



Site Characterization using Harmonic Wavelet Analysis of Wave (HWAW) Method

Hyung-Choon Park^{*1}, Dong-Soo Kim², Jong-Tae Kim³, Eun-Seok Bang¹, Jong-Ku Yoon¹

¹Chungnam National University

³Graduate Student, Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology

E-mail: civilman@cnu.ac.kr

Summary

To obtain a shear-wave velocity profile in geotechnical practice, various seismic investigation methods are being frequently used. In this paper, new site characterization method using harmonic wavelet analysis of wave (HWAW) method which is based on time frequency analysis was proposed. Field testing of this method is non-intrusive, and relatively simple and fast, and uses the signal portion of the maximum local signal/noise ratio to evaluate the phase velocity to minimize the effects of noise, and uses single array inversion which considers receiver locations. In order to estimate the applicability of HWAW method, field tests were performed at 2 sites. One is for evaluating accuracy of test method and the other is for estimating the applicability of 2-D imaging by HWAW method. Through field applications and comparison with other test results, the good accuracy and applicability of the proposed method were verified.

Introduction

The evaluation of shear modulus (or shear wave velocity) profile of the site is very important in the various fields of geotechnical engineering. To obtain shear wave velocity profile, various in-situ seismic methods using surface waves have been developed (Nazarian and Stokoe 1984, Gabriels et. Al 1987, McMechan and Yedlin 1981). These surface wave based in-situ seismic methods have their own strength and weakness.

Recently, two-dimensional (or three-dimensional) imaging of Vs profile becomes more important in Korea because of the large horizontal variation of soil stiffness. Even though many researchers have intensively investigated on 2D imaging of rock stiffness variation using tomography technique, there are relatively poor efforts to obtain a reliable 2D imaging on soil stiffness itself. Moreover, the conventional surface wave testing techniques have weaknesses to determine the detailed 2D imaging of subsurface stiffness variation because they usually provide the average Vs profile of the site by applying a long receiver spacing.

In this study, new seismic site characterization method using the harmonic wavelet analysis of wave (HWAW) was proposed to overcome some of weaknesses in the existing surface wave based seismic site characterization methods. HWAW method is based on time-frequency analysis using harmonic wavelet transform. The

seismic site characterization method using HWAW method consists of three steps: field testing, evaluation of dispersion curve, and determination of V_s profile by single array inversion process. The field testing of this method is relatively simple and fast because one experimental setup which consists of one pair of receivers is needed to determine the dispersion curve of the whole depth of interest using a short receiver spacing setup which is not contaminated by lateral variation. The proposed method uses the near field information and can sample much deeper part of the site than the conventional phase unwrapping method. Moreover, HWAW method mainly uses the signal portion of the maximum local signal/noise ratio to evaluate the phase velocity in order to minimize the effect of noise. This method uses single array inversion which considers the variation of phase velocity with receiver location without increase of calculation time and complexities because the whole dispersion curve is determined from one experimental setup. These characteristics show the good potential of applicability of HWAW method for 2-D stiffness imaging.

In this paper, the harmonic wavelet transform and the procedure of proposed method are briefly described. Then, to estimate the applicability of the proposed method, field tests were performed in the 2 sites. In site 1, the shear wave velocity profiles obtained by HWAW method were compared with those by conventional SASW test and PS-suspension logging test to verify accuracy of method. In site 2, 2D shear wave velocity map determined by HWAW method is compared with results of boring, SASW, Down-hole method.

HWAW method

Determination of Dispersion Curve

Wavelet analysis is fundamentally one of the correlation method (Newland 1999). Wavelet coefficient, $a(t)$, provides information about the structure of input signal, $s(t)$, and its relationship to the shape of the analyzing wavelet, $w(t)$. The wavelet coefficient $a(t)$ is defined by the correlation equation as follow;

$$a(t) s(t') = \int_{-\infty}^{\infty} w^*(t' - t) dt' \quad (1)$$

$w^*(t)$ is complex conjugate of $w(t)$. When $s(t')$ correlates well with $w^*(t' - t)$, $a(t)$ will be large, but when they do not correlate, $a(t)$ will be small. Any wave shape can be used for wavelet if it is localized at a particular time. Harmonic wavelet is represented as follow;

