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Key Points:
- A novel method based on SPT N values and H/V ratios is proposed for determination of national $V_{S30}$ model for South Korea
- A high-resolution national $V_{S30}$ model can be calculated using the calibrated SPT N data at densely distributed boreholes
- The $V_{S30}$ model presents high correlation with geological and topographic features

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Abstract
The average shear-wave velocity within the top 30 m from the surface, $V_{S30}$, represents site characteristics including the soil classification and site amplification that are essential information for building codes and seismic design. A novel method to determine a $V_{S30}$ model based on a composite analysis of borehole standard penetration test numbers (SPT N) and horizontal-to-vertical (H/V) spectral ambient noise ratios is introduced. A national $V_{S30}$ model for South Korea is determined using the method. The shear-wave velocity structures beneath 20 nationwide broadband seismic stations are determined using the H/V analysis. The SPT N data are collected from 175,619 nationwide densely-distributed boreholes. The shear-wave velocity models from SPT N values are calibrated for the local reference velocity models from H/V analysis. A representative relationship between the SPT N values and shear-wave velocities is introduced. A national $V_{S30}$ model for South Korea is determined using the calibrated SPT N models and the nationwide boreholes. The $V_{S30}$ model is verified by comparisons with local field measurements. The proposed model is consistent with the USGS model based on a surface slope analysis. The $V_{S30}$ structure presents high correlation with geological and topographic features. The $V_{S30}$ values are low in coastal (low topographic) areas, and high in mountain (high topographic) areas. Apparent linear relationship is observed between $V_{S30}$ and topography. The western and southeastern coastal regions may be vulnerable to strong seismic shaking.

Plain Language Summary
Seismic ground motions are an important factor to control the seismic damages. The seismic amplification is highly dependent on the shear-wave velocities at shallow depths ≤30 m, $V_{S30}$. We introduce a novel method to determine a $V_{S30}$ model based on the standard penetration test numbers (SPT N) from nationwide 175,619 boreholes and horizontal-to-vertical spectral ambient noise ratios (H/V ratios) from 20 broadband seismic stations. We determine a $V_{S30}$ model for South Korea. The shear-wave velocity structures beneath broadband seismic stations are used for local reference velocity models. The shear-wave velocity models from SPT N values are calibrated for the local reference velocity models from the seismic stations. We determine a representative relationship between the SPT N values and shear-wave velocities. We determine a high-resolution $V_{S30}$ model using the calibrated SPT N models at boreholes. The proposed model is verified by comparisons with other results. The $V_{S30}$ structure presents high correlation with geological and topographic characteristics. The $V_{S30}$ values are low in coastal areas, and high in mountain areas. The western and southeastern coastal regions may be vulnerable to strong ground motions during earthquakes.

1. Introduction

Site amplification is an important factor to be considered in seismic design and seismic hazard mitigation. The site amplification is affected mainly by shallow media beneath the surface (Bazzurro & Cornell, 2004; Hartzell et al., 2001; Scherbaum et al., 2003). Ground motions generated by seismic waves are amplified in sedimentary layers. The dependence of ground motion levels on the subsurface media causes discriminative seismic damages on the surface. For instance, during the 1988 $M_{L}6.8$ Armenia earthquake, Vanadzor (located at a far distance) was more damaged than Leninakan (near the epicenter) due to the site amplification effect of sedimentary layers (Yegian et al., 1994). Also, seismic waves from the 1985 $M_{L}8.1$ Michoacan earthquake that occurred near the Pacific coast of Mexico were highly amplified in Mexico City (located 350 km away), causing considerable damage to the infrastructures of the city (Dobry & Vucetic, 1987).

The site amplification magnitude can be estimated by various methods, including transfer function analysis based on the horizontal and vertical spectral ratios of ambient seismic noise (Castro et al., 1997; Nakamura, 1989) and synthetic site amplification analysis (Kramer, 1996; Schnabel, 1972). Various approaches have been proposed.
to determine the shear-wave velocity structure in shallow media. One approach to determine the shear-wave velocity structure is to use the ellipticity of fundamental-mode Rayleigh waves and H/V spectral ratios (Fäh et al., 2001, 2003). For example, H/V spectral ratios and spatial autocorrelation were used to identify shallow structures in Spain (García-Jerez et al., 2007).

The average shear-wave velocity up to a depth of 30 m, $V_{30}$ is widely used for soil classification (ASCE, 2010; Borcherdt & Glassmoyer, 1992; ICC, 2017). The $V_{50}$ value accounts site amplification of seismic waves, which is essential information for building codes and seismic design (ASCE, 2010). The $V_{50}$ structure has been widely determined in many regions, including the US, Japan, Canada, and Europe. In Japan, $V_{50}$ was measured at more than 2,000 locations to cover the whole Japanese archipelago (Matsuoka et al., 2005). In Canada, a $V_{50}$ map of Ottawa was created using borehole tests and a landstreamer (Motazedian et al., 2011). In the US, the relationship between topographic slope and $V_{50}$ was developed to produce a high-resolution $V_{50}$ map (Allen & Wald, 2009).

In Italy and Greece, high-resolution geological maps and in situ measured shear-wave velocity profiles were used to prepare a $V_{50}$ map (Michelin et al., 2008; Stewart et al., 2014). There were attempts to use ambient-noise H/V analysis to construct $V_{50}$ models (Castellaro & Mulargia, 2009; Kwak et al., 2017; Yilar et al., 2017). However, the near-surface shear-wave velocity structures may vary high locally. Thus, the spatial resolutions of $V_{50}$ models based on shear-wave velocity profiles from H/V analysis is dependent on the distribution of seismic stations. Various approaches have been proposed to calculate $V_{50}$. Laboratory experiments or in situ field observations may suffer from insufficient numbers of rock samples and data points (Holzer et al., 2005; Kanli et al., 2006; Kuo et al., 2012; Sun et al., 2013). There were efforts to combine the local surface-wave dispersion curves and ambient-noise H/V spectral ratios to study shallow subsurface structures in local regions (Kanli, 2010; Kanli et al., 2008). However, these methods are ineffective for the development of nationwide $V_{50}$ maps.

