Standardization of microtremor and surface wave explorations

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ABSTRACT

In recent decades, microtremor and surface wave explorations have been widely applied for geotechnical investigations to estimate the S-wave velocity profile. The estimated S-wave velocity profile provides essential information for site characterization. Since we need to solve an inverse problem with the observed phase velocity of the surface waves to estimate the S-wave velocity profile, acquiring high-quality data is the most critical part. To ensure the data quality and the corresponding results, ISO 24057:2022, array measurement of microtremors to estimate shear wave velocity profile, was developed in 2022. The document specifies appropriate equipment, procedures, data analysis, and reporting for the array measurement of microtremors as a passive geotechnical survey. Since we cannot control the frequency contents in ambient noises, the frequency range with the high power may be limited in the microtremor explorations. In this situation, surface wave exploration can supplement this shortcoming. An example of combining the two results shows that it gives us a dispersion curve in a wide frequency range to estimate the S-wave velocity profile from shallow to deep subsurface structure. Developing a new ISO standard for surface wave explorations by following the microtremor exploration enhances the quality of the estimated S-wave velocity profile. Accordingly, we expect non-destructive and cost-effective investigations to be widely accepted worldwide.

Keywords: ambient seismic noise, MASW, S-wave, Standards

1. Introduction

Geophysical explorations are non-destructive and cost-effective investigation methods, and utilizing these methods brings many benefits to the civil engineering industry. Microtremor and surface wave explorations are easier to apply than other geophysical investigation methods. The surface waves are measured and analyzed in active and passive exploration methods. In this paper, we call the "passive surface wave method" microtremor exploration and the "active surface wave method" surface wave exploration.

Because the surface wave amplitude is much larger than that of the body waves, practitioners easily adopt the microtremor and surface wave explorations to solve various geotechnical problems. The surface-wave analysis is widely adopted for building near-surface S-wave velocity models under rapid evolution (Socco et al. 2010).

Some guidelines and books are available for applying active and passive surface wave explorations (Foti, 2005, Okada, 2003). InterPACIFIC (Foti et al., 2018) is a project for creating a guideline for both surface wave explorations. It delivers a good practice of surface wave analysis. Also, application manual of geophysical methods to engineering and environmental problems edited by the Society of Exploration Geophysicists of Japan is available (EAGE 2014). These guidelines and application manuals are helpful for practitioners and engineers to perform the investigation method. However, no international standard for geophysical investigation methods exists, including microtremors and surface wave explorations. Without an international standard, there is a concern about the prevalence of low-quality data. Since we need to solve an inverse problem with the observed phase velocity of the surface waves to estimate the S-wave velocity profile, acquiring high-quality data is the most critical part.

To ensure the data quality and the corresponding results, an international standard, ISO 24057:2022, array measurement of microtremors to estimate shear wave velocity profile, was developed in 2022 (ISO, 2022).

For the sake of standardization of the method, state-of-the-art technology or new developing techniques are excluded from the ISO document. For example, the ISO documents do not consider S-wave velocity estimation including higher modes of Rayleigh wave, data analysis using horizontal components, and joint inversion of Rayleigh wave with horizontal to vertical spectral ratio measured by three-component sensors. If we included them, this standard would be a regulation for most users. It is not our purpose; thus, generally accepted procedures for the measurements and the data processing are included in the ISO document.

Microtremor exploration usually measures low-frequency ambient noise to explore deep subsurface structures, and we sometimes require additional measurements to acquire high-frequency vibration by surface wave exploration. So, applying both methods helps estimate the S-wave velocity structure from shallow to deep depth. Therefore, surface wave exploration seems to be a good candidate for a new ISO standard in geophysics.

In this paper, development of ISO standard is briefly explained, and then standardizations of microtremors and surface wave exploration are described. An example of the combination of the two methods is demonstrated to show the effectiveness of the combined usage.

2. Development of ISO standard

ISO (International Organization for Standardization) is an independent, non-governmental international organization with a membership of 170 national standards bodies. There is only one member per country.

