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Geotechnics — Array measurement of microtremors to estimate shear wave velocity profile

Géotechnique — Mesure en réseau des microtrémors pour estimer un profil de vitesse des ondes de cisaillement

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 182, *Geotechnics*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides the specifications on the equipment, survey and analysis procedure of array measurement of microtremors in order to estimate shear wave velocity profile.

This document is intended for use by administrators of infrastructure facilities (public sector institutions, such as national and local governments, and private institutions), building constructors, house builders, consultants, academia, and public/private research institutions. The array measurement of microtremors deliverable described in this document can be useful in various engineering fields such as the

— estimation of geotechnical site conditions for construction;

— stability assessment of foundations;

— evaluation of the risk for soil liquefaction;

— evaluation/prediction of earthquake ground motions.

Array measurement of microtremors is one of the geophysical measurements using surface waves, and it is a non-destructive testing method described in an application manual of geophysical methods to engineering and environmental problems[5] for estimating S-wave velocity profile from dispersive characteristics of the surface waves. Reliability of the method has been evaluated by blind tests and numerical simulations in several international projects[6],[12].

The array measurement of microtremors is a passive method using natural and artificial ambient vibrations. Since power of the ambient vibrations is highly variable from one site to the other, it will possibly not be applicable to a site where the ambient vibration level is less than internal noise of measuring instruments. The 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 is the most common surface wave method. In addition to the fundamental mode, including the processing of higher modes of the Rayleigh waves improves the reliability of the estimated S-wave velocity profile. However, a procedure for identifying the higher modes from observed microtremors is not authorized in academics yet. Hence, analysing the higher mode of the Rayleigh waves is out of scope in this document. Love waves is another type of surface waves extracted from horizontal ground vibration. Joint use of the Rayleigh waves and the Love waves also improves the reliability of the estimated S-wave velocity profile. However, the surface wave method using Love waves is not widely used in practice. Hence, the measurement and the analysing of the Love waves are out of scope in this document. Therefore, the array measurement of microtremors using vertical ground vibration and the data analysis of the microtremor records with an assumption of the fundamental mode of Rayleigh waves are described in this document.

This method provides a vertical S-wave velocity profile. The depth range of the S-wave velocity profile varies depending on the wavelength of observed surface waves. The profile estimated using surface wave has an uncertainty caused by estimation errors of the observed phase velocity. Therefore, it is important to include additional information from soundings [e.g. cone penetration test (CPT), standard penetration test (SPT)], borehole data and a prior geological information to reduce the uncertainty in the S-wave velocity profile by electing a reliable initial model or search area in the inversion analysis. Active method using artificial sources such as sledgehammer and weight drop is also useful to improve the accuracy of estimated S-wave velocity profile, particularly at very shallow depth of the profile from the additional phase velocity in high frequency. Additionally, horizontal-to-vertical (H/V) spectral ratio is useful to reduce the uncertainty of S-wave velocity profile estimated by the array measurement of microtremors from a peak frequency of the spectral ratio.

Regardless of the uncertainty in the estimated S-wave velocity profile, array measurement of microtremors has a great advantage in time, cost and environmental impact for the investigation compared to borehole measurements and soundings. Therefore, this method is expected to be widely applied in the field such as evaluation of soil structure and geotechnical site characteristics described above.

Geotechnics — Array measurement of microtremors to estimate shear wave velocity profile

1 Scope

This document specifies requirements for equipment, survey procedure, data analysis and reporting of array measurement of microtremors which is one of the non-destructive testing methods with an array of sensors deployed on the ground surface.

This document applies to the array measurement of microtremors to estimate a 1D shear wave velocity profile. This document 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.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, symbols and abbreviated terms

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Terms and definitions

3.1.1
amplifier
device amplifying signals detected by a sensor

3.1.2
array measurement of microtremors
simultaneous recording of microtremors by a set of sensors and data analysis

3.1.3
array size
distance between two sensors in the array

Note 1 to entry: For a circular array, the array size is expressed as a radius of the array.

3.1.4
data logger
device storing outputs from a sensor and time clock from a global navigation satellite system (GNSS) receiver

3.1.5
dispersion curve
phase velocity of surface waves as a function of frequency

3.1.6
huddle test
simultaneous recordings by all sensors placed as close as possible to each other, used for the array measurements of microtremors to confirm the consistency of frequency characteristics of the sensors

Note 1 to entry: In general, the consistency among sensors is evaluated in terms of the coherency, phase difference and power spectrum in the frequency range of interest.