In the frequency domain :

$$W_{m,n}(\omega) = \frac{1}{(n-m)2\pi} \quad \text{for } m2\pi \leq \omega < n2\pi = 0 \quad (2)$$

elsewhere

In the time domain :

$$w_{m,n}(t) = \frac{e^{j\omega_1 t} - e^{j\omega_2 t}}{j(\omega_1 - \omega_2)} \quad (3)$$

where $j = \sqrt{-1}$. The harmonic wavelet is localized and has a harmonic characteristic in time domain. Harmonic wavelet coefficient, $a_{m,n}(t)$ which is defined by $W_{m,n}(\omega)$ can be represented as follow (Park and Kim 2001);

$$a_{m,n}(t) = s_f(t) + jH[s_f(t)] = x(t)e^{j\theta_{m,n}(t)} \quad (4)$$

where $s_f(t)$ is the output signal of ideal bandpass filtering operation where the magnitude of filter is $\frac{1}{2}W_{m,n}(\omega)$ and its bandpass is $m2\pi \leq \omega < n2\pi$; H represents Hilbert transform; $x(t)$ is magnitude of $a_{m,n}(t)$; $\theta_{m,n}(t)$ is phase of $a_{m,n}(t)$. From Eq. (4), it can be noticed that the real part of $a_{m,n}(t)$ is output signal of bandpass filtering operation and the imaginary part of is Hilbert transform of the real part of, namely, is the analytic signal or Gabor's complex signal corresponding to. The harmonic wavelet transform functions as ideal band pass filter so that the harmonic wavelet coefficient, $a_{m,n}(t)$, for wavelet in the frequency band $m2\pi$

$\leq \omega < n2\pi$ contains information only in the selective frequency band $(m2\pi, n2\pi)$.

When the signal passes through medium between receivers 1 and 2, the real part of $a_{m,n}^1(t)$ and $a_{m,n}^2(t)$ are $s_f^1(t) = y(t - t_g^1) \cos[(m+n)\pi(t - t_{ph}^1)]$ and $s_f^2(t) = y(t - t_g^2) \cos[(m+n)\pi(t - t_{ph}^2)]$, respectively, where the upper index indicates number of receiver. If the bandwidth of $W_{m,n}(\omega)$, $(n-m)2\pi$, is sufficiently narrow, then group delay t_g and phase delay t_{ph} have sensible meaning, and the envelop and phase of $s_f^1(t)$ and $s_f^2(t)$ are obtained from magnitude and phase of $a_{m,n}^1(t)$ and $a_{m,n}^2(t)$. The group and phase delays at receiver 1 and 2 are obtained from the magnitude and phase information of $a_{m,n}^1(t)$ and $a_{m,n}^2(t)$, and then the group and phase velocities are obtained from these delays. The procedure to determine the group and phase velocities at frequency $(m+n)\pi$, where $(m+n)\pi$ is the center frequency of $W_{m,n}(\omega)$, is as follow (Park and Kim 2001);

- 1) Compute harmonic wavelet transform of signals obtained at receiver 1 and receiver 2.(Fig. 1)
- 2) Determine phase and group delays at frequency $(m+n)\pi$, which is the center frequency of arbitrary harmonic wavelet $W_{m,n}(\omega)$.
 - a) the group delays at receiver 1 and 2 which are t_g^1 and t_g^2 are obtained. The group delay is a time corresponding to the maximum of magnitude of $a_{m,n}^1$ and $a_{m,n}^2$. (Fig. 2(a), (b))
 - b) From phase information of $a_{m,n}^1$, θ_1 is taken as a phase corresponding to t_g^1 . (Fig. 2(c))
 - c) The t_L and t_R are obtained from phase information of $a_{m,n}^2$. The t_L is the time corresponding to θ_1 which is the most close to t_g^2 on the left side of