A standard penetration test (SPT) measures the number (N) of strikes required for a sampler with a diameter of 5.1 cm and a length of 81 cm to penetrate 30 cm by dropping a hammer with a weight of 63.5 kg from a height of 75 cm. The SPT N value is commonly used to assess the properties of subsurface sediments (Ameratunga et al., 2006). It was reported that SPT N values are dependent on various factors, including pressure, relative density and particle size (Robertson et al., 1983; Seed et al., 1985; Skempton, 1986). The SPT N value can be used to estimate the site characteristics, including the relative density, elastic modulus, liquefaction potential and shear-wave velocity (Cubrinovski & Ishihara, 1999; Tokimatsu & Yoshimi, 1983).

Seismic velocity structures can be estimated using the SPT N values at boreholes (Lee & Tsai, 2008; Raptakis et al., 1995). The standard penetration tests are conducted widely, composing nationwide spatially-dense data points. However, the relationship between the SPT N and shear-wave velocity is dependent on the physical properties (density and geological characteristics) and chemical composition (mineralogical and petrological). Relationships between SPT N and shear-wave velocities are determined uniquely by region (Athanassopoulos, 1994; Fujiwara, 1972; Hasanbeyi & Ulusay, 2007; Imai, 1977; Imai & Tonouchi, 1982; Imai & Yoshimura, 1970; Jafari et al., 2002; Jinan, 1987; Kiku, 2001; Lee, 1990; Lee & Tsai, 2008; Ohta & Goto, 1978; Ohsaki & Iwasaki, 1973; Raptakis et al., 1995; Seed & Idriss, 1981; Sykora & Stokoe, 1983). A previous study attempted to develop a relationship between SPT N values and shear-wave velocities for the Korean Peninsula but was based on a limited number of borehole measurements (Sun et al., 2013). Sufficient numbers of data points needed to determine the relationships stably.

Recent major earthquakes in the Korean Peninsula such as the 2016 M6.5 Gyeongju earthquake and the 2017 M5.4 Pohang earthquake produced strong ground motions, raising public concerns regarding the potential seismic hazards imposed by larger earthquakes (Hong et al., 2017, 2018). The accurate information of $V_{30}$ structures is crucial for mitigation of seismic damages in the Korean Peninsula. However, the $V_{30}$ structures in the Korean Peninsula were limitedly studied (Kim et al., 2002; Sun et al., 2007).

In this study, we propose a composite analysis technique based on H/V analysis and borehole measurements. We determine the shear-wave velocity structure beneath seismic stations based on H/V spectral ratios. We find a relationship between the shear-wave velocities and SPT N values from adjacent boreholes. We determine the relationship between SPT N values and shear-wave velocities based on dense data distributed homogeneously throughout the southern Korean Peninsula (Figure 1). We investigate the lateral variations in $V_{30}$ of South Korea.
using the SPT N values obtained from densely deployed boreholes. Finally, we study the regional characteristics of $V_{S30}$ and their correlations with geological and topographical features.

2. Theory and Methods

A series of methods are applied to estimate $V_s$ profiles at boreholes. We first derive a relationship between SPT N values and shear wave velocities for the Korean Peninsula. To derive the relationship, we obtain the reference shear-wave velocity models at seismic stations from H/V ambient-noise analysis. The procedure of analysis is given in Section 4.

2.1. H/V Spectral Ratio

We first determine the reference shear-wave velocity structures of media beneath seismic stations using ambient noises. The horizontal-vertical (H/V) spectral ratio technique measures the site amplification magnitude using the ratio between the horizontal and vertical velocity spectra of ambient seismic noise in the frequency domain (Nakamura, 1989). The values of the H/V spectral ratio are controlled by the seismic velocities in the shallow media (Arai & Tokimatsu, 2000; Lachet & Bard, 1994; Nakamura, 1989). The horizontal velocity spectra can be calculated by

$$S_{0,h}(f) = \sqrt{S_{0,E}(f)^2 + S_{0,N}(f)^2},$$  \hspace{1cm} (1)
where $S_{0,j}^u(f)$ and $S_{0,j}^s(f)$ are the EW- and NS-component velocity spectra, respectively, at the frequency $f$.

Ambient noise on the Earth’s surface originates from natural forces and anthropogenic sources (Bonnefoy-Clau- det al., 2006). The high-frequency component of ambient noise is effective for investigating shallow subsurface media. The seismic energy originating from local natural forces and anthropogenic sources is dominated by Rayleigh waves. Thus, microtremors on the surface of a sedimentary basin can be represented as a sum of body waves transmitted from the basement and local Rayleigh waves (Nakamura, 2000). On the other hand, transient motions of the basement are mainly responsible for body waves. Thus, the spectral amplitudes of microtremors in a sedimentary basin and the basement are given by (Nakamura, 2000)

$$S_{0,j}^u = S_{0,j}^b + S_{0,j}^s \approx A_j S_{1,j}^b + S_{0,j}^s,$$

$$S_{1,j}^u = S_{1,j}^b,$$

where $S_{0,j}^k$ is the spectral amplitude of the transient motion of wave $k$ ($k = u, b, s$, where $u$ stands for the full wavefield, $b$ denotes body waves, and $s$ denotes Rayleigh waves) on component $j$ ($j = h, v$ where $h$ is the horizontal component and $v$ is the vertical component) at vertical location $i$ ($i = 0, 1$ where 0 is the Earth's surface and 1 is the basement) and $A_j$ is the amplification factor of vertically incident body waves on component $j$ in the sedimentary basin.

The amplitude ratios of microtremors between the Earth's surface and basement (i.e., the amplification factors) are given by

$$R_j = \frac{S_{0,j}^u}{S_{1,j}^u} = \frac{A_j S_{0,j}^b + S_{0,j}^s}{S_{1,j}^b},$$

where $R_j$ ($j = h, v$) is the amplitude ratio. The horizontal amplification relative to the vertical amplification, $F$, is given by

$$F = \frac{R_h}{R_v} = \frac{S_{0,h}^b / S_{1,h}^b}{S_{0,v}^b / S_{1,v}^b}.\quad (4)$$

It was reported that the spectral amplitude ratio between horizontal and vertical seismic motions in the basement is $S_{1,h}^b / S_{1,v}^b \approx 1$ in a wide frequency range (Nakamura, 1989). Thus, $F$ can be rewritten as

$$F = \frac{S_{0,h}^u}{S_{1,v}^u} = \frac{A_h S_{0,h}^b + S_{0,h}^s}{A_v S_{1,h}^b + S_{0,v}^s}.\quad (5)$$

Here, the relative horizontal amplification factor presents at frequencies around the fundamental resonant frequency. Here, the fundamental resonant frequency ($f_0$) and the natural period ($T$) are given by (Kramer, 1996)

$$f_0 = \frac{\beta}{4D},$$

$$T = \frac{4D}{\beta},\quad (6)$$

where $\beta$ is the average shear-wave velocity of the sedimentary basin and $D$ is the thickness of the basin.