3.1.7
microtremors
small amplitude vibration of the ground generated by either human activities or natural phenomena

Note 1 to entry: Human activities have dominant periods shorter than one second (frequency higher than 1 Hz). Natural phenomena such as climatic and oceanic conditions, have dominant periods greater than one second (frequency lower than 1 Hz).

3.1.8
operator
qualified person who carries out the array measurement of microtremors

3.1.9
phase velocity
velocity of a seismic wave at a single frequency traveling in the subsurface structure

3.1.10
sensor
instrument capable of measuring vibration

Note 1 to entry: Different types of sensors including accelerometers and velocity meters are used depending on the frequency range of interest.

3.1.11
signal-to-noise ratio
SNR
ratio of the level of a signal to the level of a noise

Note 1 to entry: The signal is what is analysed, and the noise is what is disturbing, such as sensor instrumental self-noise, weather actions on the sensor and vibrations caused by bad coupling with soil.

3.1.12
surface wave
seismic wave that travels along the surface of the ground

Note 1 to entry: The surface wave has dispersive characteristics that the phase velocity changes as a function of frequency. There are two types of surface waves: Rayleigh wave and Love wave.

3.1.13
S-wave velocity
shear wave velocity
true speed at which the S-wave of a seismic wave travels in the soil material

Note 1 to entry: The S-wave velocity is related to shear modulus and density of the soil.

3.2 Symbols and abbreviated terms

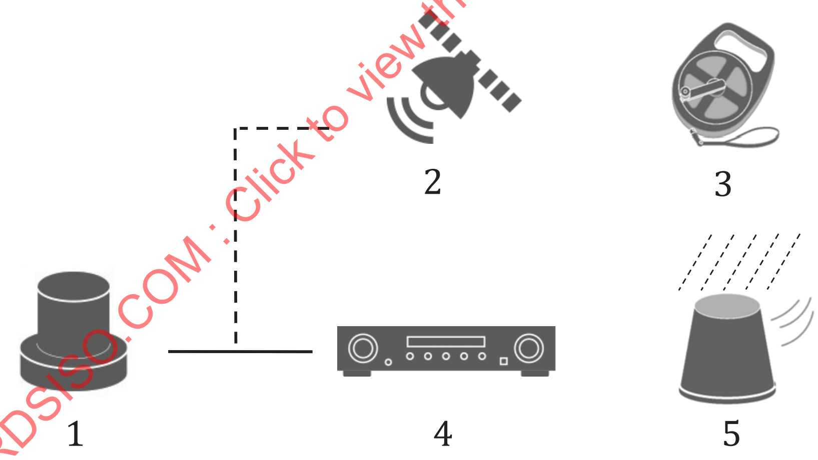
Symbol	Name	Unit
U	Displacement	m
V	Velocity	m/s
A	Acceleration	m/s^2
r	Radius of circular array	m

Symbol	Name	Unit
x	Aperture of two sensors	m
SNR	Signal-to-noise ratio	-
NS	Noise-to-Signal	-
c	Phase velocity	m/s
Vp	P-wave velocity	m/s
Vs	S-wave velocity	m/s
DEN	Density	kg/m^3
h	Thickness of layer	m
λ	Wavelength	m
ρ	Coherency	-
f	Frequency	Hz
PSD	Power spectrum density	dB

4 Equipment

4.1 General

To carry out an array measurement of microtremors, equipment which consists of several devices, as shown in Figure 1, is generally required, and the equipment shall satisfy the performance detailed in 4.2 to 4.6.



Key

1 sensor
2 time calibration equipment
3 distance and location-measuring instrument
4 data logger
5 protective products

Figure 1 — Example devices for an array measurement of microtremors

4.2 Sensor

A highly sensitive sensor, which is capable of measuring microtremors in the frequency range of interest corresponding to a depth of shear wave velocity profile to be investigated, shall be used. The sensor shall be installed horizontally using a level. The instrument noise level should be less than the targeted amplitude level of the power spectrum calculated from microtremor records at each frequency.

In the array measurement of microtremors, the same type of sensors which have the similar specification in the frequency range of interest should be used.

4.3 Time calibration equipment

The time clock of all data loggers shall be synchronous during the array measurement of microtremors, and the time calibration among the data loggers is required. Precise time synchronization shall be carried out by using appropriate devices such as time clock in GNSS. Otherwise, all the sensors shall be connected to a data logger by cables to ensure that the time is synchronous.