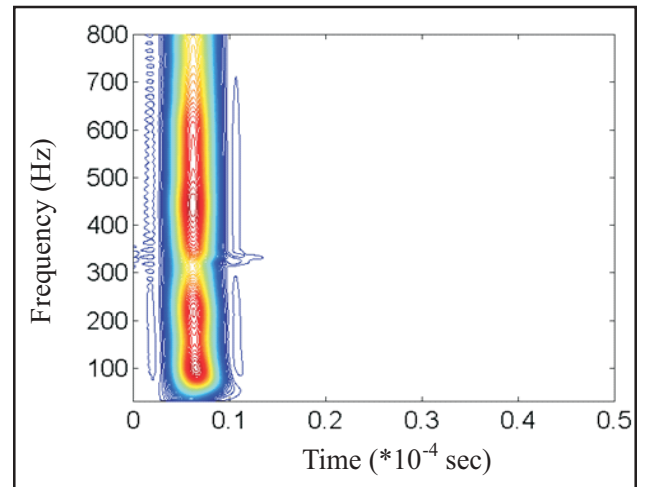


Fig. 1: Harmonic wavelet time-frequency map

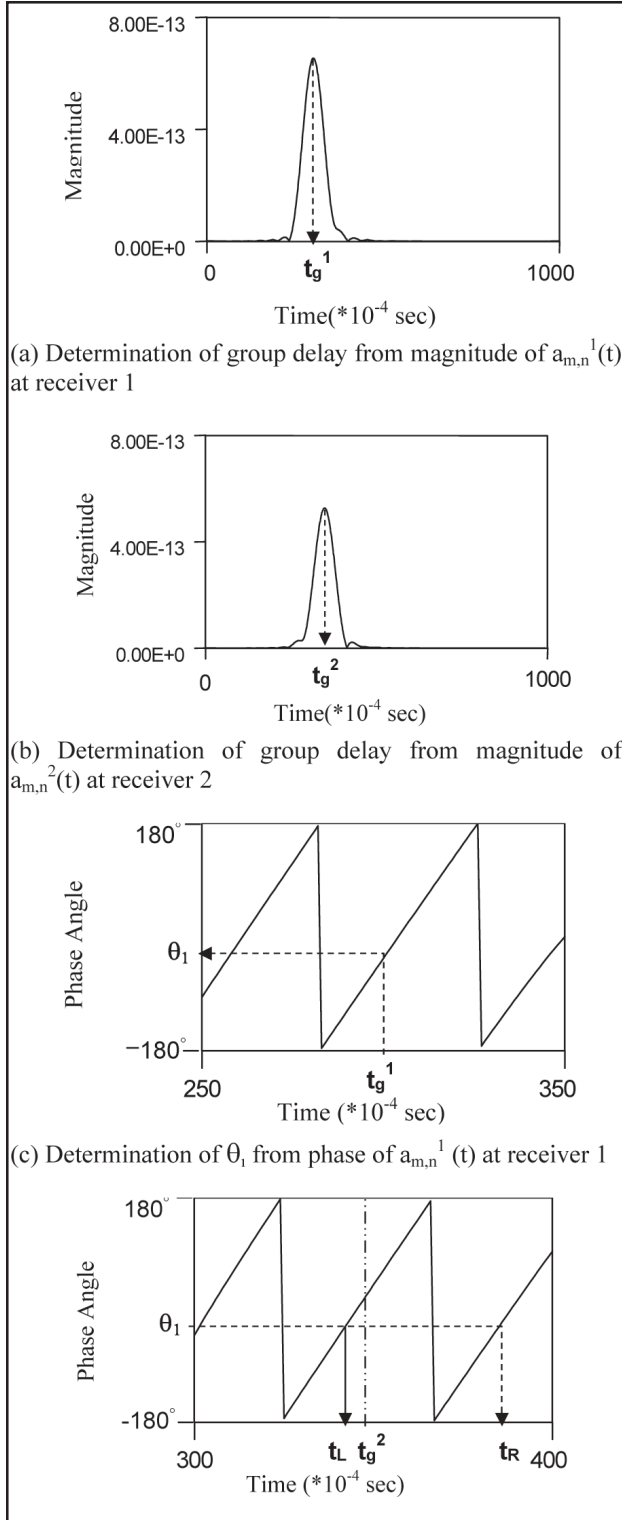


Fig. 2: Determination of the group and phase delays at frequency $(n+m)\pi$

t_g^2 and t_R is the time corresponding to θ_1 which is the most close to t_g^2 on the right side of t_g^2 . (Fig. 2(d))

- d) t_{ph}^1 is defined as t_g^1 and t_{ph}^2 is either t_L or t_R depending upon which is closer to t_g^2 . (Fig. 2(d))
- 3) To determine the phase and group delays at whole frequencies, the procedure 2) has to be repeated for all harmonic wavelet coefficients. (Fig. 3)
- 4) If the distance between receiver 1 and receiver 2 is D , then the group velocity V_{gr} and the phase velocity V_{ph} at each frequency are obtained as follow;

$$V_{ph} = \frac{D}{t_{ph}^2 - t_{ph}^1} \quad (5)$$

In order that the above mentioned procedure 2-d) is valid, the relative distortion of shape of wave groups at receiver 1 and 2 at each frequency should be within some limit. The period normalized time difference factor (Δt_T) which is a period normalized time difference between group delay times and phase delay time can be defined as follow:

$$\Delta t_T(f) = \frac{1}{V_g(f)} \cdot \frac{dV_{ph}(f)}{d\lambda} \cdot D \quad (6)$$

Where λ is a wave length. The relative distortion of the shape of wave group at receiver 1 and 2 can be determined by the period normalized time difference factor (Δt_T). The bigger Δt_T means the more distortion of shape of wave group at receiver 1 and 2. The limit value of Δt_T for procedure 2-d) is 0.5. If Δt_T is bigger than 0.5, then the phase delay time at receiver 2 corresponding to real

