Physical Modelling in Geotechnics

Characterization of V_S profile at seismic observatory stations using HVSR

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ABSTRACT: Shear wave velocity (V_S) is a fundamental property of soil representing its stiffness and dynamic characteristics. Hence, the V_S profile of soil layers is used as key parameters to model the wave propagation of a seismic motion from bedrock to surface. This paper shows characterization of V_S profiles for national seismic observatory stations in South Korea with recorded ambient vibrations using the horizontal-to-vertical spectral ratio (HVSR) technique. Inversion of an empirical HVSR to a V_S profile using the diffusion theory and forward analysis to get HVSR from V_S profile were conducted in this study. For six national seismic stations, HVSR from ambient vibrations were calculated, and measured V_S profiles using the down-hole method were collected. We found that the inverted V_S profiles were similar to the measured V_S profile when the information of concrete pad on which the sensor is sat was considered during inversion process.

Keywords: HVSR, ambient vibration, V_S profile, concrete pad.

1 INTRODUCTION

Shear wave velocity (V_S) is a ground fundamental property which is a main factor for anticipating dynamic response of ground layers against seismic loading. With V_S profiles, ground motion records observed in seismic observatory stations can be used to empirically analyse the site amplifications of ground motions. Hence, the intensities and frequency contents of ground motions at surface can be anticipated if the site V_S profile is known.

A V_S profile can be measured invasively or non-invasively. Invasive methods include down-hole, cross-hole, and suspension PS logging tests which make a bore hole by drilling the ground and measure the V_S at each layer (e.g., Garofalo et al., 2016). Non-invasive methods include active and passive surface wave methods (e.g., SASW, MASW, f-k, SPAC, HVSR) which measure active or passive surface waves at the surface and predict V_S profiles by inverting the dispersion curve of waveforms (e.g., Foti et al., 2018). Both invasive and non-invasive methods have pros and cons. Invasive methods provide more direct V_S values at each layer, but the boring cost and accessibility of boring machine to a site limit the test execution. Moreover, disturbance of soil nearby boring hole has a possibility altering measured V_S value from the in-situ condition (Moss, 2008). Non-invasive methods are less expansive and almost no limitation to perform. However, there is no unique solution so that the inversion results highly depend on the parameter set-up. Also, the test results can be varied by near-field wave sources so that experts are needed when perform data acquisition and process (Foti et al., 2018).

This study validated one of non-invasive methods, single-station horizontal-to-vertical spectral ratio (HVSR). In this study, the HVSR using ambient vibrations recorded in national seismic observatory stations in South Korea operated by Korea Meteorological Administration (KMA) were calculated, and V_S profiles were collected which can be regarded as the ground truth of V_S profiles comparing to the profiles inverted from HVSR. The HVSR method only requires single-station surface records, so this method is easily applicable to any location. Also, since the seismic stations with sensors located at surface measure continuous waveforms, characterizing V_S profiles just needs data process without data acquisition.

In this study, we selected seismic stations for which V_S profiles are available and collected ambient vibrations. Then, we validated V_S profiles inverted from HVSR. We found that the concrete pad beneath the sensor has a major effect on HVSR, which should be considered during the inversion process. Seismic stations and ambient vibrations collected, calculation of HVSR, inversion process, and discussion of the results are followed.

2 SEISMIC STATION AND AMBIENT VIBRATION

2.1 Target seismic stations

Currently (January 2022), there are 262 national seismic stations operated by KMA. For a station, sensors can be categorized as four types in terms of sensor types and installation locations: 1) accelerometer at surface, 2) accelerometer within ground, 3) velocimeter at surface, and 4) velocimeter within ground. Because we use the HVSR method, target stations are those with surface sensors and V_S profiles which can be used for validation. The number of stations satisfying these selection criteria is 14. Among those, we selected stations with V_S profiles that include soft rock layers and stations showing a clear peak of HVSR. This condition is needed because when perform HVSR inversion process, the information of depth to the bedrock is critical for the inversion results, and no peak HVSR is needed in-depth analysis for V_S profile inversion, which is out-of-scope of this study. As a result, the total number of stations used in this study is 6, where the locations are shown in Fig. 1 and V_S profiles and geologic profiles are shown in Fig. 2.

