

Constructing a system to explore shallow velocity structures using a miniature microtremor array

— Accumulating and utilizing large microtremor datasets —

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Our final goal is to provide quantitative information on subsurface S-wave velocity structures in response to a variety of social needs regarding geological and soil matters. Since S-wave velocity is a physical property directly related to site amplification and ground stiffness, it is expected to contribute to, for example, improving accuracy of seismic zoning for the mitigation of earthquake disasters. Currently, we are constructing a system for observation and analysis of microtremors to explore S-wave velocities within the depth range from several to tens of meters on the basis of 15-minute observations with a miniature seismic array having a radius of 0.6 m. The simplicity and objectivity of our system affords automatization and quality control, with an expected capacity to acquire large amounts of microtremor data.

Keywords : Microtremor survey method, array observation, Rayleigh wave, S-wave velocity, soil-structure model, seismometer

1 Introduction

While devastating tsunami damage occurred by the 2011 off the Pacific coast of Tohoku Earthquake, there were also considerable damage by strong motion and liquefaction. The damage differed according to the soundness of the ground. The S-wave^{Term 1} velocity of the ground is important information to learn about shakiness by earthquakes, and it is also useful in disaster prevention. As one of the methods to estimate the S-wave velocity, minute oscillations of the ground called microtremors can be used as data.

The microtremor array exploration method is a method for estimating the S-wave velocity structure from several tens of meters to several kilometers underground. This involves array observation of microtremors [Fig. 1(a)] over several hours by laying out the seismographs on the ground surface at several tens of meters to several kilometers scale. This is a nondestructive exploration where it is not necessary to excavate the ground as in logging.^{Term 2} Since the collected data is for microtremors that are present everywhere and anytime, the advantages are that it is lower in cost than the seismic wave exploration that uses artificial seismic sources^{Term 3} and it can be applied easily in urban areas.

The authors are constructing a system for microtremor array exploration that specializes in shallow ground, and in which the observation and analysis are thoroughly simplified (hereinafter, this will be called the “new system”). In the new system, an array with a radius of 0.6 m composed of

one seismometer in the center point of a circle and three seismometers evenly placed around the circumference (in total, four seismometers) is used [Fig. 1(b), Fig. 2]. This array is used to observe microtremors for about 15 min to estimate the S-wave velocities of shallow ground to the depths from several meters to several tens of meters. Assuming the observers to be general users (such as university labs or high school geology clubs) who are not experts on subsurface structure exploration, one-touch operated measurement equipment is adopted. After measurement, the microtremor data obtained are transmitted wirelessly to a server, and are automatically analyzed. The users are sent analysis results, and the measurement and analysis data are stored in a database in the server. Our aim is comprehensive provision of

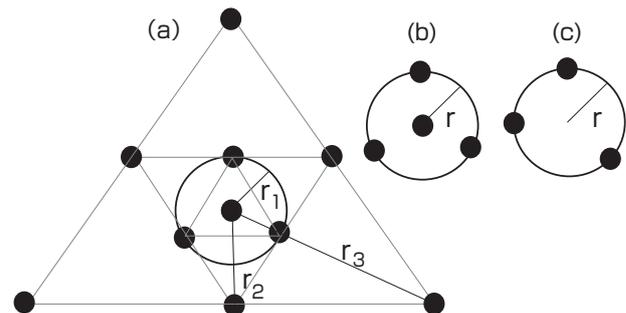


Fig. 1 Microtremor array

The “ r ” is the array radius, and black dots show the seismometers. In the conventional microtremor array exploration, the array radii range from several tens of meters to several kilometers [array (a)]. The new system will basically use 0.6 m radius [array (b)], and a radius of 5 m [array (c)] may be used supplementarily.

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this series of maneuvers. The array used in the new system is much smaller than the one used in conventional microtremor array exploration, and hereafter we call this a miniature array in this article.

The new system is an advanced version of an existing system called “i-bidou” that was created by a research group of Senna, one of the authors of this article.^[1] The i-bidou is composed of a series of maneuvers including execution of single-point measurement^{Term 4} using a microtremor measurement kit,^[2] data transfer to a server, calculation of the spectral ratios of horizontal-to-vertical components of microtremors (H/V spectrum^{Term 4}), forecasting seismic intensity during an earthquake, and delivery of these analysis results. An H/V spectrum of microtremors is said to represent the oscillating characteristics of the ground. The new system is positioned as a system that allows high precision analysis of the wave propagation velocity as well as the oscillating characteristics of the ground, by replacing the single-point measurement of i-bidou with the miniature array.

The goal of the authors is to provide information of the subsurface S-wave velocity that is of high density, high resolution, and quantitative as much as possible, in response to the various social demands related to surface geology such as earthquake disaster mitigation. To do so, it is necessary to collect, analyze, and accumulate massive amount of microtremor data, and we are attempting this using the new system. While not so much as the single-point measurement, measurement using the miniature array is still extremely simple. Therefore, by repeatedly performing measurement many times at different measurement points, the spatial changes of the S-wave velocity structure can be imaged easily. As mentioned at the beginning of this chapter, S-wave



Fig. 2 Measurement using a miniature array with a radius of 0.6 m [Fig. 1(b)]

velocity is a material property that is directly linked to the shaking and stiffness of the ground, and may contribute to achieving high precision of seismic zoning^{Term 5} to mitigate earthquake damage. That is, the ground surface shaking characteristics, which are currently estimated from the geomorphological classification^{Term 5} from the perspective of resolution, will be evaluated from the actual data such as S-wave velocities and ground oscillation characteristics, and the forecasting precision for earthquake shaking may dramatically improve. It also contributes to the evaluation of ground disasters such as liquefaction and helps determine the locational conditions of construction and civil engineering structures. Wide-ranging social value and ripple effect are expected of the results of this research.