4.4 Data logger

A data logger should equip an internal or external amplifier that has a capability to amplify a weak analog signal in case that instrumental noise level is close to the target amplitude level and signal-to-noise ratio (SNR) is low.

A data logger shall convert the analog signal from a sensor to digital value with an appropriate filter with high linearity and store it in a digital form. The conversion resolution shall be 16 bits or higher. The stored digital record (e.g. Volt) is normally used for transforming to physical properties such as acceleration, velocity and displacement [A (m/s^2), V (m/s), U (m)].

4.5 Distance and location measuring instrument

The distances between the sensors or locations of the sensors in an array measurement of microtremors shall be measured by using appropriate measuring instruments such as tape measure, laser range finder and GNSS. The distance and location measuring instruments shall be selected to satisfy the accuracy. The sensors should be deployed to designated locations within at least 5 % error of array size or investigation depth[5].

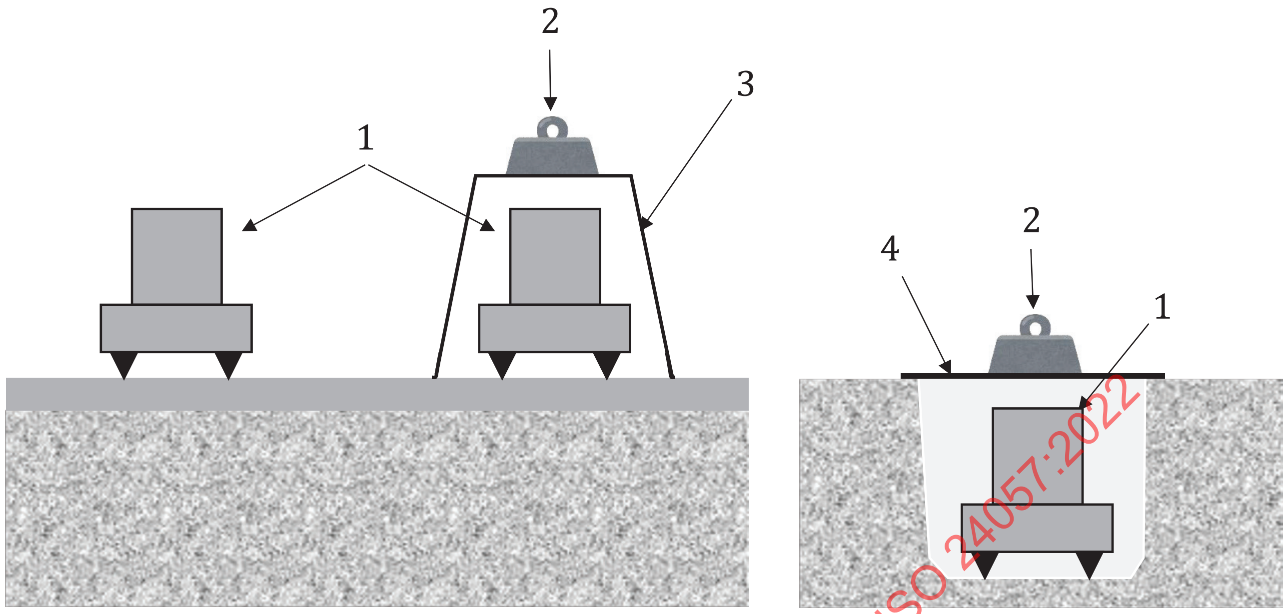
4.6 Protective products

Because wind and rain can be unwanted noise generators, protective products should be used as windshields and rain guards, when necessary. These items are also used for a safe installation of a sensor (see Figure 2 left).

— Windshield/rain guard.

— Weights.

Sensor may be buried in the ground as a substitute of using the windshield (see Figure 2 right).



Key

1 sensor

2 weight

3 windshield and rain guard

4 rain guard

Figure 2 — Example of protection of sensor from wind and rain

5 Survey procedure

5.1 General

Clause 5 describes basic requirements for a survey procedure including preparation, field observation and data organization after the field observation. The survey procedure of the array measurement of microtremors is illustrated in Figure 3. Annex B shows an example of records and analysis results for the array measurement of microtremors.

