Thessaloniki-GREECE 2007

4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1395

ESTIMATION FOR S-WAVE VELOCITY PROFILE USING RAYLEIGH WAVE INDUCED BY THE STANDARD PENETRATION TEST

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ABSTRACT

Because the earthquake ground motion is affected by the underground structure strongly, various underground structure exploration methods are developed. In this paper, the author proposes an exploration method that use Rayleigh wave induced by a weight dropping of the standard penetration test (SPT). Such kind of exploration method is already developed, while the proposed method has several advantages. One of them is an uncertainty of the initial model for inversion problem disappears, using SPT result. In addition, one can do the method more handily than a PS-logging. In this paper, the author describes advantages in detail and shows actual test results. SPT induced ground motions were actually measured in Iwaki and Inakadate, Aomori Prefecture, Japan. At Iwaki site, using soil boring log and dispersion curve, two layers model having S-wave velocities of 128m/s and 411m/s is obtained. And at Inakadate site, three layers model having S-wave velocities of 80m/s, 90m/s and 220m/s is obtained.

Keywords: Phase velocity, microtremor, apparent phase wave, higher mode

INTRODUCTION

Because the earthquake ground motion is affected by the underground structure strongly, various exploration methods are developed and used. Recently, BSSC proposed to use an average S-wave velocity for the top of 30 meter (hereafter, Vs30) as an index to classify site conditions (BSSC, 1994). Exploration for S-wave profile becomes more important. In Japan, The Headquarters for Earthquake Research Promotion (HERP) of Japan published the national seismic hazard maps of Japan in March 2005 (Fujiwara et al., 2006). In the map, an amplification factor of peak ground velocity from bedrock to surface is determined by surface geological sediment. Exactly to say, empirical relation between the surface geological sediment and Vs30 is used to evaluate the site amplification factor (Fujimoto and Midorikawa, 2003). Unfortunately, we do not have enough S-wave profile or Vs30 data in Japan. The author thinks that it may be necessary to revise the amplification factor used in the map by the area. Exploring and compiling of S-wave profile is urgent issue to reduce an earthquake hazard.

Traditionally, S-wave velocity structure is determined by seismic measurement in boreholes. However, digging a borehole takes cost. Surface wave techniques can overcome this defect. These methods are unnecessary to dig a hole in the methods. The techniques are based on the inversion of surface wave dispersion data. Another advantage is that it samples large volume of soil. Recently, the methods are often used to estimate an S-wave velocity profile.

There are passive and active methods using surface waves. Passive methods use surface wave deduced from a microtremor using array observation. This method is widely studied in Japan (Horike, 1985; Tokimatsu, et al., 1992b; Okada, 2003). In active methods, surface waves are excited by weight drop,

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shaker, and so on. These methods include the famous method that is the spectral analysis of surface waves (SASW) (Stokoe, 1988). In this paper, the author proposes to use Rayleigh wave induced by the standard penetration test (hereafter, SPT) for exploring S-wave velocity profile.

Advantages of using SPT are listed as follows.
1) At least in Japan, the SPT is widely used to estimate a various engineering soil parameters. Judging from this fact, we have more opportunities to estimate S-wave velocity profiles if proposed method works well. This leads to earthquake disaster reduction of our country.
2) The SPT uses weight of 63.5kg. This is heavier than one that is used by usual weight dropping. A drop distance of the SPT is 760mm. This is longer than one that is used by usual test. These mean that higher energy is produced at the source and excited wave propagates to the distant location.
3) Repeated blows increase the signal to noise ratio.
4) Empirical formulae for relation between N-value and S-wave are proposed in previous studies. Through the SPT, soil profile is revealed. These two facts help to establish an initial model for inversion problem efficiently.
5) Shots with different depth induce different apparent phase velocities. This might be a clue to estimate S-wave velocity profile.

The proposed method is a kind of active method. The success of active methods may promise success of the proposed method. However, we should study characteristics of waves induced by SPT before practical use. In this paper, two case histories, one is Iwaki site and the other is Inakadate site are used to show characteristics of waves induced by the SPT

RECORDING SYSTEM

We use two 3-componet seismic sensors and three vertical component seismic sensors. We mainly focus on the vertical component. Adequate frequency range of all sensors is from 0.5Hz to 20Hz. It might be narrower to do this kind of study. Frequency range of sensor will be improved in the future. We arranged sensors linearly as displayed in Figure 1. Distances of d_0, d_1, and d_2 are changed by the case. At the point T, we placed 3-component sensor. An objective of the point T is to record ground motion those will be used as a trigger signal. We aimed to measure phase differences between two sensors those are placed at the point A and the point B. A separation of two sensors at both points is two meters at all sites.