ISO/TC182 is the technical committee for Geotechnics, and the scope of the committee is standardization of geotechnical aspects in the field of building and civil engineering, including (related) properties of soil and rock. As of February 2024, TC182 consists of 25 participating members and 31 observing members, with nine working groups. Expert members from industries and academia are involved in a technical committee and work together to develop international standards in a certain working group.

Working group 9 (WG 9), Geotechnical aspects of geophysical methods, was established in 2018 to develop a new international standard for geophysical investigations and building geological models. As of February 2024, 17 committee members from 8 countries are registered in WG 9.

The first project in the working group was developing an international standard for microtremor exploration. NWI (New Work Item Proposal) was approved by voting from 24 countries in 2019. The initial draft document was accepted as WD (working draft) and then modified by expert members to reflect comments obtained at the voting. Then, the WD document was updated to CD (Committee Draft), DIS (Draft International Standard), and FDIS (Final Draft International Standard). The updated draft was approved by ballot at every stage. Finally, the draft was approved as IS (International standard) document in 2022. Timeline of the development of ISO 24057 is shown in Fig. 1.

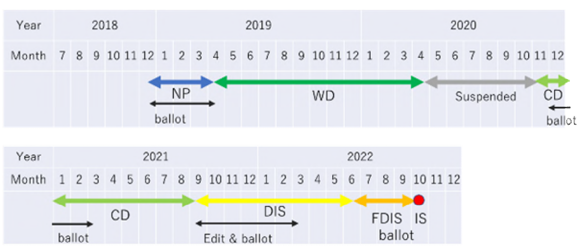

Figure 1. Timeline of the development of ISO 24057:2022

3. Standardization of microtremor exploration

A standard regarding microtremor exploration is developed as ISO24057-2022. The title is array measurement of microtremors to estimate shear wave velocity profile.

Several main targets of ISO 24057 are as follows:

- estimation of geotechnical site conditions for construction;
- stability assessment of foundations;
- evaluation of the risk for soil liquefaction;
- evaluation/prediction of earthquake ground motions.

The ISO document specifies requirements for equipment, survey procedure, data analysis, and reporting of array measurement of microtremors to estimate a 1D S-wave velocity profile. It also specifically describes array measurement of microtremors using vertical ground vibration to estimate an S-wave velocity profile by processing microtremor records based on the fundamental mode of Rayleigh waves (ISO, 2022).

The flow chart of the microtremors exploration is shown in Fig. 2.

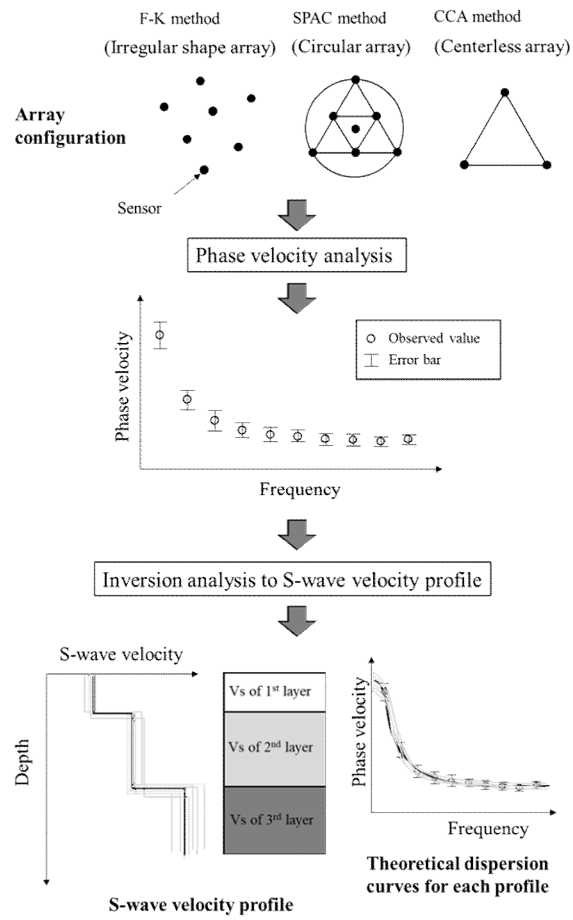

Figure 2. Flow chart of microtremors exploration (Tsuno et al., 2023)

The survey procedure is divided into three parts, including preparation, field observation, and Data organization after field observation.