The $P$-wave velocity is about 3 times larger than the $S$-wave velocity in sedimentary basins (Hamilton, 1979; Kodaira et al., 1996; Pasquet et al., 2015; Tsuji et al., 2011). The ground motions produced by $S$ waves are much stronger than those generated by $P$ waves. Thus, the ground motions in a sedimentary basin are controlled by $S$ and Rayleigh waves. $SH$ waves are effectively trapped in the sedimentary basin as a result of multiple reflections, while $SV$ waves are phase-coupled with $P$ waves. The body waves in a sedimentary basin are thus dominated by $SH$ waves.

If Rayleigh waves are dominant over body waves in the energy composition of microtremors ($S_{0,j}^b \ll S_{0,j}^u$), we have
Rayleigh waves produce vertically elliptical particle motions, and thus, \( S_{0,h}^r < S_{0,v}^r \). Thus, \( F < 1 \) in the wide frequency range. If no Rayleigh waves or only weak Rayleigh waves are present \( (S_{0,h}^r = S_{0,v}^r \approx 0) \), we have

\[
F \approx \frac{A_h}{A_v}.
\]  

(7)

For vertically incident SH waves, we have \( A_v = 1 \) at the frequencies around \( f_r \). Thus, we have

\[
F = \frac{S_{0,h}^r}{S_{0,v}^r} = A_h
\]  

(8)

at the frequencies around \( f_r \). When we stack the H/V spectral ratios over different time periods, we can enhance the peak of \( A_h \) for SH waves. Thus, the H/V spectral ratios of microtremors on the Earth’s surface allow us to assess the amplification factors of \( S \) waves in subsurface media.

2.2. One-Dimensional Equivalent Linear Analysis

We calculate theoretical H/V spectral ratios in order to compare with the observed H/V spectral ratios from ambient noise analysis. One-dimensional equivalent linear analysis (1-D EQL analysis) is widely used for the assessment of site responses (Schnabel, 1972). The subsurface layers are assumed to be horizontally layered. The ground response is calculated for vertically incident shear waves from the basement. 1-D EQL analysis calculates the frequency-dependent transfer functions of seismic site amplification according to the layers within the medium. If the medium comprises multiple layers, the transfer function through the medium is defined by the displacement ratio between the top and bottom layers.

We consider a layered, damped sedimentary basin on elastic bedrock (Figure 2). The sedimentary basin consists of \( M \) layers, where the \( M \) layer is bedrock. The sedimentary layers are composed of Kelvin-Voigt solids (Kramer, 1996). The displacement and shear stress of a vertically propagating SH plane wavefield in a Kelvin-Voigt solid is given by

\[
\begin{align*}
    u_m(z_m, t) &= A_m \exp \left[ i(\omega t + k_m^r z_m) \right] + B_m \exp \left[ i(\omega t + k_m^i z_m) \right], \\
    \tau_m(z_m, t) &= G_m \frac{\partial u_m}{\partial z},
\end{align*}
\]

(10)

where \( u_m(z_m, t) \) is the SH displacement at the vertical location \( z_m \) in layer \( m \) at time \( t \), \( \omega \) is the angular frequency, \( k_m^r \) is the complex wavenumber, \( A_m \) and \( B_m \) are the amplitudes of SH waves traveling downward and upward, respectively, \( \tau_m \) is the shear stress, and \( G_m^r \) is the complex shear modulus satisfying

\[
G_m^r = \rho_m \cdot (\beta_m^s)^2.
\]

(11)

where \( \rho_m \) is the density of layer \( m \) and \( \beta_m^s \) is the complex shear-wave velocity. The complex shear-wave velocity can be written in terms of the damping ratio in the layer, \( \xi_m^r \):

\[
\beta_m^s = \sqrt{\frac{G_m^r}{\rho_m}} = \sqrt{\frac{G_m(1 + i\xi_m)}{\rho_m}} \approx \sqrt{\frac{G_m}{\rho_m}(1 + i\xi_m)} = \beta_m(1 + i\xi_m),
\]

(12)

where \( G_m \) is the shear modulus in layer \( m \) and \( \beta_m \) is the shear-wave velocity in layer \( m \). Moreover, the complex wavenumber is given by

\[
k_m^s = \frac{\omega}{\beta_m^s} = \frac{\omega}{\beta_m(1 + i\xi_m)} \approx \frac{\omega}{\beta_m}(1 - i\xi_m) = k_m(1 - i\xi_m),
\]

(13)

where \( k_m \) is the wavenumber in layer \( m \). In this study, we set the damping ratio \( \xi_m \) to be 5% (Kaklamanos & Bradley, 2018; Kaklamanos et al., 2015; Kim & Lee, 2000; Thompson et al., 2012).
The displacement and shear stress on the boundary between layers $m$ and $m+1$ satisfy

$$u_m(z_m = h_m, t) = u_{m+1}(z_{m+1} = 0, t),$$

$$\tau_m(z_m = h_m, t) = \tau_{m+1}(z_{m+1} = 0, t),$$

where $h_m$ is the thickness of layer $m$. We then have recursive equations of amplitudes:

$$A_{m+1} = \frac{1}{2} A_m(1 + \gamma_m^*)\exp[ik_m h_m] + \frac{1}{2} B_m(1 - \gamma_m^*)\exp[-ik_m h_m],$$

$$B_{m+1} = \frac{1}{2} A_m(1 - \gamma_m^*)\exp[ik_m h_m] + \frac{1}{2} B_m(1 + \gamma_m^*)\exp[-ik_m h_m].$$

where $\gamma_m^*$ is the complex impedance ratio given by

$$\gamma_m^* = \frac{G_m^* k_m^*}{G_{m+1}^* k_{m+1}^*} = \frac{\rho_m f_m^*}{\rho_{m+1} f_{m+1}^*}. $$

The shear stress on the surface of the sedimentary basin is zero (i.e., $\tau_1(z_1 = 0, t) = 0$), which yields $A_1 = B_1$. Thus, the recursive equations of amplitudes can be rewritten simply in terms of $A_1$:

$$A_m(\omega) = a_m(\omega) A_1(\omega),$$

$$B_m(\omega) = b_m(\omega) A_1(\omega),$$

where $a_m(\omega)$ and $b_m(\omega)$ are the amplification factors of downward- and upward-traveling SH waves, respectively, at an angular frequency $\omega$ in layer $m$. Here, we have $a_1(\omega) = b_1(\omega) = 1.$
The transfer function of the displacement amplitude $F_{ij}(\omega)$ between layers $i$ and $j$ is given by

$$F_{ij}(\omega) = \frac{|u_i|}{|u_j|} = \frac{[a_i(\omega) + b_j(\omega)]A_i(\omega)}{[a_j(\omega) + b_i(\omega)]A_j(\omega)}.$$  \hspace{1cm} (18)

The transfer function of displacement amplitude between layers $1$ and $M$ is given by

$$F_{1M}(\omega) = \frac{2}{a_M(\omega) + b_M(\omega)}.$$  \hspace{1cm} (19)

Hence, the site amplification is given by the transfer function of the displacement amplitude between the surface and bedrock (Bonilla et al., 2002).