All sensors are connected to a recorder with cable. All signals are recoded simultaneously with sampling frequency of 1000Hz. The AD resolution of the recorder is 14-bit and it has built-in amplifier. We recorded a series of blows of SPT in one record.

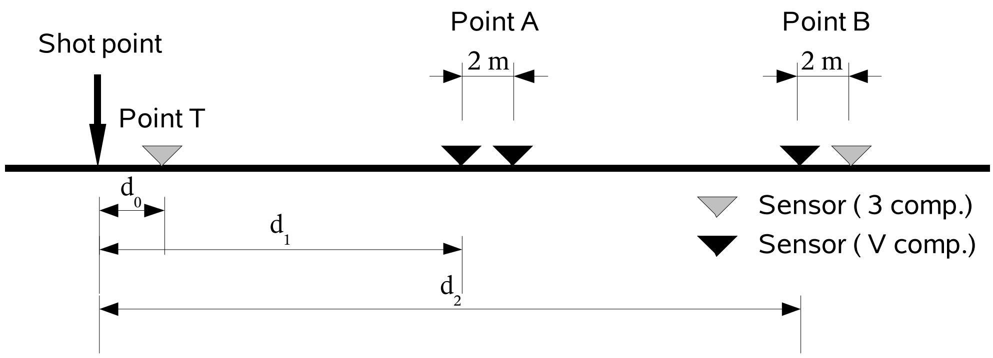

Figure 1. Sensor arrangement

IWAKI SITE

Geological condition

Iwaki site is located on the left bank of Iwaki River. The geomorphologic unit of the site is valley bottom lowland. Just above the site, valley is spread out. Soil boring log is shown in Figure 2. A soft surface layer with thickness of 3 meter covers hard sandy gravel

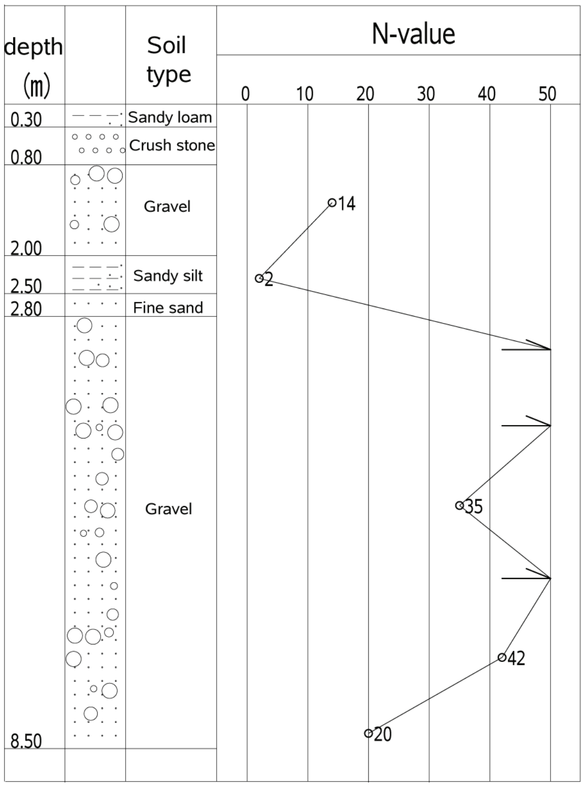

Figure 2. Soil boring log at Iwaki site

Recording data

We recorded ground motion with distances of d0, d1, and d2 of 2.5m, 14m, and 27m respectively at the depth of the SPT of 4 meters. In Figure 3, a vertical ground motion at point T is displayed. As the blow number of the SPT is over 50, in the figure ground motion corresponding to first 21 blows is displayed. From the figure, we can see peak value is almost the same and stable.