In the preparation, desk study using existing information and array design are required to be conducted before field observation. Array size must be determined by considering the wavelength corresponding to the depth range to be investigated. Array configuration, or array shape, can be selected from various configurations, as shown in Fig. 3.

In the field observation, a huddle test must be carried out to confirm the consistency of frequency characteristics of the measurement equipment, including all sensors and data loggers on site, immediately before starting array measurement of microtremors at each site.

Recording duration depends on the size of the array; however, typical duration time is listed in the ISO document.

- Array size smaller than 30 m: 30 min.
- Array size from 30 m to 100 m: 30 min. to 1 h.
- Array size larger than 100 m: longer than 1 h to several hours.

The data analysis consists of phase velocity analysis and inversion analysis. The phase velocity analysis is a process of estimating phase velocities of Rayleigh waves from the vertical component of array records of microtremors. There are several methods to estimate the phase velocity, such as F-K (frequency wavenumber method), SPAC (spatial autocorrelation method), ESPAC or ESAC (extended spatial autocorrelation method), MSPAC (modified SPAC method), and CCA (centreless circular array method). The ISO document does not require one specific method.

Even though the fundamental mode of the Rayleigh wave is only considered in the ISO document, higher modes are not neglected in some cases. If the picked phase velocity may correspond to higher modes, ISO requires for engineer to write some comments in the report.

Inversion analysis is a process of estimating S-wave velocity from the phase velocity dispersion curve. Many inversion algorithms are available, including gradient-based and non-gradient-based algorithms. Either can be used for the inversion analysis, but the ISO document requires describing the process in an analysis report to keep traceability.

Uncertainty evaluation is not required but is recommended to be included in the analysis report. Uncertainty for estimating the S-wave velocity profile originates from both data analysis processes, phase velocity analysis and inversion analysis.

For reporting, field report and data analysis report must be written. The ISO document specifies the items to be included in each report.

