 1-D equivalent-linear site-response analysis.

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]:

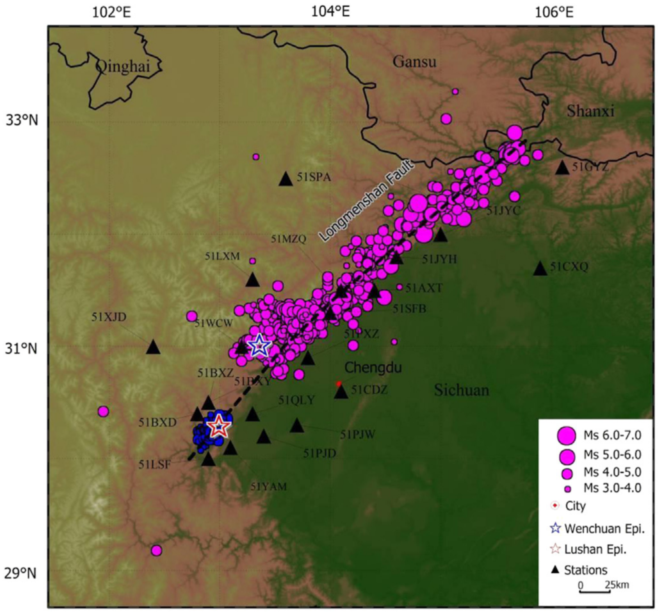

Fig. 1. Locations of the mainshock and aftershock of the 2008 Wenchuan and 2013 Lushan earthquakes and strong-motion stations within 300 km of the Longmen Shan Fault.

$$V_{S30\text{profile}} = 30/t(30) \tag{1}$$

$$t(30) = \int_0^{30} \frac{dz}{Vs(z)} \tag{2}$$

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]. Lermo 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