First, conventional microtremor array exploration and the positioning of this research will be explained (Chapter 2). Next, the core concept for the new system will be explained (Chapter 3), and the development process is discussed from a synthesiological perspective (Chapter 4). Subchapters 4.1 and 4.2 correspond to the charges of Cho and Senna, respectively. Finally, the future issues will be discussed (Chapter 5).

2 Conventional microtremor array exploration and the positioning of this research

Microtremors are minute oscillations that cannot be detected by the human body, and are caused by wind, waves, industrial activities, and other various sources of oscillations. They are superposition of P-waves and S-waves (body waves) as well as Rayleigh waves and Love waves (surface waves).^{Term 1} Since the body waves are attenuated in high degree, they are dominant only near the oscillation source. As a result, the wave field of microtremors is composed of multiple surface waves that generally arrive from various directions. Based on the theory of elasticity, the body of such microtremors can be easily assumed, but the verification by measurement data was done only after 1950s–1960s.^{[3]–[5]}

After the nature of microtremors was clarified, research to establish a method for measuring the vertical component of microtremors by arrays was conducted^{[6][7]} by extracting the propagation velocities of Rayleigh waves (phase velocity), and estimating the subsurface S-wave structure from the dispersion characteristics (the property where propagation velocity differs by frequency). This is the research for “microtremor array exploration.”

In the latter half of the 1990s, the microtremor exploration was put to practical use to estimate the deep velocity structure as part of the subsurface structure survey by the Government and local governments.^{[8][9]} Roughly explained, the estimation of the deep velocity structure is the evaluation of the foundation of S-wave velocity of 3 km/s called the seismic basement that appears at a depth of several kilometers in the cases

Table 1. Microtremor exploration methods

Item	The conventional microtremor exploration method	New system
Microtremor array layout and size	Arrays in star-shaped layout that combine four-point arrays [Fig. 1(a)]. The array radii are about several tens of meters to 1,000 ~ 2,000 m.	Basically, four-point arrays with radius of 0.6 m [Fig. 1(b)]. Three-point irregular arrays with 5 m radius [Fig. 1(c)] are used optionally.
Measurement time	Several hours. Nighttime measurement when long-period microtremors become dominant is appropriate.	15 min. Daytime observation when short-period microtremors become dominant is appropriate.
Analyzable wavelength range	The analyzable minimum wavelength is two times the array radius, and the maximum wavelength is about several times to a dozen times.	The analyzable minimum wavelength is two times the array radius, and the maximum wavelength is about several tens of times to over 100 times if the condition is good.
Exploration depth	Several tens of meters ~ a few thousands of meters	Several meters ~ several tens of meters

of the Kanto Plain and the Osaka Plain, and a manual has been created for such measurement.^{[10][11]} Specifically, the arrays [Fig. 1(a)] of large and small scale with radii of several tens of meters to about 1,000 meters are laid out, and the microtremors, whose oscillation sources are natural waves or wind, are measured overnight (in practice, 1 to 2 h or 3 h or more according to the radius of the array) (Table 1). The phase velocity of Rayleigh waves at a frequency of 0.1~10 sec is extracted from the microtremor data obtained, and the information for the seismic basement depth that may reach the depth of several kilometers is obtained.

The wavelength range analyzable with one array is dependent on the array size, and it is said to be approximately from twice to several times or dozen times the array radius.^[11] Since the maximum depth of exploration is dependent on the maximum wavelength of the analyzable waves, to obtain data at a wide wavelength range that covers the target depth, it is necessary

to make measurements using multiple arrays with different radii. For example, Fig. 3 is the dispersion characteristic (called dispersion curve) obtained by measuring microtremors with six types of triangle arrays (arrays of radii of 50 m and 100 m, 250 m and 500 m, and 1,000 m and 2,000 m; these are shown in blue, green, and red, respectively) where Fig. 1(a) are combined multiple times. For example, the 2 Hz phase velocity (blue line) was obtained using an array with 50 m radius, while 0.2 Hz phase velocity (red line) was obtained using an array with 2 km radius. The wavelengths were 125 m and 10 km, respectively, while the depth scale was several tens of meters and several kilometers, respectively. The dispersion curves of the phase velocity obtained for each array were connected to create one dispersion curve, and this is deemed as the data representing the subsurface velocity structure at the measurement points with depths of several tens of meters to several kilometers.

However, as shown in the figure, often data obtained with different radii do not connect well. Whether the dispersion curves from arrays of different sizes connect smoothly or not is the index for the reliability of data. If the connections of the analysis results of arrays are extremely poor, re-measurement must be considered. The reason for conducting array measurements of multiple sizes is not only to cover the range of exploration depth, but also to evaluate the reliability of the results.

We shall address this issue further. In the microtremor array analysis, it is assumed that the sources of microtremors are generally located sufficiently far from the array. However in practice, rarely is this assumption met. If the microtremor array of several tens of meters is laid out in the urban area, it is unavoidable that the industrial activities such as traffic vibrations will be included within the array. As a result, these add up as unforeseen record components, or noise, add