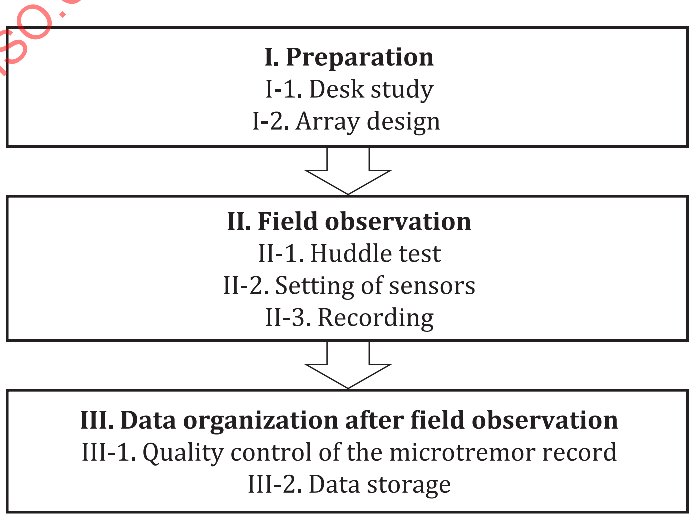


Figure 3 — Typical flow chart of a survey procedure of array measurement of microtremors

5.2 Preparation

5.2.1 Desk study

A desk study shall be performed to plan for an array measurement of microtremors at the beginning of a project.

Pre-existing information such as geological map and geotechnical borehole data shall be collected when they are available.

— Geological map.

— Geological condition.

— Geotechnical borehole data.

— Characteristics of the surface layer.

— Surface elevation.

— Underground facilities.

— Any other information available on the surrounding environment.

The field observation site shall be selected to obtain microtremor records with high quality, avoiding, if possible, contaminations from nearby traffic, industrial machinery in factories, construction, and pedestrians.

The operator shall check for special environmental conditions of installation (e.g. potentially explosive atmospheres (ATEX), safety hazard) to adapt the survey or prepare specific changes to the installation procedure.

Applications for a permission to enter a site shall be prepared and submitted to responsible organizations such as the police and local government or land-owners before carrying out a field observation if necessary.

5.2.2 Array design

Array configuration and array size shall be determined as described in Annex C by taking into account the wavelength corresponding to the depth range of shear wave velocity profile to be investigated in the project. In case that one array does not cover the depth range to be investigated, multiple array measurements shall be carried out within the perimeter delimited by the largest array, whenever possible. The location of each sensor shall be determined on a map according to the appropriate array configuration and array size designed for the project.

5.3 Field observation

5.3.1 Huddle test

A huddle test shall be carried out to confirm the consistency of frequency characteristics of the measurement equipment including all sensors and data logger in the frequency range of interest on site immediately before starting array measurement of microtremors at each site.

In the huddle test, all sensors shall be deployed within several meters in and/or nearby a site for array measurement of microtremors and record microtremor data simultaneously.

A huddle test shall be carried out in a quiet place where there are no sources of strong disturbances and a place likely to be homogeneous and without void (e.g. sewer, reservoir).

Setting of the sensors shall follow to the procedure described in 5.3.2.

As for the consistency of the frequency characteristics of all the sensors, coherency of observed microtremor records between each pair of sensors shall be confirmed as shown in Annex D. When the coherency between a pair of sensors is significantly low, it is possible that one of the sensors is malfunctioned and shall be replaced.

After it has been confirmed that the power spectrums of microtremors during the huddle test is sufficiently larger than those internal noises, the array measurement of microtremors shall be carried out. Each time sensors or some of the acquisition parameters, such as amplifier gain and sampling frequency of data logger, are changed in the array measurement of microtremors, the huddle test shall be carried out each time.

5.3.2 Setting of sensors

Each sensor shall be installed at the location described in 5.2.2. Installation on gentle slopes and mildly irregular topography are permitted, but sites with unusual topographic features (e.g. surface cracks, scarps, karstic dolines) should be avoided. The sensors of the array should be deployed in areas with topographic variations less than about 10 % of the targeted wavelengths[6].

Each sensor shall be set according to procedures as follows:

— Installation of sensors on the ground without much grass and roots to ensure good coupling with the ground by following a guideline such as SESAME[11].

— Adjusting horizontal level.

— The operator checks the recording by dropping a weight nearby or knocking a sensor and check the signal polarity.

— Measuring azimuth of sensors and aligning to the same orientation when three component sensors are used.

— Noting local/global coordinates at the locations of sensors using distance, and location-measuring instrument described in 4.5.

— Noting distance from possible sources of traffic, industrial machinery in factories, construction and pedestrians.