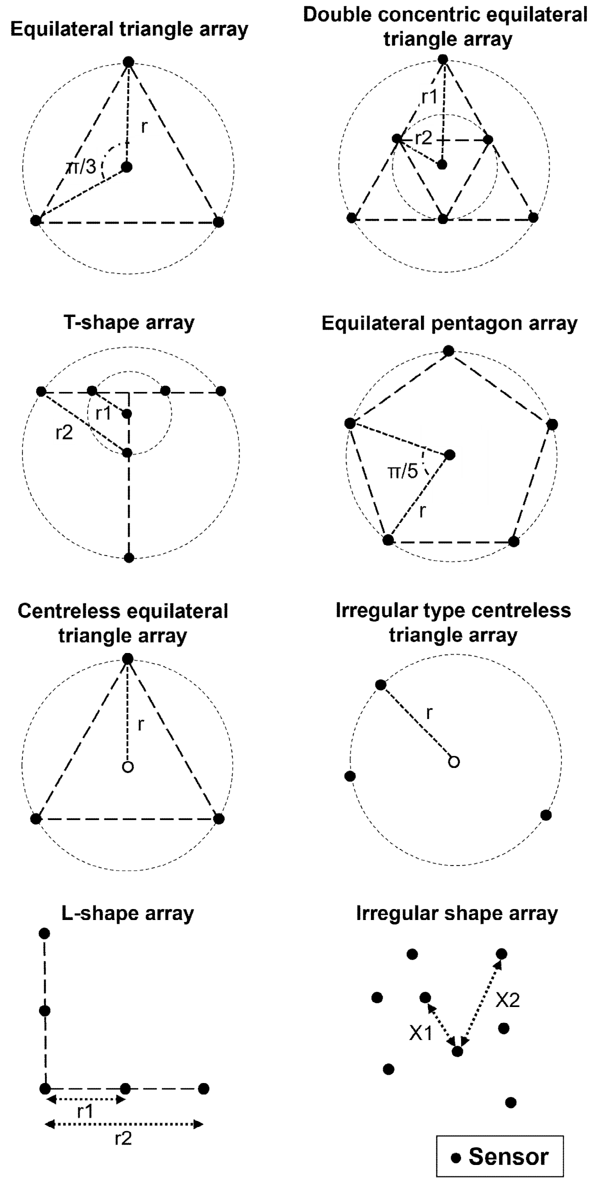

Figure 3. Array configurations described in ISO 24057 (Tsuno et al., 2023)

4. Standardization of surface wave exploration

We are developing a new standard for the surface wave exploration. We focus on multi-channel surface wave exploration for estimating one-dimensional shear wave velocity profile. Also, we focus on the processing based on the fundamental mode of Rayleigh waves.

The application is only for soil ground investigation, and applications to non-soil ground, such as the diagnosis of asphalt roads at depths of several centimeters or the diagnosis of metal plate deterioration, are excluded.

Fig.4 shows a flow chart of the surface wave exploration from measurement to data analysis. The data analysis consists of two parts as same as the document of the microtremor exploration. The difference between the microtremor exploration and the surface wave exploration is that the former measures ambient noise, and the latter measures vibrations generated by an active source on the ground.

Vertical geophones (velocimeters) are used to measure the Rayleigh waves. The natural frequency of the geophone must be adequate to sample the expected frequency band of surface waves without distortions due to sensor response. Generally, 4.5 Hz natural frequency is adequate for shallow targets (e.g., 30m). Certain types of accelerometers may be used as an alternative to geophones (Foti et al. 2018).

Multiple receivers, typically 12 or 24 geophones, are employed to measure the surface wave. Conventional surface wave exploration requires two receivers, but one receiver offset is not enough to estimate phase velocities of various wavelengths. So, typically, several measurements with different offsets must be carried out to complete the measurement. This is feasible but does not seem to be effective when a low-cost multi-channel data acquisition system is widely available. Therefore, we recommend to conduct multi-channel measurements for the surface wave exploration. This decision might be meaningful for a future amendment of the document because precise data analysis requires multi-channel dataset, and two-channel measurement will be excluded, anyway.

Aquisition layout must be determined depending on the target depth and desired resolution of the result. Typical geophone spacing and the exploration depth for 24 receivers are written in Table 1.

Table 1. Typical geophone spacing and exploration depth using 24 receivers.

Geophone spacing	**Deployment length (Array length)**	**Exploration depth**
0.5 m	11.5 m	5 m
1.0 m	23 m	10 m
2.0 m	46 m	20 m

The phase velocity analysis is a process of estimating the phase velocities of Rayleigh waves from the vertical component of active surface wave exploration record. There are several analysis methods, such as phase shift stacking, F-K, cross-correlation, and tau-p methods. As same as the ISO document of the microtremor exploration, any methods can be used if it is used appropriately and provides the correct phase velocity.

As for the inversion analysis, any methods can be used, but the ISO document requires describing the process in an analysis report to keep traceability.

As in the case of microtremor exploration, higher modes are excluded in the ISO document because data analysis considering the higher modes is not widely available yet in practice. This implies a limitation of the application of the method. However, improper data analysis by misunderstanding the higher mode is more dangerous, and we must avoid it.

Requirements for reporting are almost the same as described in the ISO 24057:2022.