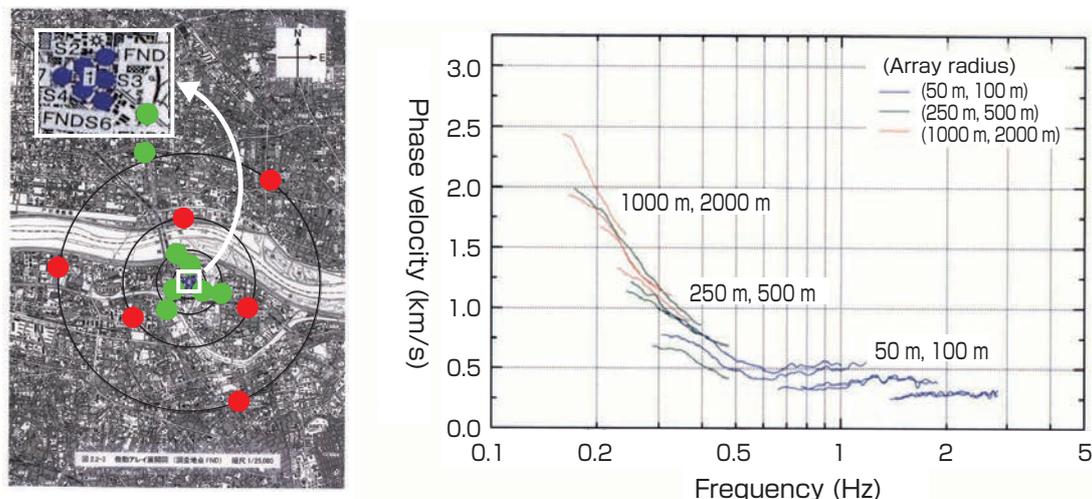


Fig. 3 Microtremor arrays in conventional exploration (left) and an example of the dispersion curve obtained for each array (right) (after Report [12] of the Tokyo Metropolitan Government)

In many cases, the data obtained from arrays with different radii do not connect entirely.

bias to the dispersion curve of each array, and may result in poor connection of the final dispersion curve. This is a fairly serious problem that accompanies the microtremor array exploration. However, there was no model to quantify this problem, no quantitative investigation was conducted, and the matter was left to the field such as re-measurement.

Against a background where much of the framework of microtremor array exploration was based on experience, Cho, one of the authors, has been working on the basic theory of microtremor array exploration since the 2000s. In the middle of the 2000s, theoretical construction to understand the limitations and potential of the microtremor array exploration was attempted.^{[13]-[19]} The idea for a “miniature array” specialized in shallow velocity structure to analyze wavelengths hundred times or more of the array size was born during that time.

On the other hand, Senna worked on modeling deep velocity structure using conventional microtremor array exploration by developing a highly mobile microtremor measurement kit,^[21] and organized systematic mass microtremor measurement through the development of a single-point microtremor measurement and analysis system called “i-bidou” (Chapter 1). The two researchers became aware of each other’s research around 2011, and started collaboration while dividing their work into the development of the theory of data processing and the development of a measurement system. That is, the idea for a miniature array was already formed at that point, and since i-bidou was already in operation, they aimed to create a new system [a shallow structure (of several meters to several tens of meters) exploration system using a miniature microtremor array] by conducting R&D to fuse the two (Fig. 4, Fig. 5, Table 1).^{[20][21]}

In terms of synthesesiology, it is an attempt to obtain information for shallow velocity structures precisely and easily by improving one of the components of the existing

integrated system called i-bidou. The i-bidou has an internal processing capability where the S-wave velocity structure is modeled from an existing geological model of the area around measurement points and an H/V spectral data. However, due to the characteristic of the data, an S-wave velocity structure model cannot be constrained so tightly, and it was positioned only as a middle process to evaluate a seismic intensity during an earthquake, rather than an exploration system. In the new system, the existing i-bidou measurement is set as the core technology, and not only ground oscillation characteristics but also the propagation velocity of waves unique to the site can be obtained as actual data, and therefore, fundamental improvement in precision is possible. When the new system is completed, it will be a new exploration device to realize mass exploration at a precision level of local exploration. While quantitative evaluation of the practicality is necessary in the future, the range of application will become extremely wide. In terms of synthesesiology, it may be an example where improvement of one component of an existing integrated system can be an innovation.

3 Development policy assuming usage by general users

Senna, one of the authors, assumed the use by general users (non-experts of microtremor analysis) in the development of the microtremor equipment including i-bidou, and took the approach of comprehensively providing a series of maneuvers from measurement and analysis to display of results. The following is the explanation of the system.

The shallow (of several meters to several tens of meters) velocity structures that are targets of our study are also interesting to the general public from the perspectives of house location or disaster prevention of towns. Since the velocity structures at this depth change locally, damage that occurs to a neighbor’s house may not necessarily happen

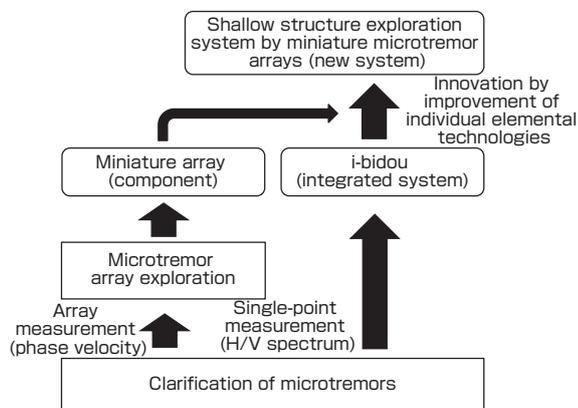


Fig. 4 Conceptual diagram of the microtremor research based on synthesesiological perspective

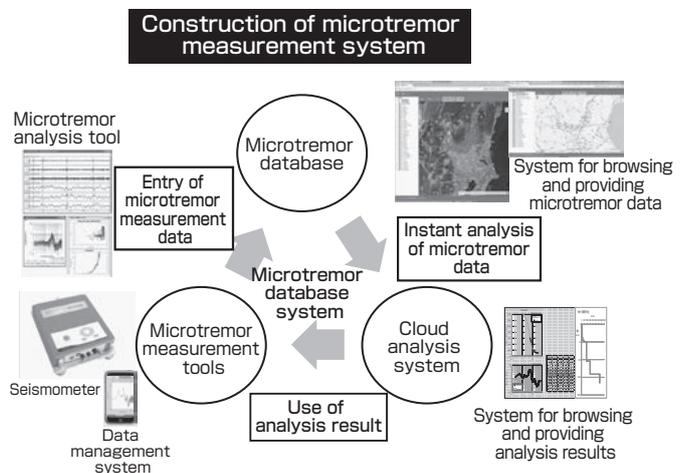


Fig. 5 Conceptual diagram of microtremor system configuration

to one's house despite the small difference in location. Therefore, in some cases, it is necessary to collect data at a several meters pitch (for example, Subchapter 4.3).