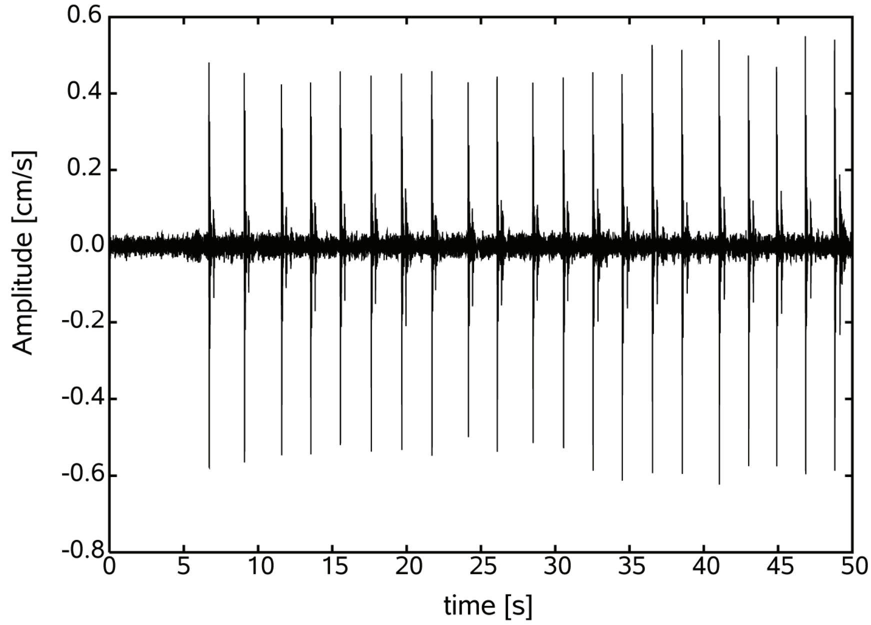

Figure 3. A sample of recording ground motion at point T in Iwaki site. This ground motion is corresponding to the blow of the SPT with depth of 4m.

Using the waveform of the vertical motion at point T, we picked up the time sections those were corresponding to the blow of the SPT and took an average of picked up data. In Figure 4, picked up ground motions and its average are displayed. It seems that the first motion arrive at around 0.2 seconds. Picked up ground motion have some amount of amplitude before 0.2 second and after 0.7 second. However, averaged motion has less amplitude than each picked up ground motion. Thus, averaging process reduces the noise. Around 0.5 seconds, there is a certain phase. This corresponds to rebound of weight of the SPT.

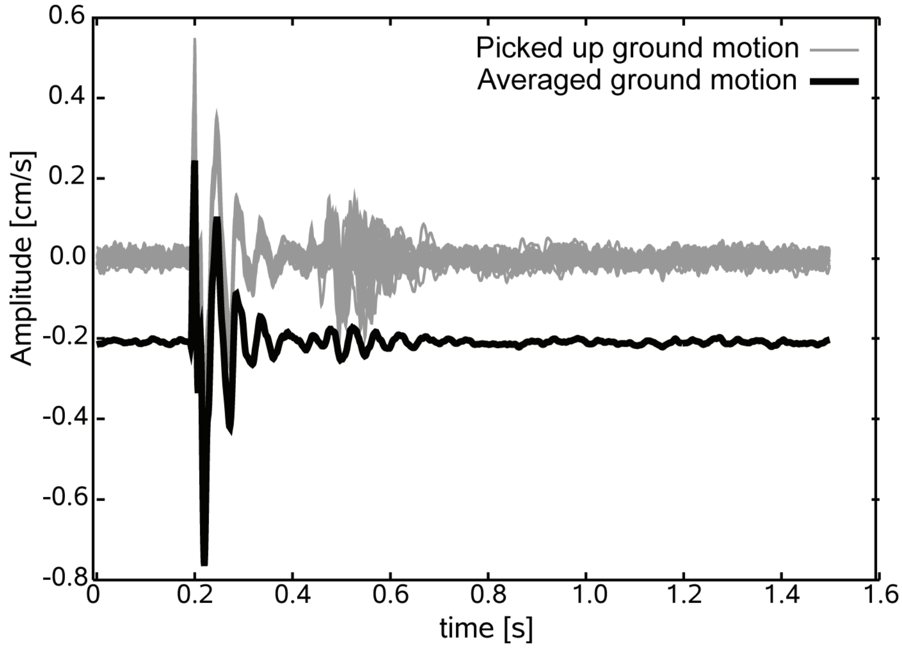

Figure 4. Picked up time sections and it average

Each averaged vertical ground motions are displayed in Figure 5. From here on, these averaged ground motions are called SPT-waves for the convenience. It is not easy to read from the figure but initial downward phase travels at about 2 km/s. The initial phase corresponds to P-wave judging from the direction and velocity but amplitude of later phase is much larger. The later phase corresponds to Rayleigh wave. We can see the phase delay at two sensors placed at point A and point B.