The displacement amplitudes of vertically traveling $SH$ wavesfields may be the same between an outcrop of bedrock and the bedrock itself. The displacement amplitudes of upward- and downward-traveling $SH$ waves are the same in a bedrock outcrop because the shear stress is zero on the surface ($A'_{M} = B'_{M}$, $a'_{M} = b'_{M}$). Thus, when we replace the displacement amplitudes in bedrock with those in a bedrock outcrop, we obtain the transfer function (site amplification) between the sedimentary basin and bedrock ($F$):

$$F(\omega) = \frac{2}{a_{M}(\omega) + b_{M}(\omega)} = \frac{1}{a_{M}(\omega)}.$$  \hspace{1cm} (20)

Here, the amplification factor $a_{M}$ can be determined with the damping ratios, densities, layer thicknesses, and shear-wave velocities in the layers between the surface and the bedrock.

### 2.3. Relationship Between SPT N Values and Shear-Wave Velocities

The SPT N values at boreholes are converted to shear-wave velocities. Relationships between SPT N values and shear-wave velocities have been developed for many regions, including the US, Japan, China, Greece, Turkey, India, Iran, and South Korea (Athanasopoulos, 1994; Hasancebi & Ulusay, 2007; Jafari et al., 2002; Lee, 1990; Lee & Tsai, 2008; Ohta & Goto, 1978; Raptakis et al., 1995; Sun et al., 2013). These relationships follow a general form:

$$V_s = a N^b,$$  \hspace{1cm} (21)

where $V_s$ is the shear-wave velocity, $N$ is the SPT N value, and $a$ and $b$ are constants.

### 2.4. $V_{S30}$ Model

The $V_{S30}$ model of the Korean Peninsula is developed based on the shear-wave velocity profiles at boreholes. We determine a seismic velocity model for each borehole using the revised relationship between the SPT N values and shear-wave velocities. The $V_{S30}$ for each borehole location is determined by

$$V_{S30} = \frac{30}{\sum_{i=1}^{M_{30}} \frac{h_i}{\beta_i}},$$  \hspace{1cm} (22)

where $M_{30}$ is the number of layers up to a depth of 30 m, $h_i$ is the thickness of layer $i$, and $\beta_i$ is the shear-wave velocity in layer $i$. Each $V_{S30}$ model is produced based on the $V_{S30}$ value at the borehole location.

Efforts were taken to infer $V_{S30}$ from boreholes with the shear-wave velocity structure up to depths of less than 30 m (Boore, 2004; Boore et al., 2011; Gallipoli & Mucciarelli, 2009; Stewart et al., 2014; Wang & Wang, 2015). We determine $V_{S30}$ using the average velocity up to the maximum depth ($V_{max}$) where shear-wave velocities (or SPT N values) are available (Boore, 2004). The $V_{S30}$ accuracy may increase with the maximum depth. However, $V_{S30}$ can be underestimated using the relationship with $V_s$ when the seismic velocities increase rapidly near the depth $d$. We modify the method to determine a $V_{S30}$ model in situations involving a rapid velocity increase near
verify the relationship between the SPT N values and shear-wave velocities to determine

To use these SPT N values, we calibrate the SPT N values for the shear-wave velocities of the media within the

Mountain areas account for approximately 75% of the surface area of the Korean Peninsula. High-elevation

Borehole cores provide information on the subsurface composition, layer thicknesses, and medium properties.

We collect ambient seismic noise data from 20 broadband velocity stations managed by the Korea Meteorological

We choose continuous three-component seismic records acquired on 20 March, 22 June, 23 August, 14 November,

The SPT N values are available from boreholes that are densely distributed over the Korean Peninsula (Figure 1).

To use these SPT N values, we calibrate the SPT N values for the shear-wave velocities of the media within the

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We combine the shear-wave velocity profiles and SPT N values, deriving a relationship between SPT N values and shear-wave velocities (Section 8).
site amplifications with the observed H/V spectral ratios. Next, we find the optimum velocity models that yield the minimum misfit errors with the observed H/V spectral ratios (Section 7).

We then collect the SPT N values of boreholes that are located adjacent to stations (Figures 1d–1f) (Section 8). We assume that the media in the boreholes can be represented by the velocity structure beneath the seismic stations. The properties of the shallow media may vary locally. We determine possible SPT N ranges using the shear-wave velocities from H/V analysis considering the reported relationships between SPT N and shear-wave velocities. We choose the data points in valid velocity ranges according to reported relationships for other regions. This procedure allows us to select valid data points. We determine the relationship between the SPT N values and shear-wave velocities for the area around each station. Finally, we determine the representative relationship for the Korean Peninsula, and we calculate a $V_{S30}$ model using the SPT N values of boreholes over the Korean Peninsula (Section 9).