However, such high resolution is difficult to realize in a wide-area survey such as earthquake disaster mitigation projects of the Government and local governments. On the other hand, a pinpoint survey is less likely to benefit the majority. Therefore, Senna considered building self-reliant tools where the users, such as local universities who are interested in their communities, can collect data on their own and are able to view the analyses and results. It is estimated that there are more potential users who wish to use such tools than the microtremor experts. Although such users' interests may be limited to their own regions, if users from many areas participate, and if the data obtained can be centrally aggregated in a database, wide-region data can be obtained. The general users are provided with lectures and rented measuring equipment to fulfill their needs. If a structure that allows accumulation of data could be built, it may benefit all parties involved.

To realize such an approach, it is necessary to develop measuring equipment that can be easily operated and managed by general users. It is necessary to conduct objective quality control and automation of data processing. To prevent scattering of data and to ensure continuous accumulation, it is also necessary to develop database related technologies at the same time. Thus, the idea (Fig. 5) for developing such elements in a well-balanced manner and to comprehensively provide equipment and services was born.

The above development policy was also applied to the new system, and care was taken to not lose the ease of measurement of *i-bidou* when using the miniature array (Sections 4.1.1 and 4.2.2). Also overall ease of use is maintained by quality control based on the theory developed together with the miniature array, automation of data processing to visualization (Section 4.1.1), and delivery of analysis results in quasi-real-time (Section 4.2.3). The users can even obtain two-dimensional cross-sections of shallow S-wave velocity structures that are directly related to earthquakes and ground disaster, as easily as with the existing *i-bidou* (Subchapter 4.3).

4 Components of the new system

4.1 Theoretical development

4.1.1 Miniature array analysis (measure: extension of analysis limit of long wavelengths)

In the case of the *i-bidou* developed earlier, the ease of measurement was emphasized for the purpose of mass measurement (Chapter 3). Since such emphasis applies to this research as well, we wish to conduct array measurement

without compromising the ease of single-point measurement. Therefore, one of the goals was to lay out the array behind a car parked on the roadside (Fig. 2), and we decided to use a four-point array with a radius of 0.6 m (Fig. 1(b)).

As long as the standard is based on the conventional microtremor array exploration (Chapter 2), the wavelengths that can be analyzed by a miniature array of a radius of 0.6m are about 1.2 to 12 m, and exploration up to several tens of meters depth is expected to be difficult. However, if the array is small, it is possible to exclude the oscillation sources within the array (Chapter 2), and taking measures such as setting them at a distance from the noise sources (e.g., construction sites) can be done easily. Therefore it is expected that the noise problem that inhibits the analysis of long wavelength ranges will be decreased and relatively longer wavelengths compared to the array size can be analyzed. Also, combining with various analysis methods developed by the authors,^{[14]-[17]} it will be possible to correct the noise effect by evaluating the SN ratio,^{Term 6} and it may be possible to analyze long wavelengths that are over 100 times the array radius. Also, based on the spectral estimation theory, it is estimated that sufficiently stable analysis can be done in measurement time of about 15 min.

The authors considered such theoretical schemes, conducted experiments at numerous sites using the actual equipment,^[2] and verified its practicality. Specifically, the time needed from arrival to pullout from the site was kept to about 30 min, and it was shown that dispersion characteristics of phase velocity in the wavelength bands of targeted several tens of meters to 100 m or more in some cases could be obtained.^[20]

4.1.2 Reading of the phase velocity (measure: evaluation of analysis limit)

As mentioned in Chapter 2, in conventional microtremor array exploration, arrays of multiple sizes are used from two perspectives: (i) to cover the wavelength range corresponding to the targeted depth range, and (ii) to maintain the reliability of the dispersion curve. However, in the new system, we wish to emphasize the ease of measurement, and the measurement should be basically done with a miniature array of a radius of 0.6 m (Fig. 1(b)). In the case of the miniature array, because it has originally limited the depth scale and has succeeded to extend the analytical limit of long wavelengths (Section 4.1.1), (i) is cleared. Therefore, the issue is how to achieve (ii).

To tackle this issue, the authors took the approach of presenting the analytical limit of phase velocity by evaluating the SN ratio and then evaluating the reliability.^[20] If the reliability of the analysis results obtained is high, measurement can be terminated by one measurement using miniature arrays. If the reliability is low, measurement using a three-point irregular array at a larger size can be conducted additionally (next

section).

When the feasibility of this idea was investigated using real data, it was found that the expected results as demonstrated by theory could be obtained (refer to Reference [20] for technical details). Let us look at Fig. 6 for an explanation. The figure is the dispersion curve of phase velocity obtained by a miniature array of a radius of 0.6 m. The purple triangle shows the phase velocity that has been corrected for noise effect and the blue cross shows one that has not been corrected. Normally for the dispersion curve, the phase velocity increases as the frequency decreases (called normal dispersion), and this is in reflection of the fact that S-wave velocity increases with the increase of depth. In the dispersion curve of the same figure, the phase velocities suddenly increase at 7.5 Hz or less. On the other hand, the phase velocities increase as the frequency increases above 7.5 Hz, and the trend called reverse dispersion is seen. This reflects the fact that there is a high velocity layer near the surface. In fact, there is a clay layer with extremely slow S-wave velocity embedded at a depth of about 5 m around the measurement point in the figure, and it is known that the S-wave velocity is faster near the surface.