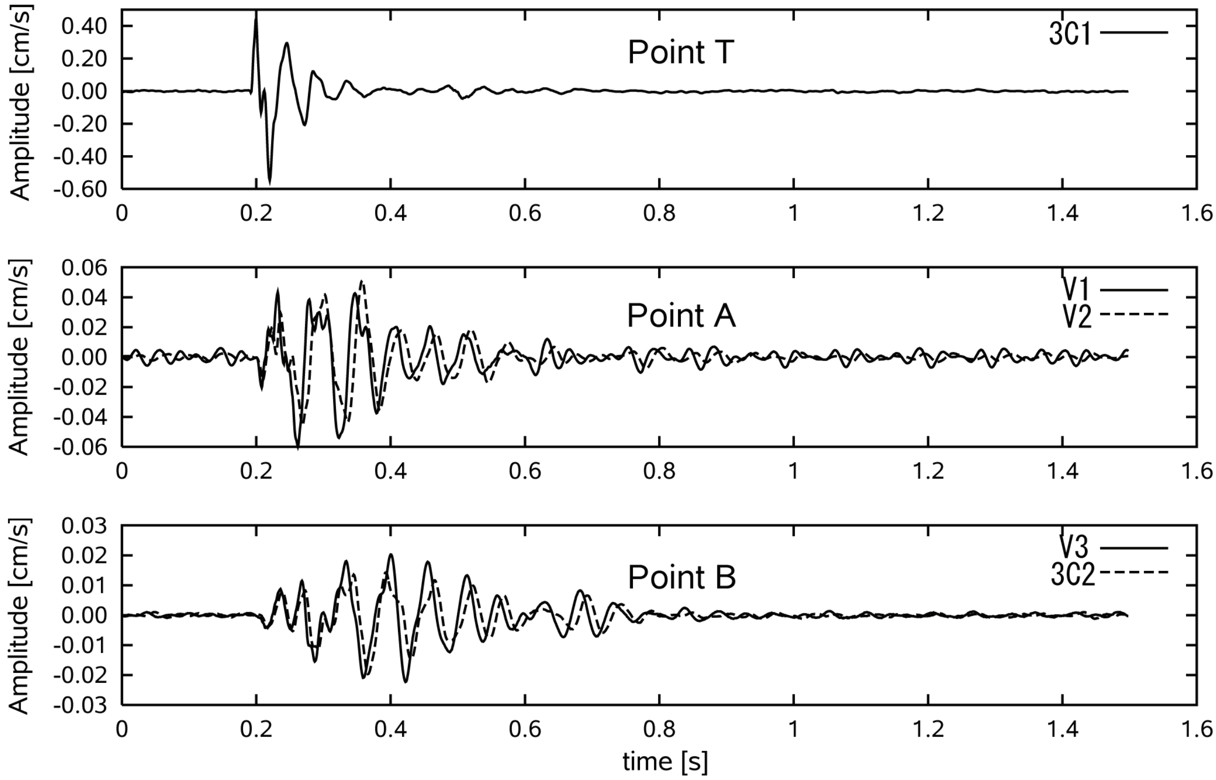

Figure 5. Averaged ground motion at each point. A solid line corresponds to nearer site to the source.

Comparing to background noise

To study characteristics of the SPT-wave, we compare the power spectrum of SPT-wave and back ground noise. In Figure 6, power spectra of SPT-waves and back ground noise are displayed. In this study, back ground noise is define as ground motion that is not excited by the SPT. We choose ground motion from the time segment between the blows of the SPT. This back ground noise mainly excited by engine of boring machine and is not corresponding to usual microtremor. The figure shows that the spectral amplitude of the SPT is larger than those of noise above the 5Hz. At the 7 Hz, the amplitude of the SPT-wave is 10 times larger than those of noise. We should focus on this range to evaluate phase velocity.

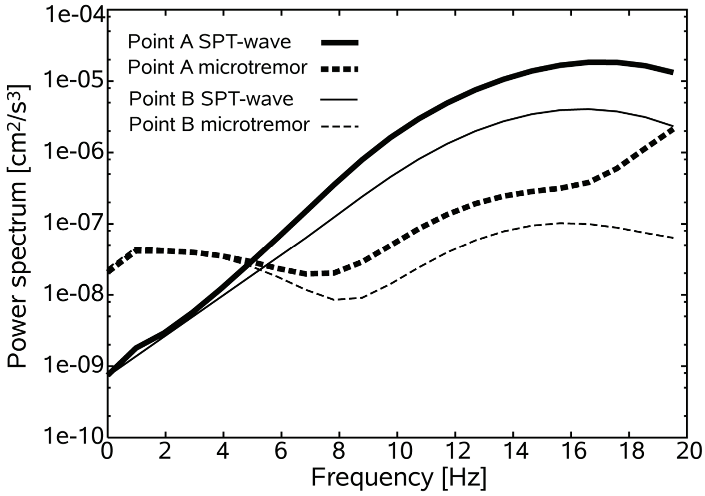

Figure 6. Power spectra for the SPT-wave and back ground noise(named microtremor in figure)

Phase velocity

Phase velocity is calculated from phase delay of two sensors. There are several ways to calculate phase delay. In this study, direct method that use FFT and the cross correlation method are used as a confirmation. Figure 7 shows the result. The results from both methods are almost the same, especially in the range of 11Hz to 20Hz. For detail, phase velocity estimated by direct method is more stable with respect to frequency than cross correlation method. On the other hand, in lower frequency range phase velocity is expected to having a high value, the result of cross correlation complies with expected tendency.