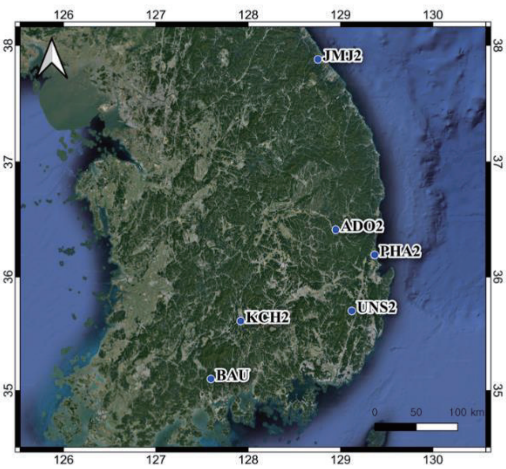

Fig. 1. Location of six seismic stations used in this study.

2.2 HVSR of ambient vibrations

The records of KMA seismic stations are distributed through a web portal, NECIS (KMA, 2022). NECIS provides records from earthquake events as well as continuous waveforms of a day. We collected ambient vibrations of the selected 6 stations (ADO2, BAU, JMJ2, KCH2, PHA2, USN2) for 10 days. For representative HVSR calculation for a site, we tried to select dates and times where ambient vibrations were not interrupted by earthquake or anthropogenic events. Dates with minimized influence of precipitation and wind speed were selected, and effects of temperature and humidity were averaged by selecting five days in summer and five days in winter. Time windows on weekends from midnight to 6 am were selected. For a day, 36 sets of HVSR using the 10 min time window were created and averaged for a day, and again averaged for 10 days.

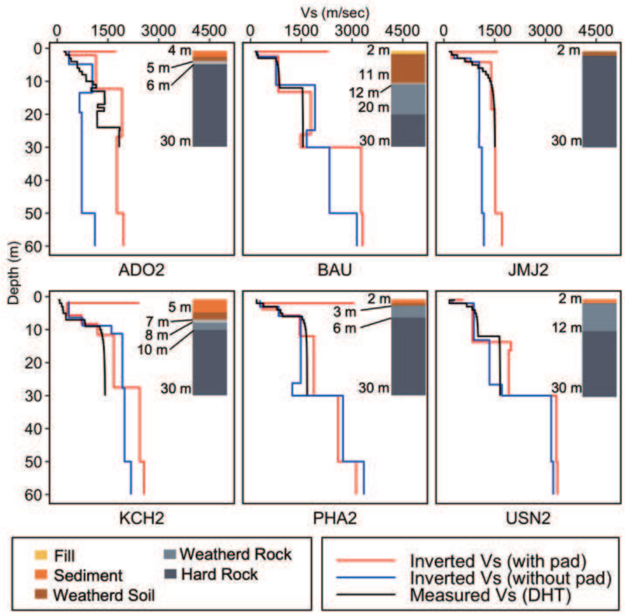

Fig. 2. V_S profiles of measured, inverted without concrete pad information, inverted with concrete pad information, and geologic profiles.

Figure 3 shows averaged HVSR for 6 stations using the selected ambient vibrations. For HVSR process, we used a Python package HVSRPY (Vantassel, 2020) that filters irregular records automatically. Since we selected time windows where human activity was minimized and sensors at seismic stations were very stable, the uncertainty of HVSR was small for the entire range of frequencies (standard deviation = 0.06 – 0.81).

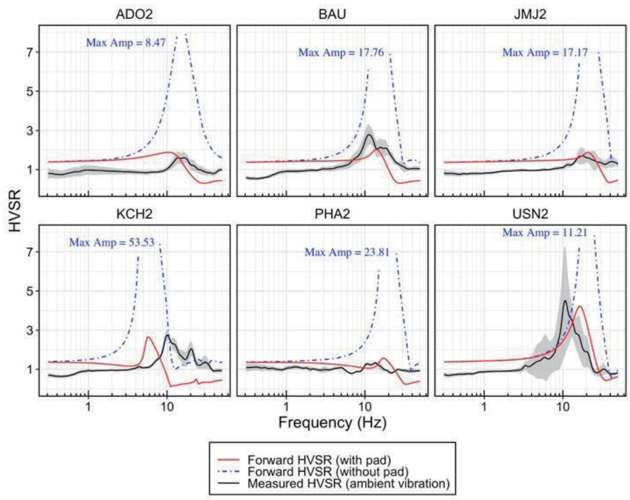

Fig. 3. Measured HVSR, forwarded HVSR with concrete pad, forwarded HVSR without concrete pad property at six KMA seismic stations. Mean of measured HVSR is a black solid line and ±1σ range is shown as a gray shade.