5. Validation Tests and Conditions

We test the validity of H/V analysis using synthetic data sets. Also, the inversion stability is examined. We compose ambient noise fields by combining the wavefields induced by 30,000 point sources that are distributed uniformly in a circular region with a radius of 20 km (Figure 4a). The point sources are randomly-oriented impulsive body forces with a common strength. Also, the points sources are activated randomly in time. We calculate three-component synthetic waveforms using a reflectivity method (Kennett, 1979, 1983). We generate 1 hr-long synthetic records for layered media (Figure 4b).
Figure 4. Synthetic experiments of H/V analysis: (a) Microseismic point source locations, (b) 1 hr-long synthetic ambient noises, (c and d) application to a three-layered model, and (e and f) application to a four-layered model with a low velocity layer. The layered model experiments present (c) and Comparison between input and inverted shear-wave velocity models are presented in (c and e). Comparison among observed, theoretical, and inverted H/V ratios are presented in (d and f). H/V inversions are conducted in three frequency bands of 1–20 Hz, 0.05–25 Hz, and 2–12 Hz. The H/V inversions in 1–20 Hz yield the best results.
The accuracy of H/V inversion may be dependent on the implemented frequency band. It is generally observed that media with a thickness of less than 100 m have fundamental resonant frequencies at $f > 1$ Hz (Ibs-von Seht & Wohlenberg, 1999; Kramer, 1996; Luzi et al., 2011; Parolai et al., 2002). Also, ambient noise is dominated by human activities at frequencies greater than 20 Hz (Hong et al., 2020). We consider three frequency bands of 0.5–25 Hz, 1–20 Hz, and 2–12 Hz in the tests.

We first consider a medium with three layers over half space (Figure 4c). We perform the H/V analysis based on the synthetic records. The H/V ratios from the synthetic records match with the theoretical variations (Figure 4d). The observation suggests that the H/V analysis of ambient noises in 1–20 Hz enables us to retrieve the shear-wave velocity profiles up to a depth of 100 m reasonably. On the other, analyses based on wider or narrower frequency bands yield velocity models with relatively large errors (Figure 4d). Further, the synthetic experiments present that the H/V ratios in frequencies $\leq 1$ Hz are hardly affected the seismic velocity structures up to a depth of 100 m.

We additionally test the H/V analysis for media with a low velocity layer (Figure 4e). The H/V analysis allows us to resolve the low velocity layer reasonably (Figure 4f). We find that the H/V analysis in frequencies of 1–20 Hz is useful to resolve the layers. We observe that a sharp velocity increase across a layer boundary can be represented by mild velocity increases with depth. However, the models from H/V analysis satisfy the general velocity profiles and average velocities. The shear-wave velocity structures from H/V analysis may be used as reference models for calibration between SPT N and $V_S$.

It is noteworthy that the inverted best-fit velocity models are apparently different by the frequency band. However, the average velocities of the inverted velocity models are similar. Further, the theoretical H/V ratios for the best-fit velocity models are comparable. Thus, the H/V analysis may yields a velocity model that is affected by the frequency band and ambient noise variation.

We examine the regional variations of SPT N profiles to compare the borehole SPT N profiles with shear-wave velocity structure beneath nearby seismic stations. We determine the size of areas in which a sufficient number of stations are available and the SPT N profiles are generally consistent with the mean profile. We find that more than 100 boreholes are available in the regions with radii of $\geq 15$ km (Figure 5). Further, the standard deviations of SPT N profiles among boreholes are dependent on the area size, varying by region (Figure 5). We find that the radius of 15 km is useful to analyze the borehole SPT N data with comparison with the reference shear-wave velocity structures beneath seismic stations.
6. H/V Analysis

We calculate the shear-wave velocity structures for the media beneath 20 seismic stations using H/V analysis. The shear-wave velocity models are used for regional reference structures. We collect continuous three-component records of ambient seismic noise (Figure 6). The instrument responses are removed from the seismic records. We then calculate the spectra every hour, and stack them for each day. We calculate the H/V spectral ratios. The daily stacked H/V spectral ratios are stable in arbitrary selected 5 days (Figure 6).

The standard deviations of the H/V spectral ratios among 5 days are ∼0.0435, which corresponds to about 3.0% variation in H/V spectral ratios and 3.7% variation in the inverted shear-wave velocity models (Figure 7). The magnitudes of induced variations suggest that the H/V spectral ratios and inverted velocity models are determined stably. We use the average H/V ratios of 5 days in this study.

We calculate the theoretical site amplification for a given velocity model using the 1-D EQL method. We compare the H/V spectral ratios with the theoretical site amplification functions (Figure 8). We assess the root mean square errors (RMSEs) between the H/V spectral ratios and theoretical site amplification functions in the effective frequency band (1–20 Hz).

We take two steps to determine the shear-wave velocity models of the media beneath seismic stations up to a depth of 100 m. In the first step, we determine the approximate shear-wave velocity models of the media beneath seismic stations considering the shear-wave velocity models at adjacent boreholes. We consider velocity models composed of 10 layers with variable thicknesses (>1 m). It is noteworthy that 10 layers are sufficient to describe the shallow subsurface structures considering the effective frequency band (1–20 Hz). We collect reference shear-wave velocity models at adjacent boreholes that are determined using the SPT N values with a relationship between SPT N values and shear-wave velocities for the Korean Peninsula (Sun et al., 2013). We determine the shear-wave velocity range for each layer from the reference shear-wave velocity models at boreholes.

We search optimal velocity models to yield the minimum RMSEs between synthetic site amplifications and observed H/V spectral ratios (Figure 8). We iteratively search for the optimum velocity models by refining the
In the second step, we refine the shear-wave velocity models up to a depth of 30 m. It is noteworthy that the media up to 30 m depth are composed of 4–6 layers in the approximate structures. We thus refine the velocity models with 1 m-thick layers. The approximate models are used as reference models. We set the shear-wave velocities in the refined models to increase linearly, ensuring that the average velocities agree with the approximate models.

7. Shear-Wave Velocity Structures From H/V Analysis

The seismic structures in the media beneath the seismic stations display topography- and location-dependent features. The seismic stations in high-topography regions generally have larger seismic velocities at common depths than those in low-topography regions (Figure 9). The seismic velocity increases rapidly with depth in high-topography regions (stations CHC2, CHJ2, CHS, DGY2, JEO2, KWJ2, and SND). The shear-wave velocities increase rapidly in the top 5 m and then increase slowly with depth (Figure 9). The shear-wave velocities reach \( \sim 450 \text{ m/s} \) at a depth of 5 m. The high-topography regions have shear-wave velocities of \( \sim 620 \text{ m/s} \) at a depth of 20 m.

Stations in low-topography regions (stations BUS2, DAG2, GKP1, NPR, SEO2, SNU, and TJN) have reversed seismic velocity structures at shallow depths (Figure 9). The low-topography regions present low shear-wave velocities of \( \sim 520 \text{ m/s} \) at a depth of 10–20 m. Stations SNU and SEO2 are placed in Seoul, presenting comparable shear-wave velocity structures. The synthetic tests suggest possible identification of low velocity layers in media.
using H/V analysis (Figures 4e and 4f). The presence of groundwater reservoirs and porosity may affect the H/V responses. However, the H/V analysis may suffer from inherent uncertainty. Further, inhomogeneous energy composition in ambient noises may cause erroneous determination of layers.