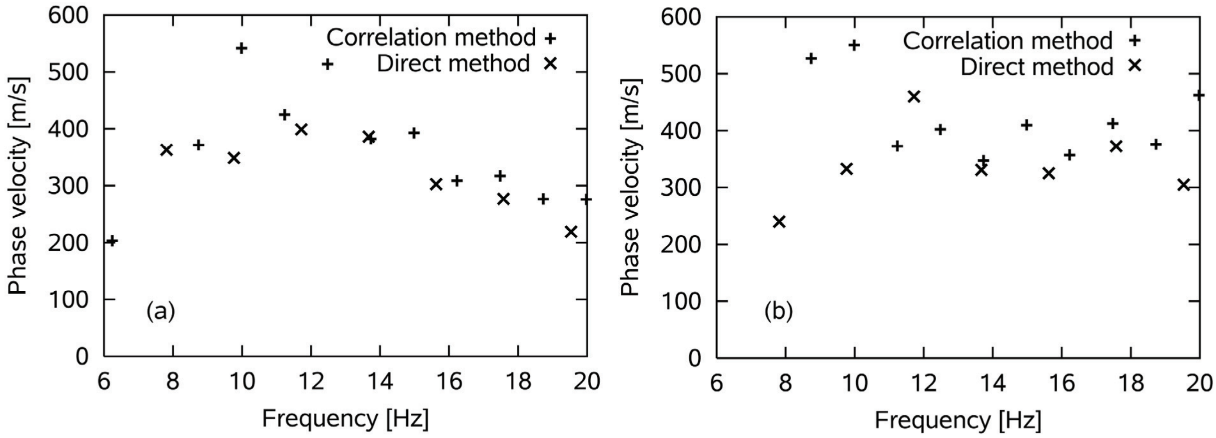

Figure 7. Phase velocities of the SPT-wave estimated from direct method (cross) and correlation method (+) at point A (a) and point B (b).

One advantage of surface techniques is sampling large amount of soil than PS-logging. We would like to study how deep the SPT-wave samples. It is not easy to answer this problem directly. We check the relation between wavelength and phase velocity. Empirical relation indicates that wavelength of Rayleigh wave almost coincident to an average S-wave velocity from the top to the same depth (Konno and Kataoka, 2000). That is Vs30 is almost the same to the phase velocity of Rayleigh wave with wavelength of around 30 meter. Figure 8 shows relations between wavelength and phase velocity of the SPT-wave. As wavelength grows long, phase velocity becomes high. This is normal tendency for surface wave. This tendency continues to wavelength of 30m clearly and to 50m bleary. We can say that the SPT-wave samples about 30m depth.

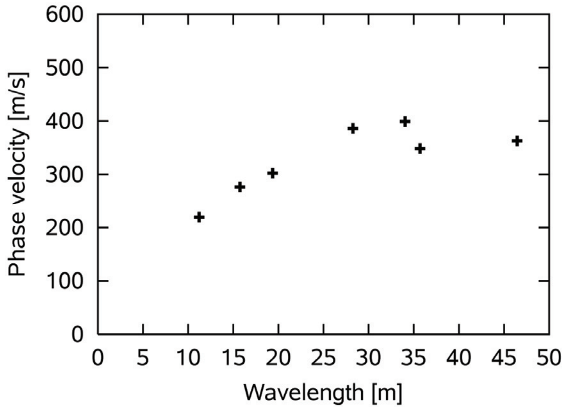

Figure 8. Wavelengths and Phase velocities of the SPT-wave obtained at point A.

S-wave profile estimation and discussion

S-wave profile is estimated using phase velocities obtained at point A by direct method. Number of layers of initial model is established by soil boring log and N-value. S-wave velocity of each layer of the initial model is evaluated by the empirical relation between N-value and S-wave velocity proposed by Imai (Imai, 1977). Inversion problem is solved by Quasi Newton method as S-wave velocities of each layer are unknown parameters. During the inversion, observed values are assumed to be fundamental mode Rayleigh wave. The final result is listed in Table 1. The change of S-wave from initial model to final model is small. This fact means that the empirical relation works well in this site.

Table 1. Estimated underground structure at Iwaki site

No.	Thickness [m]	Vs [m/s]	Vp [m/s]	Density [t/m^3]
1	3	127	1431	1.6
2	Infinite	411	1746	1.9

Theoretical phase velocity of final model and observed ones are plotted in Figure 9(a). Theoretical amplitude of Rayleigh wave is displayed in Figure 9(b). In the figure, corresponding value of the first higher mode Rayleigh wave is also plotted, From Figure 9(a), theoretical value and observed phase velocities are almost coincident. At 12Hz and 14Hz, there are discrepancies. At 12 Hz, we can find that theoretical amplitude of Rayleigh wave is very small in Figure 9(b). At 14Hz, theoretical amplitude of 1st higher Rayleigh wave is larger than fundamental one. Discrepancies may be come from these phenomena. That is first higher mode Rayleigh wave is induced by the SPT-wave. This Rayleigh wave affects the phase velocity