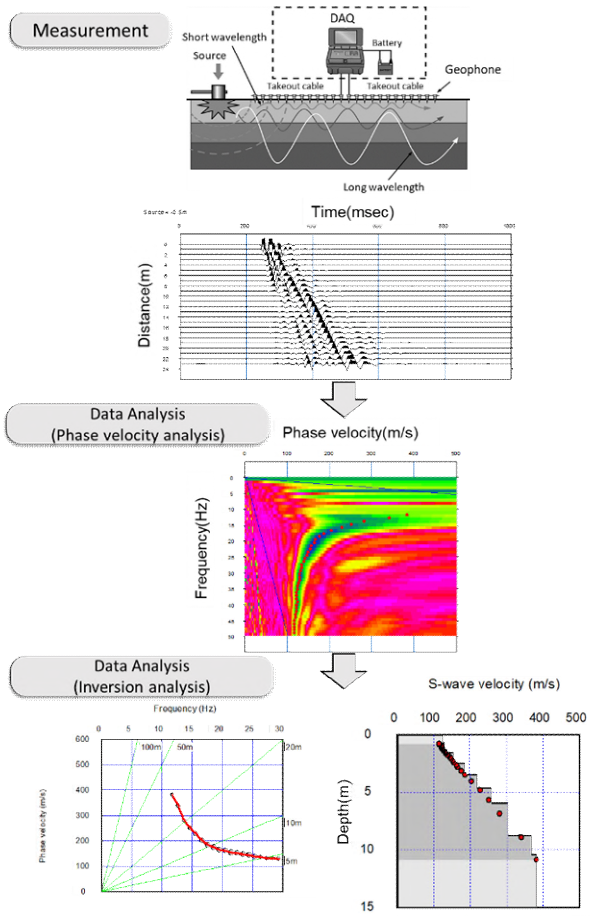

Figure 4. Flow chart of the surface wave exploration

5. Combination of microtremor and surface wave explorations

Usually, microtremor explorations are conducted by array size of tens to hundreds of meters to investigate deep subsurface structures using low-frequency ambient noise. Additional measurements with much smaller arrays are required to estimate shallow subsurface structure. However, we cannot control the frequency range of the ambient noise; thus, it is not guaranteed that we can measure enough high-frequency ambient noise to estimate the shallow subsurface structure.

On the other hand, surface wave exploration using an active source by a sledgehammer can generate relatively higher frequency waves, although it is difficult to generate low-frequency waves.

The two methods can be used as a supplement to each other. Combining the two methods, we can estimate the S-wave velocity profile from shallow to deep depth. An example of the combination is shown below.

Microtremor exploration was carried out by seven geophones with a double concentric equilateral triangle array. A side of the larger triangle was 50 m, so r1 and r2 described in Fig. 3 are 28.86 and 14.43 meters, respectively. Fig. 5 is microtremor records at seven receivers. The phase velocity was estimated by the ESPAC method. The red dots in Fig. 6 indicate phase velocity at each frequency. Blue lines in Fig. 6 indicate a constant wavelength of 28.86 and 200 meters. One is twice the smallest receiver aperture, and the other is four times the largest. Phase velocity was determined between the two blue lines from 2 to 8 Hz.

Active surface wave exploration was carried out with 24 geophones with 1m receiver interval. Fig. 7 shows an active surface wave exploration record. Using phase shift stacking (Park et al., 1999), phase velocity at each frequency was determined, as shown in Fig. 8. Obviously, phase velocity at higher frequency than microtremor exploration is determined. Blue lines in Fig. 8 indicate constant wavelengths of 2 and 46 meters, corresponding to twice the smallest and largest receiver apertures, respectively.

Fig.9 shows dispersion curves from the microtremors and the surface wave exploration. Combining the two dispersion curves allows us to cover a wide frequency range compared to the frequency range covered by each method independently. The estimated S-wave velocity profiles from each method are shown in Fig. 10. The Black curve in the bottom figure is a theoretical dispersion curve computed from the estimated S-wave velocity profile. It suggests that the result of microtremor exploration is suitable for investigating deep subsurface structures but not for shallow structures. In contrast, surface wave exploration is suitable for shallow depths but not good for deep depths.

Fig.11 is the estimated S-wave velocity profile from combined dispersion curves. This combined dispersion curve contains a wide range of frequency waves to estimate the S-wave velocity profile from deep through shallow depth intervals. The result roughly agrees with the S-wave velocity obtained by Suspension PS logging, as shown in Fig.11.