It is noteworthy that some media present poor correlations between the seismic velocities and surface topography. Station KNUD within a high-topography regime presents a reversed seismic structure. On the other hand, station GSU in a low-topography region displays a rapidly increasing velocity structure, which is a typical feature in high-topography regions. Station HKU shows seismic velocities that increase slowly up to a depth of 30 m. Stations SES2 and ULJ2 are separated by a distance of 263 km present similar velocity structures where the velocities increase slowly up to a depth of 40 m. Station MKL presents a mixed velocity structure that the seismic velocities are reversed at shallow depths, and then increasing rapidly with depth.
8. SPT N Conversion Equation

Having determined the shear-wave velocity structures beneath the seismic stations, we next determine the relationship between the SPT N values in adjacent boreholes and the shear-wave velocities of seismic stations. We use the shear-wave velocity structures beneath the seismic stations (Section 7). The distances from seismic stations to the nearest boreholes vary between 0.23 and 7.23 km. Single boreholes may not share the medium properties with seismic stations since shallow media change by location. We thus analyze the data from a set of boreholes adjacent to stations.

We collect the SPT N values from boreholes at distances less than 15 km from the seismic stations (Figures 1d–1f). The sampled depths during the SPT experiments vary among the boreholes. Thus, we resample the SPT N values at a constant depth interval of 1 m (Figure 10). We find the median SPT N values in the data sets at every depth. We consider the reported relationships between the SPT N values and shear-wave velocities to determine the possible ranges of SPT N values for given velocities. The relationships are determined for various regions (Athanasopoulos, 1994; Hasancebi & Ulusay, 2007; Jafari et al., 2002; Lee, 1990; Lee & Tsai, 2008; Ohta & Goto, 1978; Raptakis et al., 1995; Sun et al., 2013). We remove the borehole data that deviate from the possible ranges of SPT N values. We analyze the SPT N values up to a depth of 30 m (Figure 10). Approximately 94.5% of the SPT N values range between 5 and 717. The corresponding shear-wave velocities are 143–820 m/s.

Figure 9. Inverted shear-wave velocity models based on H/V analysis for the media beneath stations (a) BUS2, (b) CHJ2, (c) CHJ2, (d) CHS, (e) DAG2, (f) DGY2, (g) GKP1, (h) GSU, (i) HKU, (j) JEO2, (k) KNUD, (l) KWJ2, (m) MKL, (n) NPR, (o) SEO2, (p) SES2, (q) SND, (r) SNU, (s) TJN, and (t) ULJ2. The initial shear-wave velocity model is presented. The initial velocity models are designed considering the SPT N profiles in local regions (u) Comparison of the average shear-wave velocity structures in high-topography regions (CHC2, CHJ2, DGY2, JEO2, KWJ2, CHS, KNUD, SND) and low-topography regions (BUS2, DAG2, SEO2, GKP1, NPR, SNU, TJN). The shear-wave velocities in high-topography regions are generally larger than those in low-topography regions. A low velocity layer at depths of ∼10–15 km is observed at some stations (BUS2, DAG2, GKP1, KNUD, NPR, SEO2, SNU, TJN).
The SPT N data in the possible ranges are analyzed to determine the relationship between SPT N values and shear-wave velocities. The vertical profiles of shear-wave velocities in the media beneath seismic stations are used for the reference shear-wave velocity models. We assign shear-wave velocities at the same depths from the reference velocity models to the shear-wave velocities for the SPT N values of boreholes (Figure 0x11). We use 109,577 SPT N data points for 12,899 boreholes. We determine the representative relationship between the SPT N values and the shear-wave velocities for the Korean Peninsula. We find the best-fitting relationship for all soils in the Korean Peninsula (Figure 11a):

\[ V_S = 97.98(\pm 0.56) N^{0.305(\pm 0.001)}, \]

where \( V_S \) is the shear-wave velocity in m/s and \( N \) is the SPT N value.

We test the stability of the inverted relationship using a bootstrap analysis (Efron & Tibshirani, 1986). We produce 1,000 data sets composed of randomly chosen data points with allowance of multiple selection. The average \( a \) and \( b \) values of the bootstrap data sets are 98.66 and 0.304, respectively, and their standard errors are 0.789 and 0.002 (Figure 12). The average \( a \) and \( b \) values from the bootstrap data sets are close to those from the original data set. The similarity between the averages and the low standard errors suggest that the relationship is stable. Further, the relationship represents the borehole data set reasonably.
We additionally examine the validity of the relationship by comparison with results from other studies. We collect 377 in-situ measurements of SPT N and shear-wave velocities at 26 sites in two local regions (Sun et al., 2013). A relationship was determined based on the in-situ measurements of SPT N and shear-wave velocities (Sun et al., 2013). We compare the previous observations with this study (Figure 11b). We find that the SPT N data distribution agrees with the in-situ observations. Also, the relationship determined in this study reasonably agrees with the in-situ observations. However, we observe some differences in the relationships. This may be partly because the earlier study may be based on a small number of data set for the derivation of the relationship.

We further compare the estimated relationship with those for other regions including Greece, Turkey, Iran, Taiwan, Japan, and Korea (Athanasopoulos, 1994; Hasancebi & Ulusay, 2007; Jafari et al., 2002; Lee, 1990; Lee & Tsai, 2008; Ohta & Goto, 1978; Raptakis et al., 1995; Sun et al., 2013). The \( V_s \)-SPT N relationships vary widely, depending on the region. The estimated \( V_s \)-SPT N curve in this study is placed in a middle range among the relationships for other regions (Figure 13). We observe that the estimated relationship yields lower \( V_s \) relative to the previous reported relationship for local regions of the Korean Peninsula. The feature may be associated with the difference in data locality and number of data.

![Figure 11](image1.png)

**Figure 11.** (a) Distribution of shear-wave velocities as a function of SPT N values in local boreholes around stations. The representative relationship between SPT N values and shear-wave velocities is determined (solid line). Data point distribution is well represented by the fitted line. (b) Data population of SPT N values and shear-wave velocities. In situ field measurements (dots) are shown for comparison. The relationship from a previous study (Sun et al., 2013) is presented for comparison (dotted line). The data points of this study are consistent with the in situ measurements. The relationship of this study reasonably represents the distribution of in situ measurements.