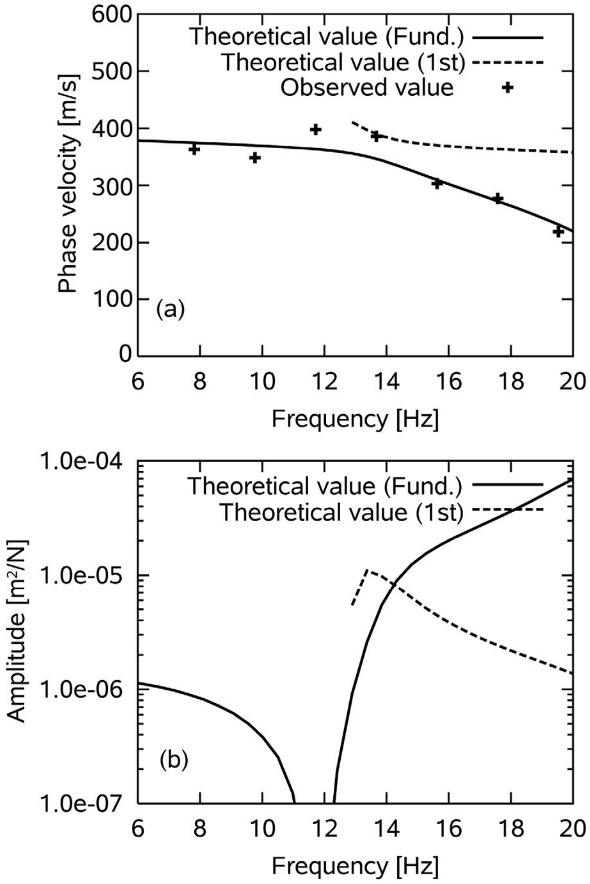

Figure 9. Theoretical phase velocity (a) and amplitude of Rayleigh wave calculated from estimated ground structure. Observed phase velocities are also plotted in (a).

Unfortunately, we don't know the exact S-wave profile at this site. We carried out passive surface wave method not far away from the site for another purpose. From the result, S-wave velocity of the base rock that corresponds to the second layer of this site is about 450m/s. S-wave velocity of the top layer is almost the same to the empirically determined value. These two facts infer the adequateness of the final model.

INAKADATE SITE

Geological condition

Inakadate site is located on the left bank of Aseisi River. Aseisi River runs into Iwaki River. The site is classified in valley bottom lowland. The site is surrounded by rice field and the site is deserted rice field. A history of rice field around the site is traced back to around 5th century. In Japan, rice field is like a shallow pond. From this fact, surface layer around this site might be soft. A soil boring log is shown in Figure 10. The top surface layer is very soft with N-values of two.

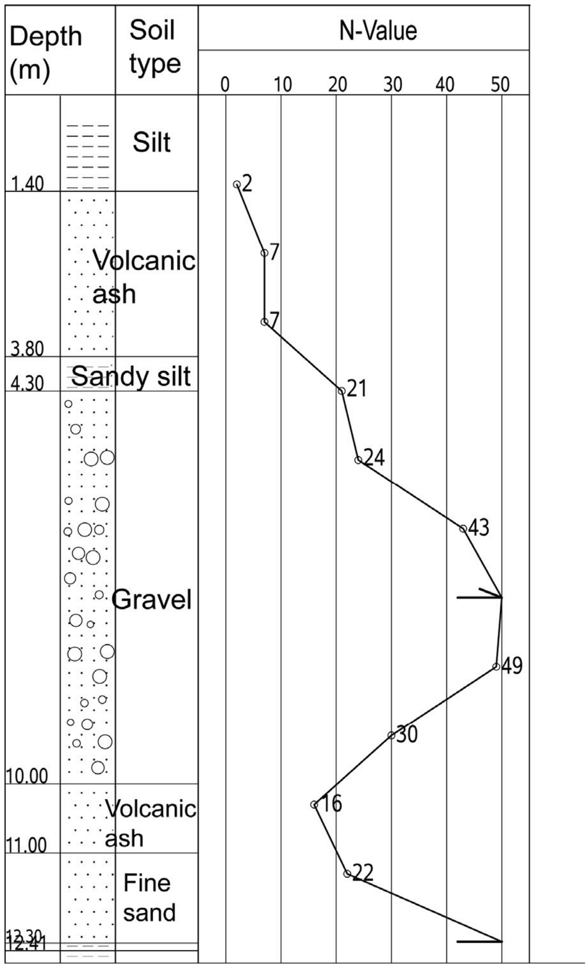

Figure 10. Soil boring log at Inakadate site

Recording data

We recorded ground motion with distances of d0, d1, and d2 of 2.5m, 14m, and 27m respectively at the depth of the SPT of 4 meters. We adopted the same manner used at Iwaki site to obtain the SPT-waves. The SPT-waves are displayed in Figure 11. In this case, only five segments can be picked up, because of small blow numbers and low amplitudes of peaks. However, back ground noise of before and after target signal is cancelled by averaging process. We can see clear phase delays at point A and point B. This phase is corresponds to Rayleigh wave.