3 INVERSION OF HVSR

A V_S profile can be inverted from a HVSR using the

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diffusion theory (Piña-Flores et al., 2017). García-Jerez et al. (2016) provide a computer code for forward calculation and inversion of HVSR (named HV-inv). The HVSR inversion module using the Rayleigh ellipticity also can be found in the Geopsy package (Wathelet et al., 2020). In this study, we used the HV-inv as the inversion tool.

Since there is no unique solution in the inversion process, the HVSR inversion results highly depend on the pre-parameter setup. Parameters, which are ground layer information, include depth, P-wave velocity (V_P), V_S, density (ρ), and Poisson's ratio (ν). If a boring log is available, the range of above parameters can be assumed. In this study, we collected boring logs and V_S profiles so that the proper layer information can be applied to the inversion process.

The KMA surface sensors at seismic stations are located on top of shallow concrete pads (Fig. 4). However, the V_S profile does not consider the concrete pad part. Due to the concrete pad, there is a possibility that the high frequency content of ground motion would be damped out so that the ground motion recorded at the sensor would be different relative to the sensor located on bare ground. This would affect to the HVSR result as well.

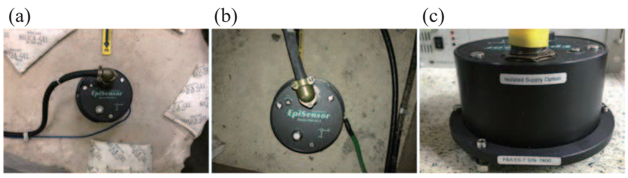

Fig. 4. Examples of surface sensors located on the shallow concrete pad at seismic stations: (a) ADO2, (b) PHA2, (c) USN2.

3.1 Forward estimation of HVSR

To check the effect of pad, we first performed the forward estimation of HVSR with and without pad information using V_S profiles and compared with measured HVSR. Forward estimation of HVSR means calculation of the theoretical HVSR from V_S, V_P, thickness, ν, and ρ profiles (García-Jerez et al., 2016). The ρ and V_P has a great effect on the amplitude of HVSR (Zaenudin and Yogi., 2021), so that information is essential when amplitudes are analyzed. Figure 3 shows forward HVSRs (theoretical HVSR) from V_S profiles with and without consideration of 1 m concrete pad and measured HVSR. The concrete pad property was set as V_S=3,000 m/s and ρ=3000 kg/m^3. As shown in Fig. 3, the forward HVSR without the pad property shows very high amplitude at the peak frequency at all stations, while the forward HVSR with the pad property shows comparative amplitude with the measured HVSR. Both forward HVSRs have higher amplitude at low frequencies than the measured HVSR, which might be attributed to that the deeper layer effect was not captured in the forward HVSR because we used V_S profiles down to 30 m depth. This result indicates that the crust effect needs to be considered for HVSR if the sensor is located on top of the solid crust.

3.2 Predicted V_S profile from inversion of HVSR

The inversion process from measured HVSR to the V_S profiles needs a pre-parameter set-up. To check the difference of inverted V_S profiles between pad information and no pad information when setting the parameters before inversion, we allocated low V_S and density ranges for the 1st case, and wide V_S and high density ranges for the 2nd case. Examples of parameter set-up for a station JMJ2 at each case are shown in Table 1 and 2. For V_S ranges deeper than 2 m, we set values based on the measured V_S profiles and set the ranges of V_P, ρ, and ν as equivalent.

Table 1. Example parameter set-up for inversion analysis without consideration of pad information (1st case for JMJ2).