![Figure 12](image2.png)

**Figure 12.** Bootstrap analysis to determine the relationship \( V_s = a N^b \) between SPT N values and shear-wave velocities based on 1,000 resampled data sets. Distributions of the (a) \( a \) values and (b) \( b \) values from analyses based on resampled data sets. The average (avg) values and standard errors (std) are presented. The averages are close to the values from the analysis based on the full data set. The average values (dotted line) and standard errors (shaded band) are indicated.
We determine the shear-wave velocity structures at boreholes with SPT N profiles using the relationship between SPT N values and shear-wave velocities. The shear-wave velocity structures at adjacent boreholes are combined (Figure 14). The median shear-wave velocity structures present general trends of velocity increases with depth. On the other hand, some reference shear-wave velocity models from H/V analysis display low-velocity layers. The feature is not apparent in the median SPT N profiles due to the statistical diversity in borehole data. However, the median shear-wave velocity structures generally agree with the shear-wave velocity models at media beneath seismic stations. We find reasonable agreement between the shear-wave velocity structures from H/V analysis and those from SPT N values at all stations. The observations suggest that the determined relationship between SPT N values and shear-wave velocities is reasonable for the SPT N to $V_s$ conversion in the Korean Peninsula.

9. $V_{S30}$ Estimation

We next determine a $V_{S30}$ model for the Korean Peninsula. We determine the shear-wave velocity structures in boreholes using SPT N values based on the above relationship between shear-wave velocities and SPT N values. However, some SPT experiments were conducted up to depths less than 30 m. We find 9,222 boreholes among all 175,619 boreholes (5.25%) with SPT experiments that extended to depths greater than 30 m. We infer $V_{S30}$ values using the shear-wave velocity structures up to available depths.

We first examine the relationships between $V_{S30}$ and $V_{Sd}$, the average shear-wave velocity up to a depth $d$. We analyze the borehole data with the maximum depths greater than 30 m to find the relationships between $V_{S30}$ and $V_{Sd}$ (Figure 15). Here, the depth $d$ varies from 5 to 29 m. Naturally, when we use the data points up to a shallow depth, we find relatively wide distribution between $V_{S30}$ and $V_{Sd}$. When the data points up to a depth close to 30 m, we find strong linear relationships between $V_{S30}$ and $V_{Sd}$. Thus, the $V_{S30}$ can be determined more accurately when we analyze the borehole data up to deeper depths. This feature is natural since the deeper medium properties may not be inferred correctly sometimes considering only the shallow medium properties.

We apply a modified method to complement the situations with rapid velocity changes near the maximum depths. The modified method extrapolates the shear-wave velocities at depths greater than the maximum depths using the average velocity slopes and the shear-wave velocities at the maximum depths. The modified method yields better $V_{S30}$ estimates than the original method (Figure 16). The differences between the actual and inferred $V_{S30}$ values decrease as the medium properties are known up to a deeper depth.

We determine a $V_{S30}$ model using the borehole data (Figure 17). The $V_{S30}$ model presents characteristic regional variations. Approximately 99% of the $V_{S30}$ estimates vary between 98 and 994 m/s (Figure 18a). The $V_{S30}$ values in major cities are relatively low. We find relatively high $V_{S30}$ values in inland regions ($\sim$550–900 m/s), while relatively low $V_{S30}$ values in coastal regions ($\sim$100–300 m/s). This feature is due to the presence of thick sedi-
ments in coastal regions. We observe apparent linear relationship between $V_{S30}$ values and logarithmic elevations (Figure 19). The relationship is determined by

$$V_{S30} = 541.61(\pm 7.67)\log h - 536.78(\pm 12.48),$$

Figure 14. Distribution of shear-wave velocities estimated from SPT N values at local boreholes around stations (a) BUS2, (b) CHJ2, (c) CHJ2, (d) CHS, (e) DAG2, (f) DGY2, (g) GKP1, (h) GUS, (i) HKU, (j) JEO2, (k) KNUD, (l) KWJ2, (m) MKL, (n) NPR, (o) SEO2, (p) SES2, (q) SND, (r) SNU, (s) TNJ, and (t) UJ2. The shear-wave velocity profiles in the media beneath seismic stations are presented (solid line). The data point populations are presented (color bar). The shear-wave velocities from the SPT N values in local boreholes are consistent with the shear-wave velocity profiles at seismic stations.
where \( l \) is the elevation above the sea level in m. The relationship is determined based on the 175,619 \( V_{S30} \) values at the borehole locations with elevations above the sea level between 10 and 2,000 m. The observation suggests that the \( V_{S30} \) increases with the topography.

10. \( V_{S30} \) Model Comparison

We examine the validity of the \( V_{S30} \) model from comparison with in-situ field measurements in local regions. We collect in-situ measurements at 28 sites in Gyeongju and 16 sites in Hongseong (Kim et al., 2002; Sun et al., 2006, 2007, 2013) (Figures 20a and 20b). The in-situ measurement sites are located in small regions (Figures 20c and 20d). We choose the \( V_{S30} \) values at the boreholes that are located near the in-situ measurement sites. We compare the \( V_{S30} \) values determined herein with in situ \( V_{S30} \) measurements. We find that the modeled \( V_{S30} \) values are consistent with the in situ measurements (Figure 20). The observation suggests that the proposed method based on SPT N values may yield reasonable \( V_{S30} \) estimates.

Figure 15. Comparison between the average shear-wave velocities for media in the top 30 m (\( V_{S30} \)) and the average shear wave velocities for media in the top \( d \) m (\( V_{Sd} \)): (a) \( d = 5 \) m, (b) 6 m, (c) 7 m, (d) 8 m, (e) 9 m, (f) 10 m, (g) 11 m, (h) 12 m, (i) 13 m (j) 14 m (k) 15 m (l) 16 m (m) 17 m (n) 18 m (o) 19 m (p) 20 m (q) 21 m (r) 22 m (s) 23 m (t) 24 m (u) 25 m, (v) 26 m (w) 27 m, (x) 28 m, and (y) 29 m. The data points present stronger linear relationships with increasing depth (d) The \( V_{S30} \) are better determined as the medium properties are known up to deeper depth.
We next compare the nationwide results of this study with other model. The United States Geological Survey (USGS) presents a $V_{S30}$ model for the Korean Peninsula (https://earthquake.usgs.gov/data/vs30/) (Figure 21a). The USGS estimates the $V_{S30}$ based on the surface topography, slope and soil conditions (type, weathering degree) (Allen & Wald, 2007; Wald & Allen, 2007). Surface topography-based $V_{S30}$ measurements are easy to apply to wide regions where field observations are not available. It was reported that the topography-slope-based method may have limited accuracy for both high- and low-topography regions (Allen & Wald, 2007). The topography-slope-based method may need to reflect the soil conditions, basement type and weathering degree. For instance, a low-topography region in Las Vegas within a limestone basin has $V_{S30}$ values as high as 500–600 m/s (Scott et al., 2004).