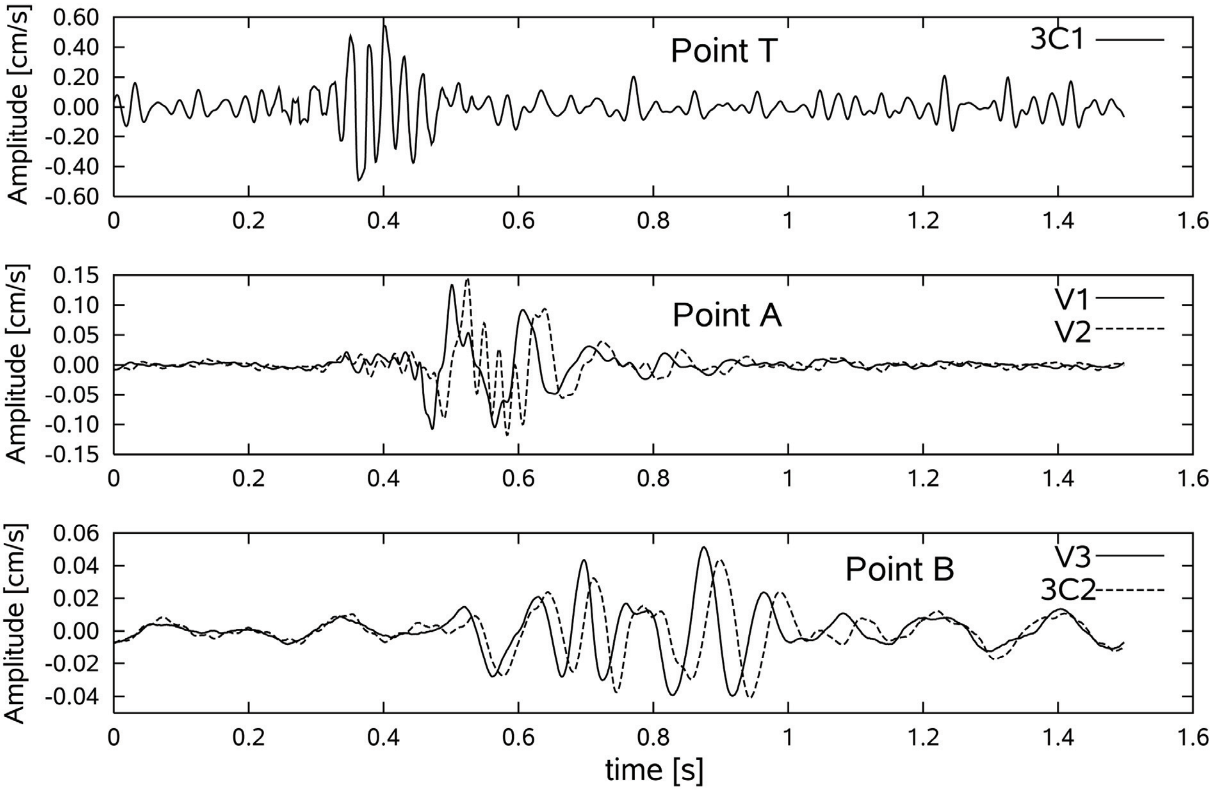

Figure 11. The SPT-wave obtained at all points. A solid line corresponds to nearer site to the source.

Phase velocity
Figure 12 shows phase velocities estimated from the SPT-wave. Phase velocities at point A and point B are almost the same in the frequency range of 7Hz to 20Hz. Power spectra of the SPT-wave overcome to back ground noise in that range.

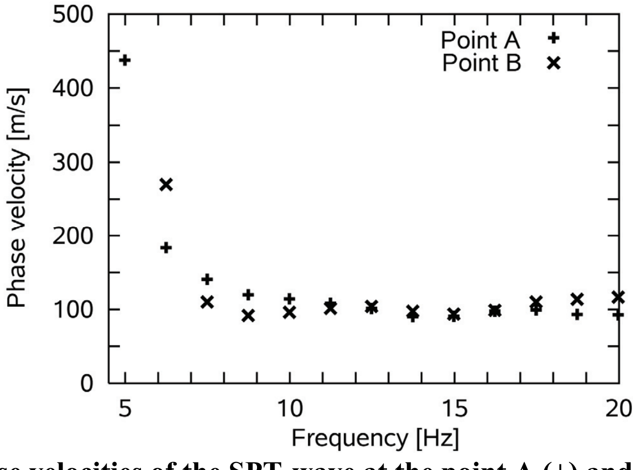

Figure 12. Phase velocities of the SPT-wave at the point A (+) and point B (cross)

A wavelength is also interesting point. If phase velocity of 440 m/s at 5Hz is good enough, corresponding wavelength is 88m. It might be a sort of overconfidence. However, even if we accept 140m/s at 7Hz, we get wavelength of 20m. It means that the SPT-wave samples to the depth of around 20 meters.