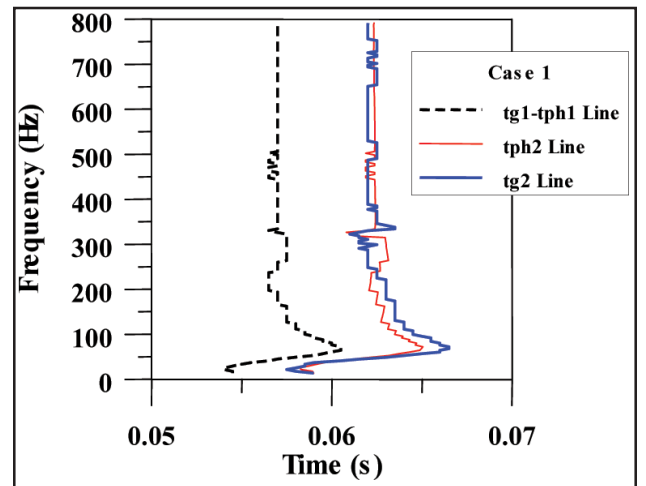


Fig. 3. Phase and group delay in time-frequency domain

phase velocity can move systematically from t_{ph}^2 calculated by the procedure 2-d). That is, if Δt_T is $N-0.5 < \Delta t_T < N+0.5$ where N is integer, then the phase delay time at receiver 2 corresponding to real phase velocity is exactly located (period) $\times N$ apart from t_{ph}^2 calculated by the procedure 2-d). Therefore, even though the relative distortion of shape of wave group is severe at certain frequency and Δt_T is over 0.5, t_{ph}^2 corresponding to the correct phase velocity can be determined from t_{ph}^2 of procedure 2-d). The procedure to determine the correct t_{ph}^2 from t_{ph}^2 of procedure 2-d) is called as data recovery process. The procedure obtaining the group and phase velocity in HAW method consists of preliminary calculation and data recovery process. The proposed method is so straightforward that it has possibility of the potential of automation in the calculations of experimental dispersion curves.

For non-stationary signals typically generated by impact source, the signal amplitude varies with time. In the conventional phase unwrapping method using Fourier transform, the signal to noise (S/N) ratio is measured at each frequency in the average sense. In the proposed method using time-frequency analysis, however, only information around t_g , where the signal energy is dominant, is utilized to evaluate the phase velocity at each frequency and the local S/N ratio around t_g is much greater than that in the average sense. This means that the proposed method is less affected by noise.

Test Setup, Inversion and 2D imaging

For the site characterization, HAW method can use two test setups; short receiver spacing setup and conventional test setup (Fig. 4). In the short receiver spacing setup, source-receiver spacing (R) is 6~12m and receiver spacing (D) is 1~3m. In the conventional test setup, source-receiver spacing is over 10m and receiver spacing is same as source-receiver spacing. The proposed method also uses near field information to determine dispersion curve of whole depth from single test setup. It has been found that the near field dispersion curve includes long wave length component enough to explore deep layer and is more sensitive to deep layer material properties than far field dispersion curve (Park and Kim 2001). The dispersion curve determined by HAW method and the theoretical dispersion curve using in the inversion process reflect the near field effect in the same way. Therefore, the near field dispersion curve can be used to evaluate deep soil profile. In general, for phase unwrapping method, average signal to noise (S/N) ratio is too low in the near field to determine the correct phase velocities. HAW method can determine the correct

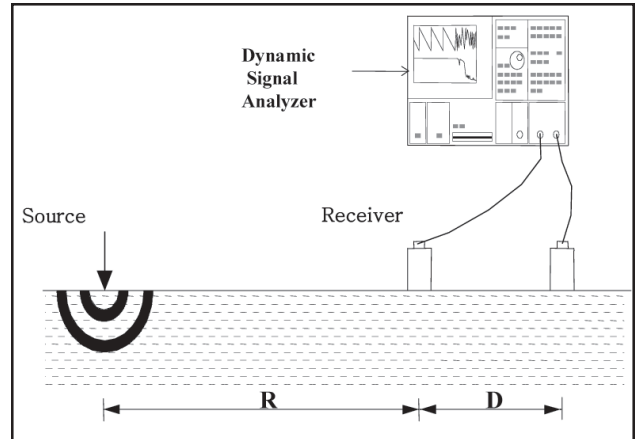


Fig.4: HAW testing setup

phase velocities in the near field because the HAW method uses local information where signal energy is dominant. The phase velocities vary with receiver location, so test setup has to be considered for the inversion process. In the proposed method, the signal array inversion in which the theoretical dispersion curve is generated at receiver locations same as field test setup, is used to determine the shear wave velocity profile. Because the proposed method uses just one test setup in the field, the single array inversion can be possible without increasing calculation time and complexity. If the proposed method uses short receiver spacing setup, the proposed method can minimize the possibilities of error due to lateral non-homogeneity and can obtain reasonable 2D imaging on soil stiffness by obtaining detailed local soil profile along lateral direction through series of tests. By performing series of tests along testing direction, 2-D subsurface stiffness imaging can be obtained by interpolating all local Vs profiles of interested region. Even though this is not a tomography but a simple interpolation job, this simple interpolation can provide detailed 2-D stiffness contour because receiver spacing is close enough. The overall flowchart of 2-D Vs imaging in the HAW method is described in Fig. 5.