We compare the results of this study with the USGS $V_{S30}$ model. The USGS $V_{S30}$ model has a spatial resolution of 0.0083° in both longitude and latitude (Figure 21a). The lateral variations in the $V_{S30}$ model of this study are similar to those in the USGS model (Figure 21a). The $V_{S30}$ values in costal sedimentary regions, including Busan...
and Gunsan, are approximately 200 m/s in both models. The USGS $V_{S30}$ model presents values up to 900 m/s in high-topography regions. Approximately 95% of the $V_{S30}$ differences between the two models range between −540 m/s and 540 m/s (Figure 21b). The inland regions of the Korean Peninsula present high-topography slopes where the USGS $V_{S30}$ values are larger than those of the model from this study. On the other hand, the USGS model presents lower $V_{S30}$ values in low-topography regions. The apparent differences between the USGS $V_{S30}$ model and the model presented in this study may be partly associated with the inherent limitations of the topography-slope-based method.

We additionally compare the $V_{S30}$ values of this study with those in the eastern US that presents a stable intracontinental environment like the Korean Peninsula. We collect 66 local in situ measurements in the eastern US (McNamara et al., 2015) (Figure 18b). The available in situ measurements may not be sufficient for the representation of overall features in the eastern US. We find that the overall distribution of $V_{S30}$ estimates is similar

![Figure 17. Spatial distribution of (a) $V_{S30}$ values in boreholes and (b) $V_{S30}$ values after kriging interpolation. The $V_{S30}$ values are large in mountainous (high-topography) regions and small in coastal (low-topography) regions.](image)

![Figure 18. (a) Data population of $V_{S30}$ values in boreholes across the Korean Peninsula. Approximately 99% of the $V_{S30}$ estimates vary between 98 and 994 m/s. (b) Comparison of $V_{S30}$ data population between the Korean Peninsula and eastern US. The $V_{S30}$ values for the eastern US are based on 66 in situ local measurements (McNamara et al., 2015). The overall distribution of data population is similar between the Korean Peninsula and eastern US.](image)
between the Korean Peninsula and eastern US (Figure 18b). These observations support the $V_{S30}$ model of this study.

11. Discussion and Conclusions

Site amplification is an important factor for the estimation of seismic hazard potentials. $V_{S30}$ maps were developed in many regions and are used for seismic design. Implementing the standard penetration test (SPT) in boreholes allows the direct measurement of $V_{S30}$. However, the relationships between SPT N values and shear-wave velocities vary regionally due to differences in medium properties and rock composition.

Dense borehole measurements are available in the Korean Peninsula. To use these borehole measurements, we calibrate the borehole measurements for the shear-wave velocities. We introduced a method to combine borehole in-situ analysis with ambient seismic noise analysis for the development of a $V_{S30}$ model. We first determined the subsurface shear-wave velocity structures beneath seismic stations across the Korean Peninsula using H/V analysis. We analyzed the SPT N values in boreholes around the seismic stations. The shear-wave velocity structures beneath the stations were used as local reference shear-wave velocity models. We found a representative relationship for the Korean Peninsula based on these local reference shear-wave velocity models and SPT N values from local boreholes. The relationship is based on a large amount of data and allows us to determine shear-wave velocities from SPT N values in the Korean Peninsula. The SPT N models of boreholes in the peninsula were converted into shear-wave velocity structures using the representative relationship between SPT N values and shear-wave velocities. We then determined a $V_{S30}$ model of the Korean Peninsula.

We conducted a series of tests and comparisons to examine the inversion stability and accuracy. The ambient seismic noise data of 5 different days produced stable H/V spectral ratios. The inverted shear-wave velocity model from the H/V spectral ratios presented a small velocity variation depending on the data set (standard deviation of $\sim$3.7% in the inverted velocities), supporting the stability of inversion. Synthetic tests of H/V analysis presented that H/V analysis in a frequency band of 1–20 Hz is effective for the shallow subsurface structure inversion. The representative relationship between SPT N values and shear-wave velocities could be confirmed through a bootstrap analysis.

The $V_{S30}$ model was verified by comparison with local in situ measurements in two local regions of the Korean Peninsula. The inverted models are high correlated with in-situ measurements. Further, the lateral $V_{S30}$ distribution in this study is comparable with the USGS $V_{S30}$ model that is calculated by a topography-based approach. We compared the $V_{S30}$ distribution between the Korean Peninsula and the eastern US, both of which are situated atop Precambrian basement. We found that the $V_{S30}$ distribution in the Korean Peninsula is similar to that in the east-
ern US. This observation suggests that the geological composition is an important factor in the $V_{30}$ distribution. These tests and comparisons confirm the validity and accuracy of results.

The $V_{30}$ model presents characteristic features. Regions of high topography (high standing areas) present larger $V_{30}$ values since the regions generally correspond to older exhumed dense terrains. On the other hand, regions of low topography (low standing areas) show smaller $V_{30}$ values since they are mostly infilled with younger less consolidated sediments. That is, the $V_{30}$ values are low in coastal regions and high in inland mountainous regions, varying between 98 and 994 m/s in the Korean Peninsula. The $V_{30}$ values present an apparent linear relationship with surface elevations. The general features of the lateral variation in the $V_{30}$ model are consistent with the features reported in other studies (McNamara et al., 2015; Worden et al., 2015). The low $V_{30}$ values in coastal regions suggest high seismic damage potentials. The western and southeastern coastlines of the peninsula may be vulnerable to strong seismic shaking.

Figure 20. Comparison between the $V_{30}$ values from this study and in situ measurements (Kim et al., 2002; Sun et al., 2007) for 28 sites in (a) Gyeongju and (b) 16 sites in Hongseong. Spatial distribution of $V_{30}$ values in the (c) Gyeongju region and (d) Hongseong region. Surface topography is presented on the maps. The $V_{30}$ values are similar between this study and in situ measurements.
Data Availability Statement

The data sets and results of this study are available on Dryad (https://doi.org/10.5061/dryad.05qftf44).

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