Figure 6 shows the lines that correspond to the wavelengths of 25 m (red), 40 m (purple), and 100 m (green), as the reference indices that show up to which depth the data can be obtained using the miniature array. The intersection points of the dispersion curve and these lines represent the frequencies and phase velocities that correspond to each wavelength. It can be seen from this figure that the phase velocities of slightly less than the wavelength of 100 m are obtained if the noise is not corrected, and phase velocities of wavelengths surpassing 100 m are obtained if corrected for noise. Here, by visual inspection of the noise-corrected results (shown by crosses), the phase velocity surpassing the wavelength of 100

m is identified. A wavelength of 100 m is about 167 times the radius of the array. The adequacy of this visual inspection was verified by separately executing with an array of a radius of about 5 m.

Up to now, the performance of the miniature array has been described while explaining how to read the figure. However, what we wish to present in Fig. 6 is the evaluation of reliability based on the analytical limit of the phase velocity. In the figure, the upper limit for analysis is shown as a yellow broken line. This is the limit for analysis that is set strictly based on the developed technology, which separates the microtremor record into the components of surface waves (signals) crossing the array and the components of noise unrelated to such signals. If the upper limit is sufficiently high compared to the estimated value of phase velocity, it can be judged that the estimated value of phase velocity is safe to use. In the figure, the long wavelengths are automatically read up to the phase velocity surpassing the wavelength of 40 m (yellow square), based on this upper limit for analysis. That is, in this case, the objective quality control of the analysis result was done based on the data from the miniature array only, and it was automatically determined that the data up to at least the wavelength of 40 m can be “used.” Of course, this information is provided regardless of whether the recipients are experts or non-experts.

In this way, we came to be able to obtain the phase velocity of the Rayleigh waves as new data to determine S-wave velocity by using miniature arrays. This is the core of sophisticating i-bidou. Objective quality control, automation of the analysis, and therefore, the use by general users are made possible by the theoretical development allowing the data-based evaluation of the upper limits for analysis.

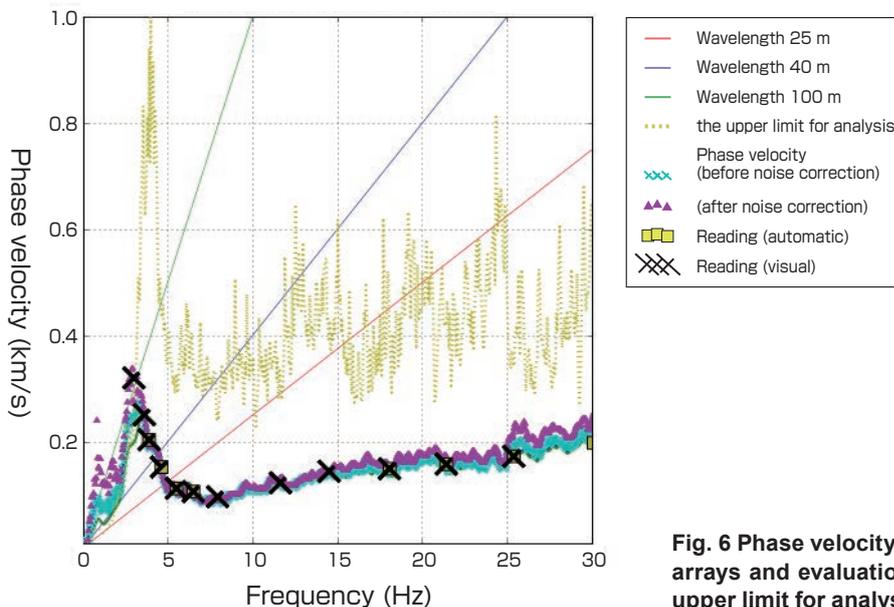


Fig. 6 Phase velocity (dispersion curve) by miniature arrays and evaluation of automatic reading and the upper limit for analysis

4.1.3 Three-point irregular array analysis (measure: evaluation of irregular array layout)

In cases where the analysis results of a miniature array with a radius of 0.6 m are of low quality, arrays with a larger size are used to supplement the data. Here, arrays larger by one order (radii of several meters) are considered. However, arrays of this size do not fit behind a car parked on the roadside. Conventionally, arrays of Fig. 1(b) where the seismometers are laid out at equal intervals on a circle are used, but due to the problem of roads and buildings in the urban areas, one cannot expect the arrays to be laid out neatly.

As a measure for this, we considered using three-point irregular arrays [Fig. 1(c)] of a radius of about 5 m as supplementary arrays. In conventional microtremor array exploration, data processing is done assuming that arrays are laid out at equal intervals, and it is difficult to apply such three-point irregular arrays. However, the authors have already proposed a data processing method in cases of unequal intervals, and have theoretically evaluated the effect on the analysis results.^[13] In this research, using an actual equipment,^[2] field experiments were repeatedly conducted by combining miniature arrays and three-point irregular arrays of several meters size, and the applicability to the new system was studied. As a result, it was shown that the supplementary data that fulfill the objective could be obtained by applying this idea, and that it is sufficiently practical without much difference in measurement time and amount of labor.^[22]

4.1.4 Estimation of velocity structure (measure: use of simplified analysis)

What we ultimately want is the S-wave velocity structure of the ground. To model the velocity structure, nearby logging data and wide-area geological structures are referenced as initial models, and in many cases, iterative inversion analyses are conducted to optimize a model to fit the phase velocity obtained in array measurement.