— Taking photos of installation of the sensors and surrounding the environment at each sensor.

In case local disturbance unavoidably occurs, an operator shall take a detailed note of possible sources.

In case of bad climate, sensors shall be protected from wind and rain using the protective products described in 4.6. Climate during array measurement of microtremors shall be noted. When the protective products are used or sensors are buried in the ground, the sensor installation condition shall be noted.

5.3.3 Recording

5.3.3.1 Recording duration

Recording duration shall be set according to the wavelength related to array size of array measurement of microtremors. An indication of the recording duration for the different array sizes is as follows:

a) Array size smaller than 30 m: 30 min.

b) Array size from 30 m to 100 m: 30 min to 1 h.

c) Array size larger than 100 m: longer than 1 h to several hours.

NOTE The array size is usually expressed as a radius of a circular array.

These durations should be increased for environments with transient disturbances such as town centres.

5.3.3.2 Sampling frequency

Microtremor records shall be sampled by appropriate sampling frequency, considering the Nyquist frequency and reproduction of digitized waveforms. The sampling frequency of 100 Hz to 200 Hz should be applied.

5.4 Data organization after field observation

5.4.1 Quality control of the microtremor record

The microtremor record should be verified roughly on site whether they are sufficiently stationary at all sensors by checking waveforms and/or PSD in the frequency range of interest, excluding a harmonic vibration and impulsive disturbances by nearby traffic, industrial machinery in factories, construction and pedestrians. When a time-correction by GNSS is applied in array records of microtremors, the reception of GNSS shall be confirmed. In case that poor quality of the record is found, determine the causes such as failure of a time-correction by GNSS, malfunctions of equipment, strong disturbances in and around an array. After removal of the causes of the poor quality of the records, re-measurement shall be carried out. Examples of good and poor-quality records are shown in Annex E.

5.4.2 Data storage

Storage of retrieved data from data logger to other devices shall be performed with an open format (e.g. ascii, csv) or a standard binary format (e.g. SEG-2, SEG-Y, SAC). Information of data is given in Clause 7.

6 Data Analysis

6.1 Data organization after field observation

Clause 6 describes basic requirements for data analysis of the array measurement of microtremors. The data analysis consists of two parts as below:

— Phase velocity analysis: a process of estimating phase velocities of Rayleigh waves from vertical component of array records of microtremors.

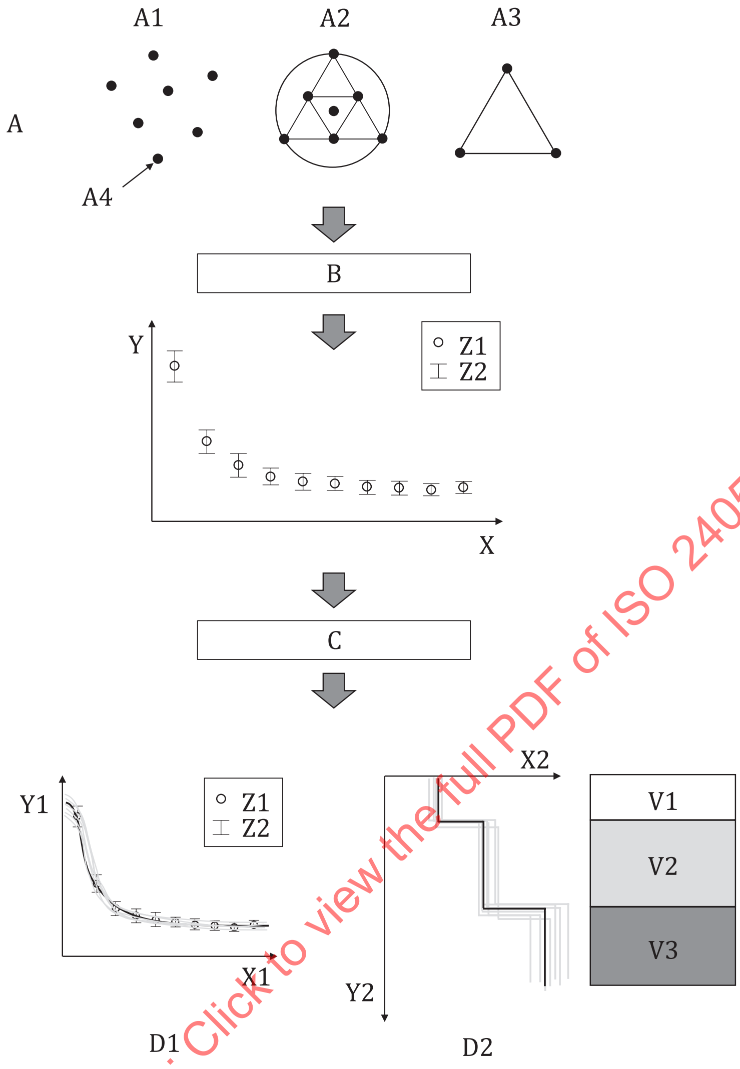
— Inversion analysis to S-wave velocity profile: a process of inverting phase velocity to an S-wave velocity profile.

