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Site correction of a high-frequency strong-ground-motion simulation based on an empirical transfer function

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ABSTRACT

In this study, an empirical transfer function (ETF), which is the spectrum difference in Fourier amplitude spectra between observed strong ground motion and synthetic motion obtained by a stochastic point-source simulation technique, is constructed for the Taipei Basin, Taiwan. The basis stochastic point-source simulations can be treated as reference rock site conditions in order to consider site effects. The parameters of the stochastic point-source approach related to source and path effects are collected from previous well-verified studies. A database of shallow, small-magnitude earthquakes is selected to construct the ETFs so that the point-source approach for synthetic motions might be more widely applicable. The high-frequency synthetic motion obtained from the ETF procedure is site-corrected in the strong site-response area of the Taipei Basin. The site-response characteristics of the ETF show similar responses as in previous studies, which indicates that the base synthetic model is suitable for the reference rock conditions in the Taipei Basin. The dominant frequency contour corresponds to the shape of the bottom of the geological basement (the top of the Tertiary period), which is the Sungshan formation. Two clear high-amplification areas are identified in the deepest region of the Sungshan formation, as shown by an amplification contour of 0.5 Hz. Meanwhile, a high-amplification area was shifted to the basin's edge, as shown by an amplification contour of 2.0 Hz. Three target earthquakes with different kinds of source conditions, including shallow small-magnitude events, shallow and relatively large-magnitude events, and deep small-magnitude events relative to the ETF database, are tested to verify site correction. The results indicate that ETF-based site correction is effective for shallow earthquakes, even those with higher magnitudes, but is not suitable for deep earthquakes. Finally, one of the most significant shallow large-magnitude earthquakes (the 1999 Chi-Chi earthquake in Taiwan) is verified in this study. A finite fault stochastic simulation technique is applied, owing to the complexity of the fault rupture process for the Chi-Chi earthquake, and the ETF-based site-correction function is multiplied to obtain a precise simulation of high-frequency (up to 10 Hz) strong motions. The high-frequency prediction has good agreement in both time and frequency domain in this study, and the prediction level is the same as that predicted by the site-corrected ground motion prediction equation.

1. Introduction

Reductions of estimation errors for ground motion are important in engineering seismology. In practice, the ground motion prediction equation (GMPE) is applied to target sites. However, as site classification for a given location is typically not sufficiently clear in many regions, the GMPE should first consider rock site attenuation. Using typical estimation methods, basin and sedimentary data are either excluded in order to check the response of a rock outcrop or are not discriminated, and anomalies are explained in terms of site effects (Boore and Joyner, 1982; Douglas, 2003). In recent years, soil site amplification has been highlighted separately for prediction purposes given the site conditions. Jean et al. (2006) constructed a two-phase regression procedure that combines the rock site attenuation equation and a site-dependent ground motion prediction model for different sites in order to incorporate

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a site-correction term in the GMPE. Meanwhile, a global crustal ground motion database was constructed based on the Next Generation Attenuation of Ground Motions Project (NGA) at the Pacific Earthquake Engineering Research Center (PEER, UC, Berkeley). Several unsolved effects in the GMPE were extracted, in which the site classification technique (using the average shear wave velocity up to 30 m in depth, Vs30) was one of the most important criteria for reducing prediction errors (Abrahamson et al., 2008; Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008).

As mentioned above, the GMPE is frequently used for different engineering purposes, such as hazard analysis, structural seismic design, and disaster prevention. However, seismologists apply wave propagation theory to one-dimensional, two-dimensional (2D), and three-dimensional (3D) models of subterranean velocity structures to simulate the full waveforms at each target site. Strong site effects induced by sedimentary basins such as the Taipei Basin can already be considered in a 3D simulation, but the reliable frequency band is still lower than 1 Hz, owing to shallow velocity structures not being sufficiently clear. Current techniques, such as the spectral element method and finite difference method cannot achieve the high-frequency (of at least 10 Hz) responses that are mainly induced by site effects (Lee et al., 2008a,b; Miksat et al., 2010).

To realize a high-frequency ground motion simulation, there are two common techniques, namely the empirical green's function (Irikura, 1986; Miyake et al., 2003) and the stochastic ground motion simulation (Boore, 1983, 2003, 2009; Beresnev and Atkinson, 1998a; Motezedian and Atkinson, 2005). The main concept of the former is that only a source scaling relationship between small and large earthquakes is considered if they are located in the same seismogenic source zone. This means that the observed waveform of a small earthquake can be treated as a Green's function and that the response of a large earthquake can be predicted after considering the reliable strong motion generation area (Kurahashi and Irikura, 2011). The simulated results can yield reasonable time histories, as the true phase spectra of small earthquakes are applied initially. However, suitable small earthquakes might not have occurred previously in some seismogenic zones, so the technique might not be applicable to some target sites, such as for the analysis of seismic responses for metropolitan areas of Tokyo or Taipei.