Field application

Site-1

First, the proposed method was applied in the field to verify accuracy of method. The short receiver spacing setup ($R_1=12.9m$, $R_2=14.7m$) and conventional test setup ($R_1=24m$, $R_2=48m$) were used to determine dispersion curves and the single array inversion was used to evaluate soil profile. The soil profiles by the proposed method were

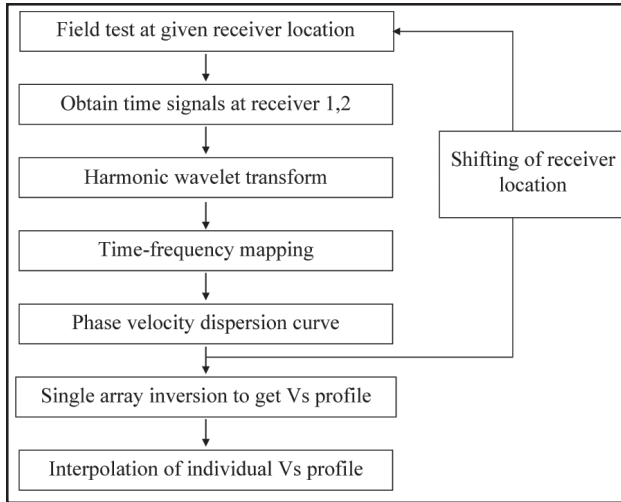


Fig.5 :The flowchart of 2D-HWAW method

compared with those by SASW and PS-suspension logging tests.

Fig. 6 shows the comparison of shear wave velocity profiles determined by the proposed method using short receiver spacing setup, SASW test, and PS-suspension logging test. The result of PS-suspension logging test represent local characteristic of site. In the Fig. 6, V_s profile by SASW test shows a little difference with those by the other methods. This difference can be due to the lateral non-

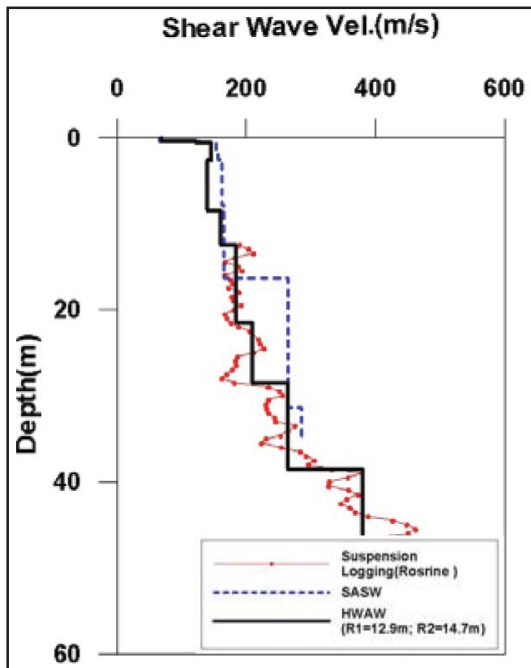


Fig.6: Comparisons of V_s profiles determined by short receiver spacing HWAW, SASW, and PS-suspension logging tests

homogeneity of the site. In the SASW test, a long test line is needed to explore deep layer and SASW test determine the soil profile between receivers in the average sense when lateral non-homogeneity exists. However, HWAW method uses just short receiver spacing setup to determine dispersion curve of whole depth of interest. The short receiver spacing setup having receiver spacing of 1~3m can minimize the effect of lateral non-homogeneity and it has potentials to determine the detailed local V_s profile along the lateral direction such as two dimensional V_s map of the site.

Fig. 7a) shows the phase spectrum of wave signals recorded in the conventional test setup where receiver locations are 24m and 48m from impact source. Frequency range under 5Hz corresponding to wave length over 40m in this case is very important to explore the deep layer. However, as shown in the figure, in the region under 5Hz, signal quality is too low to determine phase velocities by phase unwrapping method because of the characteristic of impact source.

Fig. 7b) shows dispersion curve determined by HWAW method using conventional test setup where receiver locations are 24m and 48m from impact source. It can be noticed that HWAW method can determine reasonable dispersion curve over all frequency range including the range under 5Hz, even though signals have low average signal to noise ratio, because so HWAW method use local information with maximum local signal to noise ratio that the effect of noise can be minimized.

Fig. 8 shows comparison of V_s profiles determined by HWAW methods using short receiver spacing and long receiver spacing setup and SASW test. V_s profiles show a little difference at depths of about 20m. These differences between soil profiles may be explained by the variation of phase velocities with receiver locations and lateral non-homogeneity of the site. Single array inversion was used for the proposed method. If site has no lateral non-homogeneity, V_s profiles determined by the proposed HWAW methods using short and long receiver spacing setups would be same. At this site, however, HWAW methods using different test setups are different each other, explaining that this site has some lateral non-homogeneity. It is also interesting to notice that V_s profile determined by HWAW method with long test setup is more similar to that by conventional SASW test and the longer the receiver spacing the more averaging the lateral non-homogeneity of the site. So, to evaluate detailed local properties of ground and 2-D stiffness image, it is recommended to use short receiver spacing setup.