Figure 4 shows a flow chart of the data analysis of array measurement of microtremors, and an example of data analysis results is shown in Annex B.

NOTE This method assumes one-dimensional laterally homogeneous layered structure, thus, provides an average S-wave velocity profile within an array even if there are lateral variations in S-wave velocity.

6.2 Phase velocity analysis

Phase velocity of Rayleigh waves at each frequency shall be calculated from array records of microtremors by appropriate method as shown below:



Key

A	array configuration	X1	frequency
A1	F-K method (irregular shape array)	Y1	phase velocity
A2	SPAC method (circular array)	X2	S-wave velocity
A3	CCA method (centreless array)	Y2	depth
A4	sensor	V1	Vs of 1st layer
B	phase velocity analysis	V2	Vs of 2nd layer
C	inversion analysis to S-wave velocity profile	V3	Vs of 3rd layer
D1	theoretical dispersion curves for each profile	Z1	observed phase velocity
D2	S-wave velocity profile	Z2	±2σ (error bar)

Figure 4 — Flow chart of the data analysis of array measurement of microtremors

— F-K method (frequency wavenumber method)

— SPAC method (spatial autocorrelation method)

— ESPAC method (extended spatial autocorrelation method)

— MSPAC method (modified SPAC method)

— CCA method (centreless circular array method)

The details of each method are described in Annex F.

NOTE 1 Phase velocity of Rayleigh waves is generally calculated by using vertical components, while phase velocity of Love waves is calculated by using horizontal components.

NOTE 2 In principle, for the laterally layered structure, there are several propagation modes in the surface waves. Among the several modes such as fundamental mode and higher modes, fundamental mode mostly has dominant energy compared to higher modes. Thus, we process the data as the fundamental mode; however, higher modes are not neglected in some cases, and the data analysis with assumption of the fundamental mode causes a certain bias for the true S-wave velocity profile.

The operator shall comment if the picked phase velocity can correspond to higher modes.

6.3 Inversion analysis to S-wave velocity profile

A S-wave velocity profile shall be estimated from the observed phase velocities by an inversion analysis. In the inversion analysis, a horizontal layered structure is assumed, and each layer is characterized by four parameters which influence to Rayleigh waves as shown below:

— S-wave velocity (Vs)

— Thickness (h)

— P-wave velocity (Vp)

— Density (DEN)

Since S-wave velocity and thickness are influential parameters on the characteristics of the dispersion curve, S-wave velocity and thickness of each layer are treated as unknown variables in the inversion analysis. When the thickness of each layer is known in the desk study in 5.2.1, only S-wave velocity of each layer is treated as a variable in the inversion analysis. P-wave velocity and density are mostly assumed using an empirical relation to S-wave velocity or fixed as given values. Underground water table depth helps to define the P-wave velocity below the water table since it governs the P-wave velocity of soft sediments.

The details of the inversion analysis are described in Annex G.

6.4 Uncertainty of phase velocity and S-wave velocity profile

The uncertainty of the following results should be evaluated.

— Observed phase velocity.

— Estimated S-wave velocity profile.

In the estimation of S-wave velocity profile by the array measurement of microtremors, the uncertainties arise from the phase velocity analysis and the inversion analysis. The former uncertainties of the observed phase velocity are caused by the errors in time synchronization and distance measurement, poor data quality, and so on in the part of phase velocity analysis. The latter uncertainties of the estimated S-wave velocity profile are caused by the error propagation from the observed phase velocities in the part of inversion analysis to S-wave velocity profile.

Moreover, there is a non-uniqueness of the S-wave velocity profile estimated from the observed phase velocity in the inversion analysis using the heuristic methods such as the simulated annealing and the genetic algorithm. When the heuristic methods are used in the inversion analysis, the non-uniqueness of the S-wave velocity profile should be evaluated.