However, expert knowledge is necessary to create the initial models, and this does not match the demands for automatic processing and instant delivery of analysis results. Therefore, here, a simple conversion method is adopted, where the dispersion curve that is expressed as frequency versus phase velocity is converted to the relationship between wavelength and phase velocity, and this is deemed as the relationship between depth and S-wave velocity through appropriate scaling.^[22] A method where the phase velocity that corresponds to the wavelength of 40 m is deemed as the average S-wave velocity from the surface to a depth of 30 m is also used concurrently.^[23]

This falls within the range of a standard preliminary analysis, but we believe that analysis results in a sufficiently satisfying range can be obtained (for example, Subchapter 4.3) when considering the balance between supply and demand.

However, currently, we are also investigating the possibility of some advanced inversion methods such as a simultaneous inversion^[24] of the H/V spectrum and the dispersion curve.

4.1.5 Automation of the data analysis (measure: optimization of the parameter)

From the perspective of use by general users, all processes including the selection of analysis intervals^[19] and reading of phase velocity (Fig. 6)^{[25][26]} should be automated. This doubles the measures for maintaining objectivity in reading, time reduction, and human error countering. The design also allows visual checking of the results of automated processing afterwards, and re-reading.

In the estimation of velocity structures, the analysis results for each measurement point are presented, but in many cases the interpretation is shaky with only those results. It will be very effective in supplementing the interpretation if there is a two-dimensional velocity cross-section made by connecting together the results of multiple measurement points. Therefore, we created a tool that automatically draws the S-wave velocity cross-section simply by setting the cross-section line on the map (Subchapter 4.3).

4.1.6 Quality control of the raw data and analysis results (measure: creation of index)

In cases where there are problems in the raw data due to lack of data, failure to synchronize time on GPS, poor installation environment, or others, the decision of whether to conduct re-measurement can be made on the spot, by presenting these facts in quasi-real-time. In cases where the quality of the analysis results is low (such as when exploration does not reach the target depth due to low SN ratio since the microtremor intensity is low, etc.), deciding to conduct additional measurement by three-point irregular arrays becomes possible. To avoid overinterpretation of the analysis results, it is necessary to conduct thorough quality control. The index for quality control will be presented by combining the maximum amplitude of waveform, spectral density, SN ratio, and other quantities. Details are currently being investigated.

4.2 Development of the measurement system

4.2.1 Development of the seismometer (measure: maintaining mobility, robustness, stability, and simplicity)

The seismometer used in the microtremor array exploration must have small individual differences in response characteristics, and they must be particularly uniform in phase characteristics. Also, to obtain high quality data in regions with small microtremor levels, it is important to have low self-noise. Considering the possibility that they may be used for microtremor arrays of several hundred meters size, a wide-frequency-range seismometer that has

time synchronization by GPS and analyzability of the low frequency ranges is necessary. Considering the possibility for use in single-point measurement of the H/V spectrum, sensors that can detect ground motions in the horizontal direction as well as the vertical direction are necessary.

To maintain mobility, the conditions set are as follows: the device must be small, lightweight, and the content can be stored in a single box; there must be no maneuvers of wiring and clamp removal on site; it must have short recharge time and the power source must last throughout the day of measurement; and the recording can be started stably soon after turning the power on. It is also important to minimize the exposure of the terminals in addition to being drip-proof and vibration resistant for transport by vehicles.

To fulfill these requirements, Senna *et al.*^[2] developed a seismometer that is highly sensitive, that has wide dynamic range, low noise, and high bias temperature stability. In the development of this seismometer, attention was especially paid to the amplitude resolution and SN ratio of the recording device. It has been demonstrated that this equipment can be applied to miniature arrays.^[20]

4.2.2 Development of the data transfer system (measure: handling of lacking data)

In order to conduct mass measurement with microtremor arrays and to smoothly manage the analysis results, it is necessary that the procedures from the measurement to result evaluation be few in number and simple. Particularly, from the measurement data collection to analysis, much time must be spent on preparatory work, such as data check, data format conversion, organizing photographs, and others. However, if it becomes possible to gather data easily on site and store them in a database, vast amount of measurement data can be managed easily, and mass measurement management becomes possible along with the simple measurement equipment described earlier.

To achieve this objective, it is necessary to create a mechanism where the series of maneuvers from data organization on site to analysis (data entry of location information, photographs, measurement data, chronological information, analysis results, etc.) can be done easily, and thereby reducing human error. Specifically, we focused on the construction of a mechanism where data can be sent, received, aggregated stably through a standard format from multiple units of measurement equipment, and the data can be shared through the database system and analysis software.

To solve this issue, we created a system composed of one master equipment and a corresponding slave equipment, where individual seismometers automatically determine the positions, with added function of aggregating data to the master equipment. We employed the ACT protocol^{Term 7} that

has redundancy, so the data can be sent and received from the master equipment to the terminals such as PCs and tablets without loss of data.^[27]

4.2.3 Delivery of the analysis result (measure: maintaining quickness)

The data entered in the database must be automatically quality controlled and analyzed, and the S-wave velocity (soil structure model) from the analysis results must be delivered and be checkable on WEBGIS and others along with the map information. For the observer to check quality control and analysis results on site, it is necessary to be able to analyze and browse the results of the data sent to the database in near real-time.