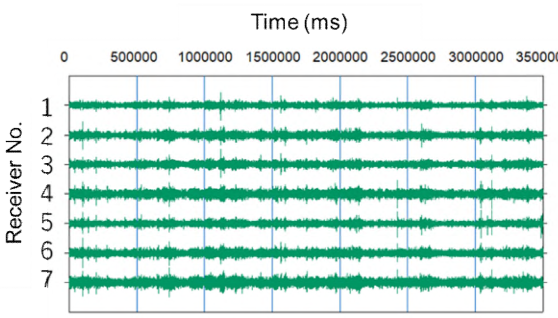

Figure 5. Microtremors record

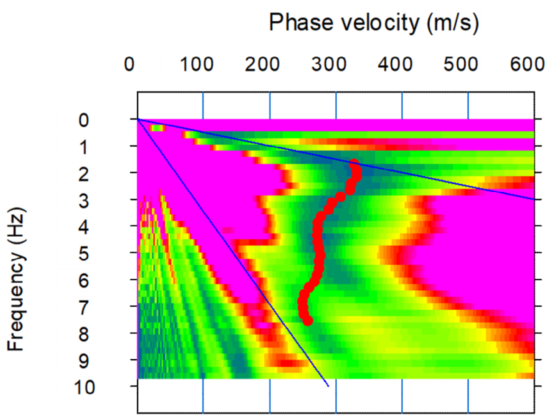

Figure 6. Frequency - Phase velocity obtained from microtremors records.

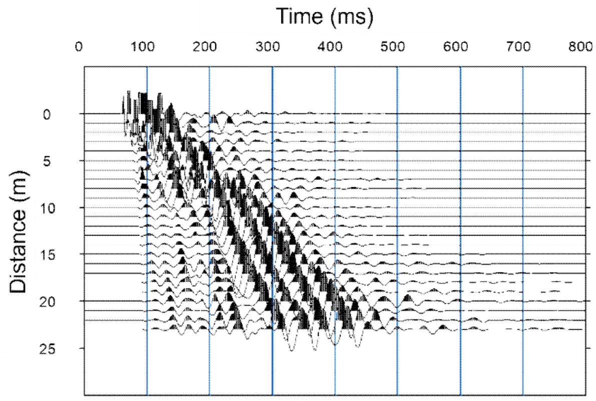

Figure 7. Active surface wave exploration record

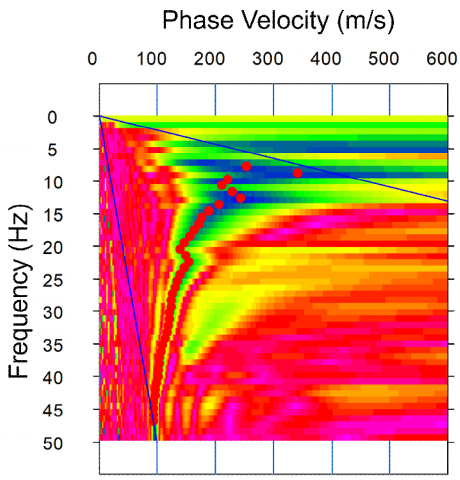

Figure 8. Frequency - Phase velocity obtained from active surface wave exploration record. Red dots indicate picked phase velocities at each frequency.

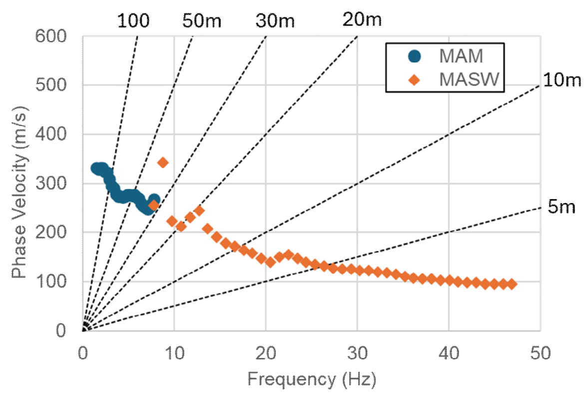

Figure 9. Dispersion curves from the microtremors exploration (MAM) and the surface wave exploration (MASW).