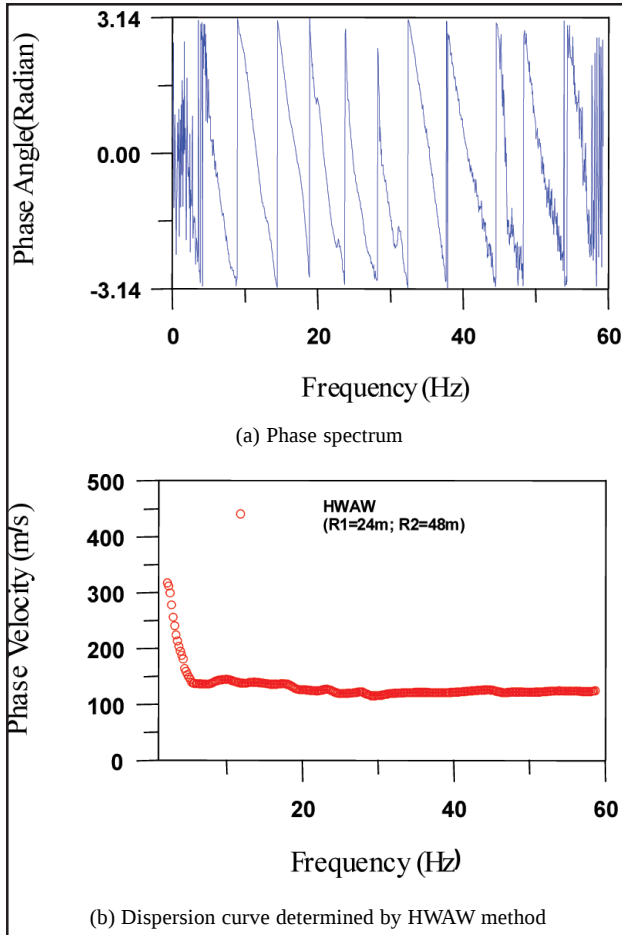


Fig. 7: Phase spectrum and dispersion curve determined by HWA method

Site-2

The next test site is the Seohae Great Bridge site in Pyungtaek where field tests such as Down-hole, SASW and HWA were performed to evaluate applicability of 2-D imaging by HWA method. Among the intermediate-spaces between two separate piers, space between P-27 and P-28 was selected as main target site for overall comparison. Before the formal field test, several borings were performed to investigate the subsurface geometry. Then, Down-hole, SASW and HWA tests were performed. Total three borings were performed at BH-1, BH-2 and BH-3 indicated in Fig. 9 which shows the boring results. It is obvious that soil layers are not horizontally uniform from Fig. 9. Ground water level is about 4m depth, and the depth of weathered rock varied dramatically from 12m depth to 16.5m. Above weathered rock layer, there exist 2 layers of fill soil and weathered soil. Soft rock layer is located below the weathered rock layer. Initially, HWA test and SASW test

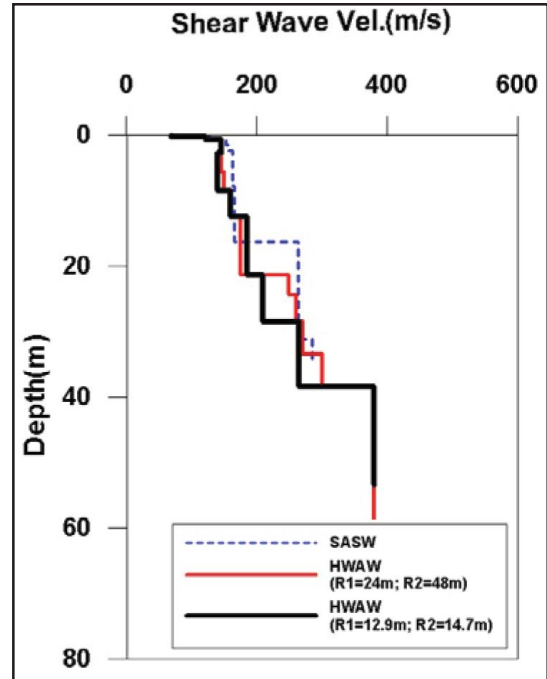


Fig. 8: Comparisons of Vs profiles determined by HWA methods using short and long spacing setup and conventional SASW test