Vs profile estimation and discussion

S-wave profile is estimated using phase velocities obtained at point A. Number of layers of initial model is established by soil boring log and N-value. S-wave velocity of each layer of the initial model is evaluated by the empirical relation. At first we performed inversion to obtained optimal model numerically with several initial models. However, results branch off into two patterns. One is velocity of the top layer is higher than those of second layer. The other is normal velocity distribution. Judging from land use, we think that normal velocity distribution is adequate. Thus we performed trial and error procedure to find the optimal structure as S-wave velocities of each layer are unknown parameters. The final result is listed in Table 2.

We set the thickness of the second layer is 2.9m from the boring log at shot point. If we use the value, goodness of fitting is not good below 11Hz as shown in Figure 13(a). At the point A, there is another soil boring log. The log shows that thickness of the second layer is 3.9m. This value improves the fitting as shown in Figure 13(b). In the figure, apparent phase velocity of Rayleigh wave is also drawn. An apparent velocity is evaluated from fundamental and first higher mode (Tokimatsu et al., 1992a). Fitting to apparent velocity is god around 16Hz.

Table 2. Estimated underground structure at Inakadate site

No.	Thickness [m]	Vs [m/s]	Vp [m/s]	Density [t/m^3]
1	1.4	80	1500	1.6
2	2.9 or 3.9	90	1500	1.6
3	Infinite	220	1800	

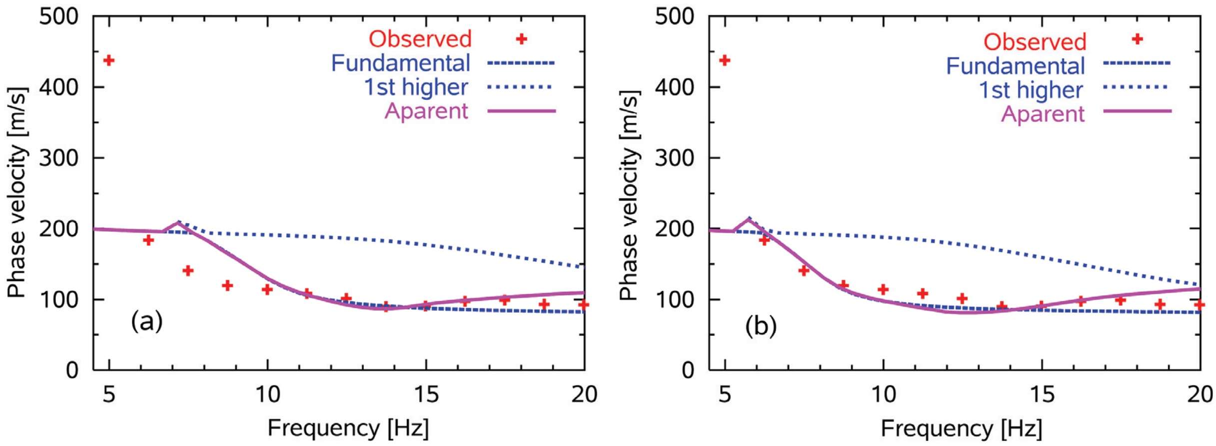

Figure 13. Theoretical phase velocities and observed values. (a) is original model and (b) is revised model with layer thickness.

CONCLUDING REMARKS

In this paper, the author proposes to use Rayleigh wave induced by the standard penetration test for exploring S-wave velocity profile. The test is widely used to estimate engineering soil parameters. If we can explore the S-wave profile at the same time, the opportunity for getting S-wave information dramatically grows. This leads to reduction of seismic hazard. There are advantages of using the standard penetration test. Through this study, these advantages are confirmed. An averaging process that comes from repeated blow can reduce back ground noise. Initial model for inversion is easily established from boring log and some empirical relations.

Additional findings through this study are listed as follows:

(1) The SPT-wave can reach at least 30m.

(2) Judging from the spectra, amplitude of the SPT-wave is larger than those of back ground noise in the frequency range from about 5 Hz to 20Hz.
(3) Effects of higher mode Rayleigh wave are not negligible.

The proposed method is promising. However, we should study two more things before practical using. First one is to enlarge the frequency range. The second one is to include effect of higher mode Rayleigh wave in inversion process.

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