Soil Dynamics and Earthquake Engineering 104 (2018) 106–116

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Site amplifications and the effect on local magnitude determination at stations of the surface–downhole network in Taiwan

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ARTICLE INFO

Keywords:
Site amplification
Downhole
Local magnitude
HHSR
HVSR

ABSTRACT

This study analyzed site effects including PGA and empirical transfer functions at 15 selected surface–downhole stations by using ground motion recordings of earthquakes with $M_L > 4$ during 2012 and 2013 in Taiwan. In addition, we used all strong motion recordings of four large earthquakes ($M_L > 6$) to generate intensity distribution maps and assess the differences in magnitude at the surface and downhole. The site amplification factors of the PGA were calculated using the ratio between the surface and downhole recordings. The mean PGA amplification factors ranged from 2 to an exaggerated value of 20 at different stations. In addition, the power law relationships between the PGAs at the surface and downhole were evaluated to understand how amplification varies as PGA increases. Strong ground motions with and without site effects throughout Taiwan could be observed by comparing intensity distribution maps generated using the surface and downhole accelerations from four large earthquakes with magnitudes > 6. Empirical transfer functions derived using the single-station and two-station methods at the same stations showed comparable dominant frequencies and amplification factors; however, the empirical transfer function derived using the two-station method showed clearer resonance peaks, not only at fundamental frequencies but also at higher mode resonance frequencies. The HHSR and the HVSR were highly similar, particularly at medium frequencies. This finding indicates that the HVSR can be used instead of the HHSR when only the surface recording is available. Moreover, the local magnitudes calculated using surface recordings were higher than those calculated using downhole recordings. The differences are attributed to the amplification caused by the sedimentary layers and resultant in 0.36, 0.46 and 0.49 on average for events with M_L of > 6, 5–6, and 4–5. Furthermore, HHSRs at 5–10 Hz and 1.1–1.7 Hz were strongly correlated with PGA amplifications and M_L differences, respectively.

1. Introduction

The site effect is an important characteristic caused by local unconsolidated sediments and usually results in significant enlargement of the amplitudes and durations of seismic waves. Although their source and path conditions are similar, two adjacent stations may experience a large difference in seismic amplifications when their geological conditions are different [1,2]. Typical cases of site amplifications for strong motions in Taiwan were observed inside the Taipei Basin during the 1986 and 2002 Hualien offshore earthquakes and the 1999 Chi-Chi earthquake. During these large earthquakes, the soft sediments covering the bedrock inside the basin caused significant amplification of the seismic waves, which in turn caused significant damage to buildings, despite the epicentral distances to the Taipei Basin exceeding 90 km.

The two-station [3] and single-station [4] methods are the most widely used approaches for analyzing seismic site effects. The two-station method is widely used to estimate site amplification factors and the horizontal-to-horizontal spectral ratio (HHSR), particularly for seismic design codes [5,6]. This approach requires the identification of an adequate reference site, usually a hard rock site without site effects, for estimating site amplification factors; however, such a site is usually difficult to identify in practice. The single-station method calculates the horizontal-to-vertical spectral ratio (HVSR) to assess the site effect and to obtain a result comparable with that of the two-station method [7]. The simple HVSR method has therefore become extensively applied in site effect studies [2,8,9].

The Taiwan Strong Motion Instrumentation Program (TSMIP) is a national high-density strong ground motion network that has been operating in Taiwan since 1992 [10], with more than 700 stations

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http://dx.doi.org/10.1016/j.soildyn.2017.10.003
Received 14 March 2017; Received in revised form 18 September 2017; Accepted 1 October 2017
0267-7261/

installed currently. In recent years, the seismic site conditions of more than half of the free-field TSMIP stations have been investigated [11,12]. These data have been used for both local [13–16] and global [17,18] strong motion and site effect studies and for the seismic design code in Taiwan [19]. More detailed site characterizations for TSMIP stations are underway [20–22].

Several downhole seismic arrays have also been installed in Taiwan. In 1985–1991, the Lotung Large-Scale Seismic Test (LLSST) project was conducted by the Taiwan Power Company (TaiPower) and the US Electric Power Research Institute to install free-surface downhole arrays and structural accelerometers in Lotung Town, Ilan. Two downhole arrays consisting of four downhole accelerometers were installed at depths of 6, 11, 17, and 46 m. Subsequently, the Hualien Large-Scale Seismic Test (HLSST) project was conducted to construct a free-surface downhole array and to deploy structural accelerometers in Hualien City for recording near-field strong motions. A total of 12 downhole accelerometers were deployed in 3 downhole arrays at depths of 5, 16, 26, and 53 m. The LLSST and HLSST arrays were a part of the Strong Motion Array in Taiwan project as phase 1 (SMART1) and phase 2 (SMART2), respectively. The two networks played an important role in early strong ground motion monitoring and studies in Taiwan from the 1980s to 1990s [23–25].

To understand the influence of sedimentary layers on the propagation of seismic waves inside the Taipei Basin, the Central Geological Survey and Academia Sinica Institute of Earth Sciences successively deployed 12 strong motion downhole arrays inside the basin, starting in 1991. Currently, eight of these arrays still monitor strong motion. Three to five accelerometers were installed in each array at the surface and at different depths. The obtained strong motion recordings have been used by several studies evaluating site effects and soil nonlinearity in the Taipei Basin [26,27]. In addition, since 2005, seven broadband downhole seismic arrays have been constructed inside the Taipei Basin to monitor microearthquakes. Each array consists of two broadband sensors installed at different depths.