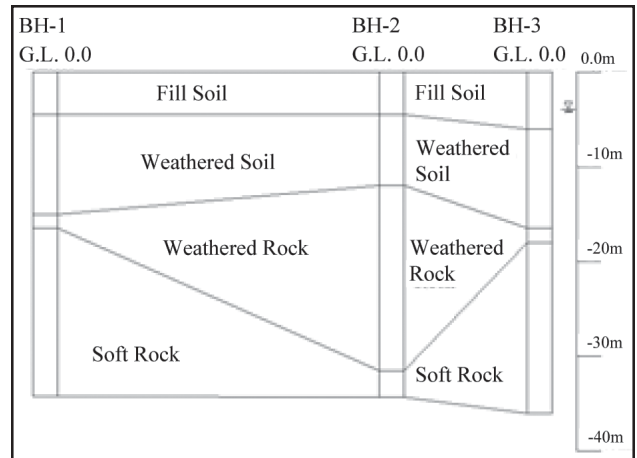


Fig. 9: The three boring investigation results

were performed along the straight line through BH-1, BH-2 and BH-3 boring holes. HWA test used two 1Hz vertical geophones as receiver and a hammer as impact source. Source to receiver spacing was 6m and receiver to receiver spacing was 2m. SASW test used conventional test setup. SASW test used two 1Hz vertical geophones as receiver, and sledge hammer and drop weight (30kg) as impact source and a back-hoe as continuous source. Source to receiver spacing and receiver to receiver spacing were same and broadened as 2m, 4m, 8m, 16m, 32m in sequence to explore deep layer properties. Then, the Down-hole test was carried



out at three bore-holes. Source was SH-wave generating impact hammer and receiver was 3-component receiver consists of three 4.5Hz vertical geophones.

Fig. 10 shows V_s profiles determined by HWA and down-hole test at BH-1 and BH-3, in sequence. And Fig. 11 shows V_s profiles determined by HWA, SASW, and down-hole tests at BH-2. In HWA test, source to receiver spacing was 6m and receiver to receiver spacing was 2m. Whereas, receiver spacing in SASW test was broadened to 32m as fixing center of two receivers at BH-2. Down-hole test was performed to about 30m depth. As shown in Figs. 10 and 11, three field tests derived V_s profiles up to 30m depth. Although there are some differences among three results, it can be said that three V_s profiles are similar over whole depth range. The differences between HWA and SASW method can be explained by the lateral stiffness variation of the site, differences in sampled region and inversion process. And V_s profiles determined by down-hole method are similar to results by surface wave method. Data reduction in down-hole test was performed using direct method. Through three comparisons, it can be verified that HWA can give a reliable V_s profile to the including deep depth (about 30m) properties with short receiver spacing setup, too

Then, HWA test was repeated shifting source and receiver setup parallel at space, and total 14 dispersion curves were evaluated. Single array inversion analysis was carried out for all the dispersion curves to obtain 14 V_s profiles as

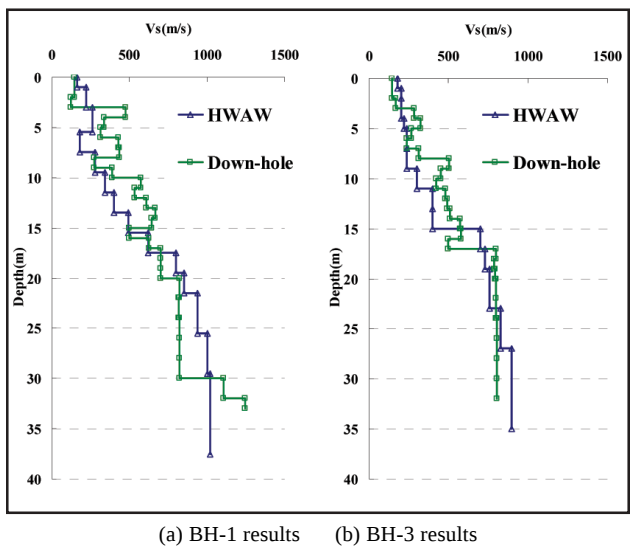


Fig.10: V_s profiles obtained by HWA and down-hole test at BH-1, BH-3

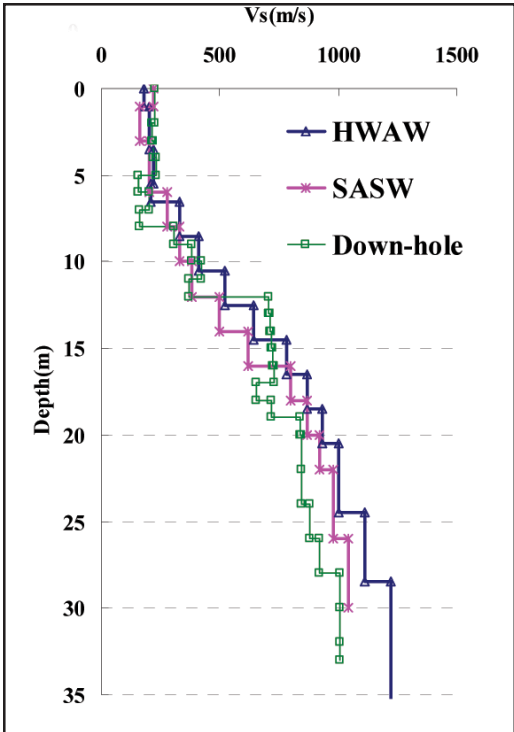


Fig.11: V_s profiles obtained by HWA, SASW and down-hole test at BH-2

shown in Fig. 12. Finally, the interpolation of each V_s profiles was performed to derive the 2-D V_s image as shown in Fig. 13. This 2-D V_s image was drawn to 30m depth and the horizontal width was 26m. Also, the V_s boundary was from 0