An example of uncertainty of the observed phase velocity and the estimated S-wave velocity profile is shown in Annex H. Also, a non-uniqueness of the S-wave velocity profile in the inversion analysis using the heuristic method is shown in Annex H.

NOTE In case the site condition is laterally and vertically complexed, the uncertainty estimated on the assumption of the one-dimensional layering is not valid.

7 Reporting

7.1 General

Clause 7 describes basic requirements for field and analysis reports to be easily accessible to the data and results in digital form by third parties.

7.2 Field report

The field report shall contain all data collected in the field. The following information shall be included for each array measurement of microtremors, if available.

a) General information

   1) Name of the client

   2) Name of the contractor

   3) Name of the project

   4) Name of the site

   5) Name of the field operator in charge

   6) Name of the field manager in charge

b) Information of the equipment

   1) Sensor

      — Type of sensor (accelerometer or velocity-meter)

      — Number of component (e.g. 3 components, 1 component)

      — Polarity

      — Sensitivity [e.g. V/(m/s^2), V/(m/s)]

      — Frequency characteristics

      — Manufacturer, model and serial-number of the sensor, if available.

   2) Time calibration equipment

      — Method used

      — Manufacturer and model when it applies

   3) Data logger

      — Amplifier gain (e.g. 20 dB)

      — Sampling frequency (e.g. 100 Hz)

      — Characteristics of filter

- — Specification of A/D converter (e.g. 16 bit, 24 bit)
- — Least significant bit (e.g. µV/LSB)
- — Recording storage devices (e.g. SD card)
- — Manufacturer, model, and serial-number of the data logger
- — Data format

4) Distance and location-measuring instrument
   - — Type of the measuring instrument (e.g. tape measure, laser range finder, GNSS)
   - — Distance error of measuring instruments

5) Protective products
   - — Whether it is used or not
   - — Type of the protective products (e.g. windshield, rain guard)
   - — Sensor is buried or not

c) Information on the huddle test

1) Date and time
2) Field sketch
3) Name of the project photos of the installation of the sensors
4) Name of the site weather condition
5) Place and coordinates (latitude, longitude, altitude)
6) Surface condition (e.g. sensor is set on the soil/concrete)
7) Azimuth of sensors when three component sensors are used
8) Recording duration
9) File list
10) Records of huddle test [open format (e.g. ascii, csv) or a standard binary format (e.g. SEG-2, SEG-Y, SAC)]
11) Implementation or absence of time correction by GNSS
12) Unusual events and/or interruptions during the measurement

d) Information on array measurement

1) Date and time
2) Field sketch
3) Photos of the installation of each sensor and array
4) Weather condition
5) Place and coordinates (latitude, longitude, altitude) of the site (e.g. the centre of the array)
6) Array design (array configuration and array size)
7) Locations of each sensor in the array or coordinates of each sensor

8) Surface condition (e.g. sensor is set on the soil/concrete)
9) Azimuth of sensors when three component sensors are used
10) Frequency range of interest determined by the array design
11) Recording duration
12) File list
13) Records of array measurement [open format (e.g. ascii, csv) or a standard binary format (e.g. SEG-2, SEG-Y, SAC)]
14) Implementation or absence of time correction by GNSS
15) Unusual events and/or interruptions during the measurement

e) Other information
1) Overall plan of field observation for array measurement of microtremors
2) Permission to enter a site by responsible organizations or land-owners

7.3 Analysis report

The following information shall be included for each data analysis of array measurement of microtremors when they are available.

a) General information
1) Name of the client
2) Name of the contractor
3) Name of the project
4) Name of the site
5) Name of the analyst in charge

b) Information of the equipment
1) Geological information
2) Geophysical and geotechnical information (e.g. borehole data)
3) Other information

c) Information on the huddle test
1) Waveforms
2) Power spectra
3) Coherence, phase difference and amplitude spectrum ratio

d) Information on the array measurement of microtremors
1) File list of the microtremor records used in the data analysis
2) Explanation of the selection of the time period from the microtremor records
3) Analysis methods applied to the microtremor records in the phase velocity analysis (e.g. F-K, SPAC, ESPAC, CCA)

4) Details of the phase velocity analysis
5) Comments if the picked phase velocity can correspond to higher modes
6) Results of phase velocity (e.g. individual, integrated/averaged)
7) Inversion methods applied to the phase velocity
8) Details of the inversion analysis (e.g. parameters, initial model/search area)
9) Results of estimated S-wave velocity profile
10) P-wave velocity and density profiles used
11) Waveforms used in the data analysis
12) Fourier/power spectra of the waveforms used in the data analysis
13) Uncertainty in the phase velocity and S-wave velocity profile and the uncertainty quantification methods
14) Non-uniqueness of the S-wave velocity profile in the inversion analysis
15) Application software used in the data analysis