The stochastic ground-motion simulation technique constructs a random-phase waveform and considers the ω^2 source spectrum model (Aki, 1967; Brune, 1970) combined with correction factors for source, path, and site effects. This technique applies a point source and finite-fault simulation, depending on the earthquake magnitude as well as source-site distance. It then predicts the level of strong motion using a spectrum-fitting process in the frequency domain. However, simulated waveforms cannot match the real time histories, because of the random phase setting at the beginning, and only a seismic wave-like envelope function can be applied in the time domain. Nevertheless, they can still produce good agreement in strong motion levels, such as peak ground acceleration (PGA) or the frequency spectrum; hence, it is still useful for producing preliminary evaluations for possible future earthquakes. Therefore, the stochastic ground-motion simulation technique is employed in this study.

Numerous correction factors have been taken into account over the past few decades for stochastic simulations. Each factor has been discovered and solved step-by-step since the discovery of the stochastic simulation technique in the 1980s (Boore, 1983). Site amplification is one of the most important factors, which still needs to be carefully determined for each site, except for some well-studied common factors, such as path attenuation, high-frequency attenuation, geometric spreading, and the crust transfer function. These well-known factors should be adjusted using empirical observation data in different seismogenic regions (Atkinson, 1995; Atkinson and Silva, 1997; Atkinson and Beresnev, 2002; Atkinson and Boore, 1998, 2006; Boore et al., 1992; Chandler et al., 2006; D'Amico et al., 2012; Hung and Kiyomiya, 2013; Sokolov et al., 2000). Most of the site responses used in the stochastic ground-motion simulation technique are simplified and only the rock-like site response is considered. For example, the generic rock site response of Western North America from Boore and Joyner (1997) was used to simulate the 1994 Northridge earthquake (Beresnev and Atkinson, 1998b). Atkinson and Boore (2006) constructed site amplification factors for Eastern North America (ENA) for site A (where Vs30 > 1500 m/s) and the B C boundary (Vs30 = 760 m/s) based on empirical data from Siddiqqi and Atkinson (2002) and Frankel et al. (1996). A series of site effect studies in the frequency domain for Taiwan were conducted based on spectral differences between synthetic very hard rock (VHR) and observed soil records, as a traditional reference rock site cannot be easily applied to a spectral ratio calculation in many cases (Sokolov et al., 2000; Sokolov et al., 2001, 2003, 2009).

The Taipei Basin, Taiwan, has been greatly influenced by site effects during an earthquake (Fletcher and Wen, 2005; Wen et al., 1995; Wen and Peng, 1998). The basin is triangular and the subsurface structure is deeper on the west side than on the east side. The deepest geological basement (top of the Tertiary period) is located at approximately 680 m and the deepest engineering basement (the bottom of the Sungshan formation) is approximately 100 m (Wang et al., 2004). The engineering basement is the boundary of shear-wave velocity within 300–700 m/s, and the majority of short-period site amplification of seismic waves will be affected in the topmost shallow subsurface layer (NIED, 2009; Irikura and Miyake, 2011). The Sungshan formation was found to be composed of unconsolidated sand, silt, and clay (Wang et al., 2004) and related to the main amplification of PGA and the dominant frequency during earthquakes (Wen et al., 1995; Wen and Peng, 1998).

The issue of seismic disaster prevention within the basin is quite important, as ground motions have been enlarged in historical earthquakes. For example, in the case of the Chi-Chi earthquake in 1999, even though the epicenter was 100 km away, damage was caused to over 450 houses in the Taipei Basin (Tsai et al., 2000). The March 31, 2002, M_L-6.8 earthquake resulted in five deaths and injuries to over 250 people in the basin; although the epicentral distance was also >100 km, more damage was caused in the basin than in the nearby regions (Chen, 2003). Therefore, in this study, site correction was performed for the Taipei Basin by applying the stochastic simulation in order to reduce the uncertainties in high-frequency simulation.

2. Methodology for stochastic simulation

The central concept of the stochastic ground-motion simulation technique is that a seismic source can be treated as a circular rupture process and propagated forward to target stations. Thus, the source spectrum should correspond to a ω^2 model and, as the real seismic phase cannot be easily predicted, a random phase was used for this technique.

The point source method mentioned above is typically used to deal with small earthquakes. On the other hand, for some complex rupture earthquakes, the finite fault model should be taken into consideration. A rectangular fault composed of several point source