To realize the above, the construction of application for smart phones and the construction of a “cloud analysis system” that analyzes and quality controls microtremor data at high speed are issues to be tackled. For the smart phone application, the functions of i-bidou^[1] are used to enable reception of data in real time, checking of waveforms and spectrum, and conducting data quality control such as simplified SN ratio management of the microtremors. In cloud analysis, detailed analysis of the entered data and quality control is done.^[20] Using this cloud system, about five to ten times increase in speed can be achieved. It is known that the current i-bidou can deliver results within several minutes.^[27] This high speed will be incorporated in the new system (a shallow structure exploration system using miniature arrays).

4.2.4 Database related (measure: definition of the format)

The format of the database is considered to enable efficient browsing and utilization of raw and analysis data of microtremors. Specifically, an XML^{Term 8} format is defined for microtremor measurement data, and raw measurement data and analysis result data will be stored in several formats that allow high degree of general use.

4.3 Integration of the components

Arranging the components of Subchapter 4.1 in order enables the development policy of Chapter 3 to be realized. The level of completion can be measured by the general users’ convenience or inconvenience, the basic policy of development, as well as by the reliability of the results. Since the usability and reliability tend to have a trade-off relationship, here, we shall deem that the goal of usability has been achieved when the general users are able to obtain the results easily, and the development will be terminated at that point. The reliability of the new system will be evaluated by comparing the data obtained with the verification data. Then, it will become a product with a given “range of application.”

Currently, we are in the process of development, but we are gaining a certain degree of progress. Figure 7 illustrates

this as an example. This is the S-wave velocity cross-section obtained when we had geology researchers (non-experts of microtremor exploration), who wished to evaluate the subsurface velocity structure of the grounds of Urayasu High School in Chiba Prefecture to study the liquefaction phenomenon, use the new system in a trial. This result was used in a conference presentation by Sato *et al.*^[29] After receiving a simple lecture on miniature array measurement, the researchers drew two measurement lines of 40 m and 120 m on the grounds of the high school, and repeated miniature array measurement at about 5 m intervals. About 20 min were spent per point, or a total of 12 hours. However, the total measurement time for the shorter measurement line was less than 2 hours.

Since the data transfer system (Section 4.2.2) and the analysis result delivery (Section 4.2.3) were incomplete, we received the measurement data when the equipment was returned. Figure 7 shows the complete automated process from data analysis to drawing for the 120 m measurement line. From the survey for the landfill work of 1965-1971 as well as from hand-operated auger boring,^{Term 2} it is known that the topmost part of the grounds of Urayasu High School is 3 m of landfill layer that is composed of a sand layer and a silt layer in the east and west of the center of the measurement line.^[30] In the part up to 10 m of depth of the velocity cross-section in the figure, clear difference is shown at about 45 m horizontal axis.

5 In the future

We believe about 70 % of our goal has been completed. It is necessary to work on the components that have not been addressed (data transfer system and analysis result delivery) and parts that can be refined (such as an estimation method

for ground structures).

Currently, there is a plan for measurement using miniature arrays at 1 to 2 km grid for the entire Kanto Plain area, and it has been partially conducted.^[30] We wish to utilize this data to discern the limitations and possibilities of the new system and to consider future development.

The research group to which Cho, one of the authors, belongs is working on the high resolution geological ground maps.^[31] We are considering the application of this new system and adding the quantitative evaluation using the microtremor data.

Terminologies

- Term 1. S-waves: A type of seismic wave. The seismic waves that travel through materials internally are called body waves, and they can be separated into P- and S-waves according to the relationship of directions of propagation and particle motion. The seismic waves that travel on material surfaces are called surface waves, and can be separated into Rayleigh and Love waves according to the relationship of directions of propagation and particle motion.
- Term 2. Logging: Measurement of the subsurface geology and ground conditions using boreholes. Boring is the term used for the act of digging a cylindrical hole in the ground or for the hole itself. Hand-operated auger boring is boring using hand drills.
- Term 3. Artificial seismic source: Vibrations caused by explosion, pounding, or a vibrator (truck-mounted device) that are instigated near the surface to artificially generate seismic waves. The exploration

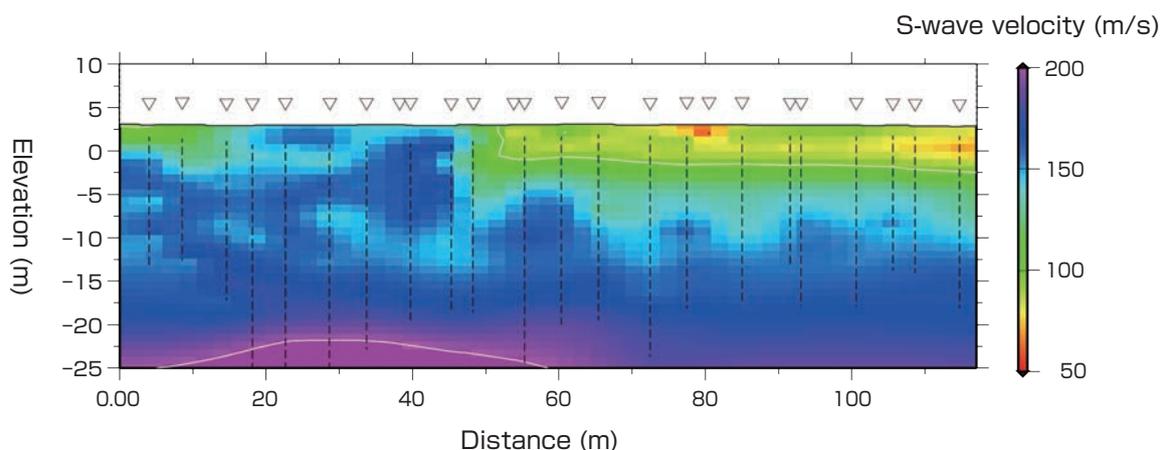


Fig. 7 S-wave velocity cross-section by miniature array exploration conducted on the Urayasu High School grounds

The right and left part of the cross-section diagram corresponds to the south-east and north-west directions, respectively. The legend of the cross-section shows the S-wave velocity with unit m/s. The triangles in the cross-section diagram show the positions of miniature arrays, and the dashed lines show the range of depth where the velocity structure data exist. Generic Mapping Tool^[28] was used for drawing.

conducted using seismic waves generated by artificial seismic sources is called the seismic wave exploration.