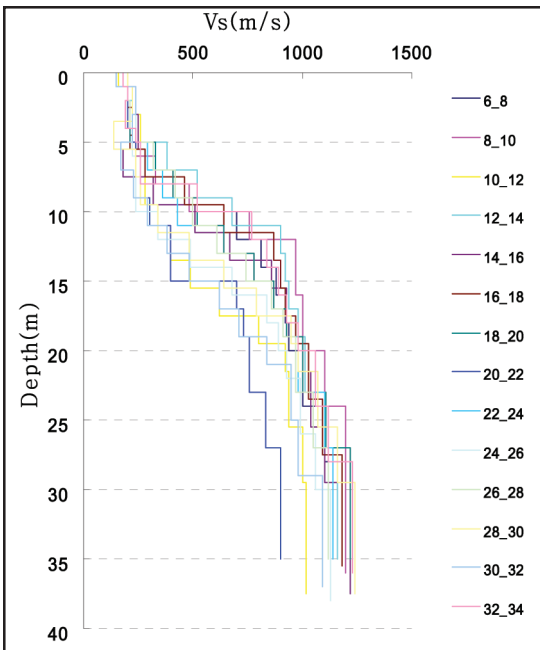


Fig. 12: Total 14 V_s profiles obtained by repetition of HWA test

to 1200m/s and image was contoured at every 200m/s, respectively. This 2-D V_s image shows the horizontal irregularity, and the boundaries of weathered soil and weathered rock assumed by the shear wave velocity contours of around 250m/s and 600m/s and boring profiles marked in Fig. 13, respectively, in the 2-D V_s image. Thus it is possible to distinguish boundaries of layer by wave velocities. Also, It can be insisted that assumed weathered soil and rock lines in the 2-D V_s image accord well with 2-D boring geology as shown in Fig. 9. Therefore, by comparing site geology determined by bore holes, the good applicability to develop 2D V_s profile using HWA method was verified.

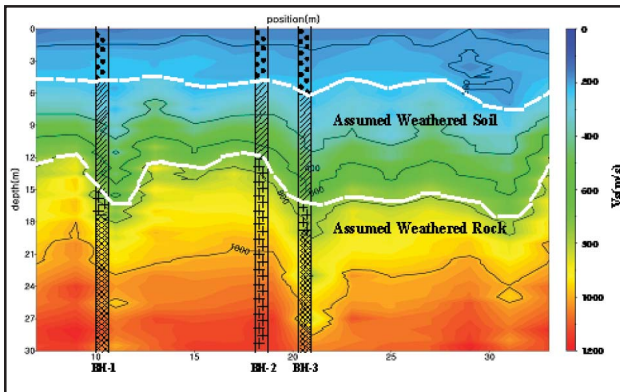


Fig. 13: 2-D V_s Image by HWA

Conclusions

In this study, the new seismic site characterization method using the harmonic wavelet analysis of wave (HWA) method and its application to the 2D shear wave velocity imaging were proposed. Field testing of this method is relatively simple and fast because one experimental setup which consists of one pair of receivers is needed to determine the dispersion curve of the whole depth. To

estimate the applicability of the proposed method, field tests were performed at 2 sites. In site 1, the shear wave velocity profiles obtained by the proposed method were compared with those by conventional SASW test and PS-suspension logging test and accuracy of HWA method was verified. In site 2, 2-D V_s map determined by HWA method is compared with results of boring, SASW, Down-hole test. Through field applications, the good applicability of the proposed method is verified.

Acknowledgments

This study is supported by fund of Construction Research and Development Program (04 construction kernel B01-04) contributed by Ministry of Construction and Transportation (MOCT) and committed by Korea Institute of Construction and Transportation Technology Evaluation and Planning (KICTTEP). All of them are gratefully acknowledged.

References

- Nazarian S, & Stokoe KH. 1984. In situ shear wave velocities from spectral analysis of surface wave. Proc. 8th Conf On Earthquake Eng. S.Francisco: 31-38.
- Gabriels P, Snider R, & Nolet G. 1987. In situ measurements of shear wave velocity in sediments with higher-mode Rayleigh waves. Geophysical Prospecting Vol 35: 187-196.
- George A. McMechan, & Mathew J. Yedlin. 1981. Analysis of dispersive waves by wave field transformation. Geophysics Vol 46 (No. 6): 869-874
- Newland DE. 1999. Ridge and phase identification in the frequency analysis of transient signal by harmonic wavelet. J Vib And Acoustics Vol 121: 149-155.
- Park HC, & Kim DS. 2001. Evaluation of the dispersive phase and group velocities using harmonic wavelet transform. NDT&E Int Vol 34: 457-467.