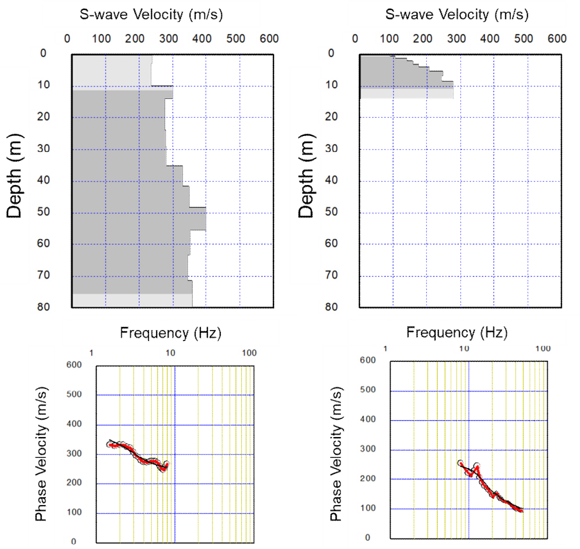

Figure 10. Estimated S-wave velocity profiles (Top) and dispersion curves (bottom). Left side is a result of microtremors exploration and right side is a result of surface wave exploration.

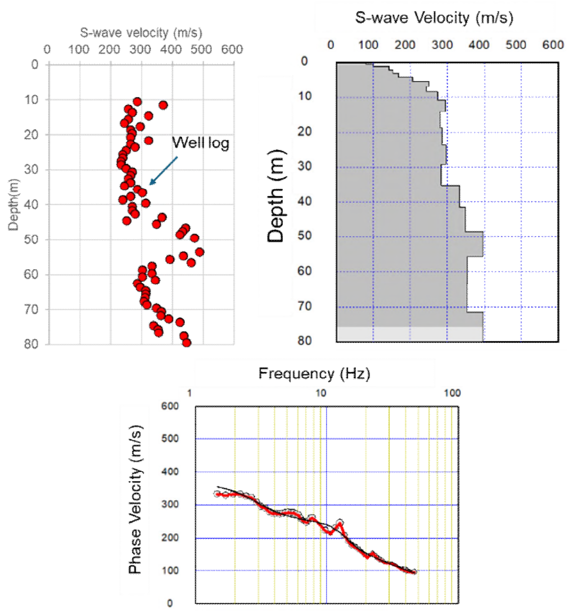

Figure 11. Estimated S-wave velocity profiles from combined method (Top right) and dispersion curves (bottom). Top left is the Suspension PS log acquired at near borehole.

6. Conclusions

International standardization for the microtremor exploration (ISO 24057:2002) was developed as the first ISO standard of geophysical investigation methods in Geotechnics. The document specifies appropriate equipment, procedures, data analysis, and reporting for the array measurement of microtremors to estimate the S-wave velocity profile. This standard will be helpful to prevent submitting a wrong estimation result to a client due to a low-quality measurement. Also, the report is useful to ensure the traceability of the investigation procedures.

To supplement the shortcoming of the microtremor exploration, the international standard for the surface wave exploration, which is so-called "active surface wave exploration" is now under development. Because we cannot control the frequency contents in ambient noises, the frequency range with high power may be limited in the microtremor explorations. On the other hand, surface wave exploration using an active source by a sledgehammer can generate relatively higher-frequency waves, although it is difficult to generate low-frequency waves. The two methods can be used as a supplement to each other. Combining the two methods, we can estimate the S-wave velocity profile from shallow to deep depth interval.

Developing a new ISO standard for surface wave explorations by following the microtremor exploration enhances the quality of the estimated S-wave velocity profile. Accordingly, we expect non-destructive and cost-effective investigations to be widely accepted worldwide.

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We appreciate all members in the committees established in SEGJ and JGS for developing the standard.

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