The 1999 Chi-Chi earthquake resulted in damage to the Taichung Harbor area, because of liquefaction caused by strong motion. The Center of Harbor and Marine Technology set up seismographers and piezometers at different depths to monitor seismic waves and pore water pressures in several harbor areas [28]. These downhole arrays can facilitate the understanding of the local site effects in Taiwan, particularly in the Taipei Basin. The downhole seismic arrays introduced above were plotted in Fig. 1 to show their locations.

After the 1995 Hyogoken-Nanbu (Kobe) earthquake in Japan, the National Research Institute for Earth Science and Disaster Prevention installed two nationwide strong motion seismograph networks, the Kyoshin Network (K-NET) and the Kiban Kyoshin Network (KiK-net), to uniformly monitor strong motion throughout Japan [29]. The K-NET is a free-field strong motion network, whereas the KiK-net is an uphole–downhole observation network. Each KiK-net station consists of a strong motion seismograph at the surface and a strong motion seismograph together with a high-sensitivity velocity seismograph (Hi-net) at the bottom of the observation boreholes. The uphole–downhole strong motion stations in Japan (KiK-net) provide useful data for site effect studies [30–32].

To improve earthquake monitoring, earthquake location determination, and early warning capabilities, the Central Weather Bureau (CWB) of Taiwan continues to upgrade seismographs and to construct a national network of surface–downhole stations for the whole of Taiwan. A total of 70 surface–downhole stations are expected to be installed under this project. Twenty-eight stations had been installed by 2013. Wang *et al.* [33] used these data to estimate the attenuation and velocities at the 28 stations. Lai *et al.* [34] studied the spectral decay parameter kappa (κ) in Taiwan by using borehole array data.

To evaluate site effects, this study analyzed the site amplifications of peak ground acceleration (PGA), empirical transfer functions, and the variations of local magnitudes by using the strong motion data recorded by the surface–downhole network. In addition, both the P-wave and S-wave velocity profiles measured by the suspension PS-logging systems at 12 stations were compiled in this study to calculate the average S-wave velocity of the top 30-m layer (Vs30) and the average S-wave velocity for the whole borehole depth (VsZ).

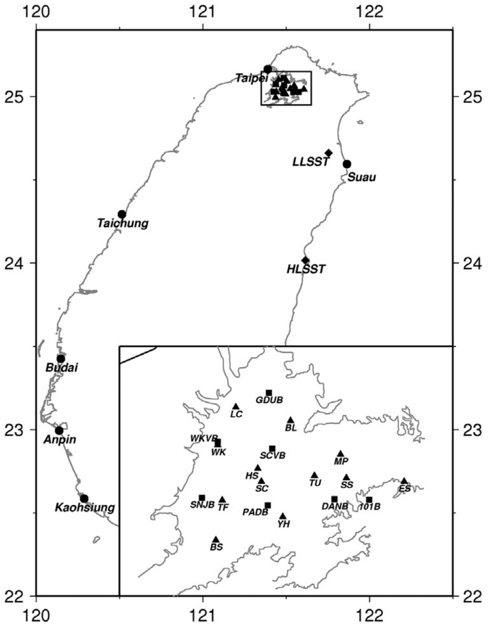

Fig. 1. Locations of downhole seismic arrays in Taiwan. The lower right map show the distributions inside the Taipei Basin. The circles are Harbor downhole arrays; the diamonds are LSST downhole arrays; the triangles are strong motion downhole arrays in the Taipei Basin; the squares are broadband downhole arrays in the Taipei Basin.

2. Data acquisition and processing

In this section, we briefly introduce the national surface–downhole network, which is under construction by the CWB, and the selected 15 stations that had already recorded a number of data sets for the analysis of the local site effects. In this study, the accelerations were processed as described below before use. In addition, we employed data from 26 stations that recorded four large events to generate intensity distribution maps for both the surface and downhole conditions. The data were also used to examine the difference between the estimated local surface and downhole magnitudes.

2.1. Surface–downhole network

A network of surface–downhole stations is under construction by the CWB to improve earthquake monitoring, earthquake location determination, and early warning capabilities. The real-time digital data recorded by all stations in the network are delivered to the Seismological Center of the CWB. The 15 stations shown in Fig. 2 were selected in this study to evaluate site effects. Each station includes a pair of force balance accelerometers, one at the surface and another at the borehole, and a broadband velocity seismometer. Fig. 3(a) illustrates the equipment configuration at the stations. A 24-bit data recorder is placed at the surface to receive seismic data from three sensors at a sampling rate of 100 Hz. The layout of the network is similar to that of the KiK-net of Japan. The strong motion data derived from this network are suitable for studying site effects in Taiwan, because this network provides accelerations both at the surface and bedrock.

Each observation borehole is drilled into engineering bedrock (S-wave velocity of the engineering bedrocks may vary from 300 m/s to larger than 1100 m/s), reaching an average depth of 300 m, to enable the accelerometer pairs to record ground motions both at the bedrock