- Term 4. Single-point measurement: Measurement conducted using one seismometer. H/V spectrum is the spectral ratio of ground motion in the horizontal and vertical directions obtained in single-point measurement.
- Term 5. Seismic zoning: A map expression of the seismic hazard and damage of buildings, taking into consideration the ground conditions. The ground conditions include the geomorphological classification that are small-scale undulations that may be difficult to be shown clearly on 1:50,000 scale topographic maps.
- Term 6. SN ratio: Ratio of the intensities of signal strength to background noise.
- Term 7. ACT protocol: Autonomous cooperative data transfer (ACT) protocol was developed to stably transfer data for the Metropolitan Seismic Observation network (MeSO-net). Protocol is a set of rules and procedures to mutually transfer information.
- Term 8. XML: General-use data descriptive language suitable for handling various data on the internet.

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Discussions with Reviewers

1 Overall

Comment (Akira Kageyama, Research Support Adviser, AIST; Chikao Kurimoto, AIST)

The microtremor array exploration method allows estimation of the S-wave velocity structure at several tens of meters to several kilometers underground, as well as assesses the shakiness by earthquakes. In this paper, the target is specified to shallow ground, and the goal is set to clarifying the subsurface S-wave velocity structure at high density, high resolution, and quantitatively, for the urban areas in which damage due to strong motion and liquefaction are expected. The authors appropriately present the progress of their research along a steady scenario, including correct response to social demands, theoretical development of miniature microtremor array analysis, application to existing microtremor array technology, development of an automatic analysis system, and actual trial by general users. Therefore, we consider this paper appropriate for publication in *Synthesiology*. Also, this paper shows that a system can be given an innovative function by advancing the core technology with a new idea, in a system that is composed of multiple elemental technologies. It can be said that it proposes a new synthesis method for papers of *Synthesiology*.

2 Outline

Comment (Akira Kageyama, Chikao Kurimoto)

Please state, “How the results of this research is useful to society.” Also, you give as the goal of research, “to provide information for subsurface S-wave velocity structure,” but I think the readers can deepen their understanding if you also address the ripple effect of this research.

Answer (Ikuo Cho)

The subsurface S-wave velocity structure is directly linked to the “shakiness or stiffness of the ground.” If this information can be obtained at high density and high resolution, it will lead to “dramatic improvement of the forecasting precision of earthquake shaking.” I explained this point in the beginning.

3 Composition of the paper and its significance in synthesiology

Comment (Akira Kageyama)

The technology described in this paper is development of new technology including the theoretical investigation specifically for earthquake disaster prevention and mitigation, by enhancing the exploration precision of surface geology, using as a fundamental system the microtremor array exploration that one of the authors has been researching and putting to practical use for many years. It is an attempt for complementarity and strengthening of the fundamental system using new technology, and provides a new type of paper configuration for *Synthesiology*. Please keep this in mind and review the composition of the whole paper.

Answer (Ikuo Cho)

As you indicated, we wrote this paper as an example where the problem that could not be solved with conventional

technology was solved by partial improvement of an existing system. To clarify this point, in the final paragraph of Chapter 2, we emphasized that the precision of the new system could be improved essentially by obtaining wave propagation velocity of the ground, not just the ground oscillation characteristics, and that the improvement of one component of the existing integrated system can be an innovation. Also, in the final paragraph of Chapter 3 and the final paragraph of Section 4.1.2, we organized the technological development points such as the simplification of measurement, quality control, complete automation from data processing to visualization, quasi-real-time delivery, and others.

4 Advantage of S-wave velocity measurement

Comment (Akira Kageyama)

You discuss the velocity structure of S-waves, but can you more specifically address how you can provide merit to society with this technology? For example, you discuss “high precision of earthquake zoning,” but I think it will be easier to understand if you explain what the user can understand from this and how it will serve as material for making decisions.

Answer (Ikuo Cho)

We explained that the forecasting precision of earthquake shaking could be improved by using the actual data of ground oscillation and material properties that were only estimated based on a geomorphological classification.

5 Figure 4

Comment (Chikao Kurimoto)

Figure 4 contains the components of this research, and I think you should show the scenario of the paper using this figure.

Answer (Ikuo Cho)

The important point is the development from “microtremor array exploration” to “miniature arrays,” and we think this process is the major synthesesiological point of this paper. Therefore, the paper is composed around this process. In the paper, the “shallow velocity structure exploration system using a miniature microtremor array” is called the “new system.”

6 Three-point irregular array of Section 4.1.3

Question (Akira Kageyama)

In Paragraph 2, Section 4.1.3, you write, “such application of three-point irregular arrays is impossible in the conventional microtremor array exploration.” Is this because the data processing method for uneven intervals were not studied or developed? If so, is it correct to say that although the authors were preparing a measurement data processing method assuming equal interval layout of the array in the conventional microtremor array exploration, the authors returned to the “basic question” and newly developed and evaluated the data processing method for irregular array layout, and demonstrated that it was practical?

Answer (Ikuo Cho)

Yes, it is correct. Based on your question, we added “the data processing is done assuming that the arrays are laid out in equal intervals in the conventional microtremor array exploration,” and supplemented our insufficient explanation.