Depth (min, max)	Vp (min, max)	Vs (min, max)	ρ (min, max)	ν (min, max)
1, 2	400, 6000	200, 300	2000, 2500	0.25, 0.4
3, 3	400, 6000	200, 300	2000, 2500	0.25, 0.4
4, 5	400, 6000	600, 900	2000, 2500	0.25, 0.4
6, 30	400, 6000	1000, 1800	2000, 2500	0.25, 0.4
30, 50	400, 6000	1000, 1800	2000, 2500	0.25, 0.4
0, 0	400, 6000	200, 3400	2000, 2500	0.25, 0.4

Table 2. Example parameter set-up for inversion analysis with consideration of pad information (2nd case for JMJ2).

Depth (min, max)	Vp (min, max)	Vs (min, max)	ρ (min, max)	ν (min, max)
1, 2	400, 6000	200, 2500	3000, 3000	0.25, 0.4
3, 3	400, 6000	200, 300	2000, 2500	0.25, 0.4
4, 5	400, 6000	600, 900	2000, 2500	0.25, 0.4
6, 30	400, 6000	1000, 1800	2000, 2500	0.25, 0.4
30, 50	400, 6000	1000, 1800	2000, 2500	0.25, 0.4
0, 0	400, 6000	200, 3400	2000, 2500	0.25, 0.4

Figure 5 shows theoretical HVSR that best-fitted to the measured HVSR using the ranges of parameters set-up before inversion. The fitted HVSR without consideration of pad property (Table 1) resulted in the higher amplitude than one of the measured HVSR except a station USN2 case. On the other hand, the fitted HVSR with pad property (Table 2) showed comparative amplitude to the measured HVSR at all six stations. This amplitude difference affected to the inverted V_S profiles. Figure 2 shows V_S profiles measured, inverted without pad information (1st case), and inverted with pad information (2nd case). For ADO2, the inverted VS at bedrock layer (~ 30 m) for the 2nd case is closer to the measured VS than the 1st case. For JMJ2, two cases are in good accordance with the measured Vs down to 5 m depth, but for depth deeper than 5 m, only the 2nd case follows well the measured VS profile. For USN2, which has comparative amplitude of the best-fitted HVSR (Fig. 5), inverted VS profiles with and without pad information are not different much. For BAU, KCH2, and PHA2, there are not much differences between 1st case and 2nd case down to 30 m depth where measured VS profile is available even though the best-fitted HVSRs are different.

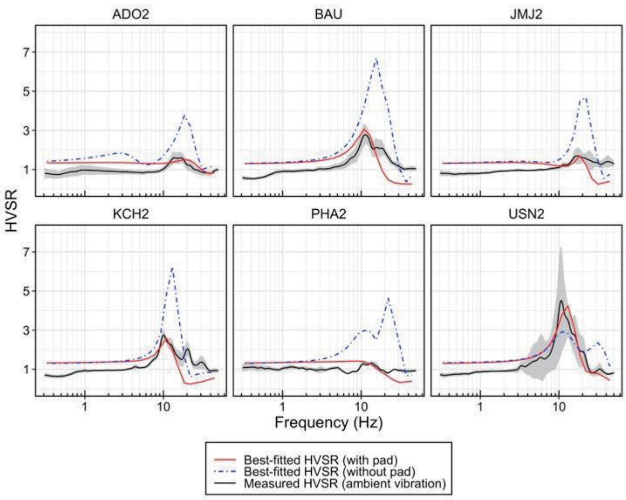

Fig. 5. HVSR of ambient vibrations at six KMA seismic stations.

4 CONCLUSION

This study validated the HVSR inversion method predicting V_S profiles using KMA seismic station records where measured V_S profiles from down-hole method are available. Forward HVSRs from measured V_S profiles were calculated, and inverted V_S profiles from measured HVSR were also estimated. During the forward and inversion processes, we used two cases of information: one without concrete pad property (1st case) and the other with concrete pad property (2nd case). From this study we found following conclusions:

1) The inverted V_S profile from HVSR is sensitive to the parameter set-up;
2) HVSR from records where the sensor is sat on a concrete mass can have lower amplitude than the case where the sensor is sat on the ground;
3) Consideration of concrete pad information for the inversion process results in the better VS profiles.

This indicates that when analyze the HVSR of seismic stations, the sensor installation environment should be considered at least if HVSR is used for VS profile inversion. The effect of the environment to the seismic records will be the promising topic for the future study.

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