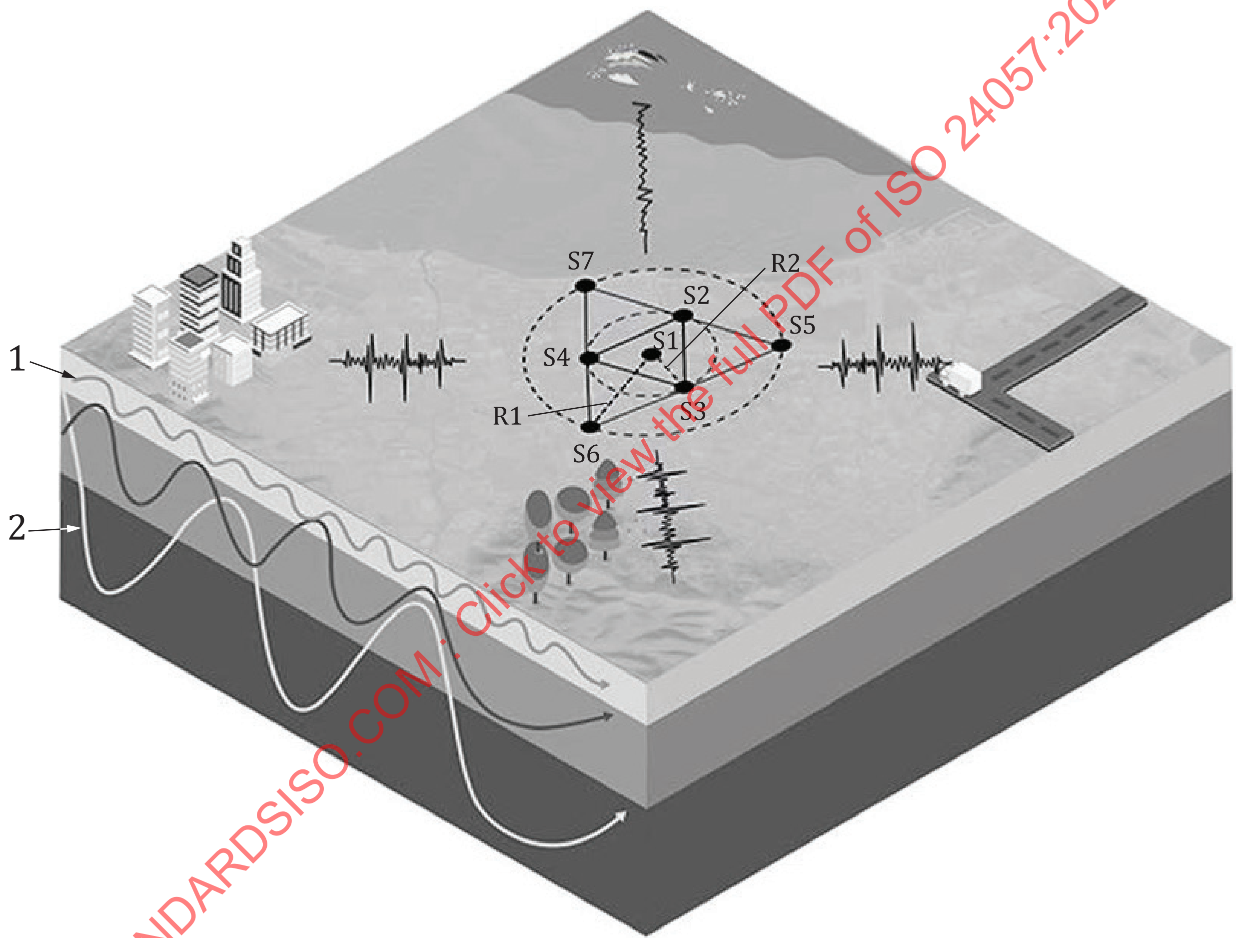
e) Other information/remarks

1) Figures for supplementing the results
2) Comments for the results
3) References

Annex A
(informative)

Example of a figure and a table schematic figure of array measurement of microtremors

A schematic figure of array measurement of microtremors is shown in Figure A.1.



Key

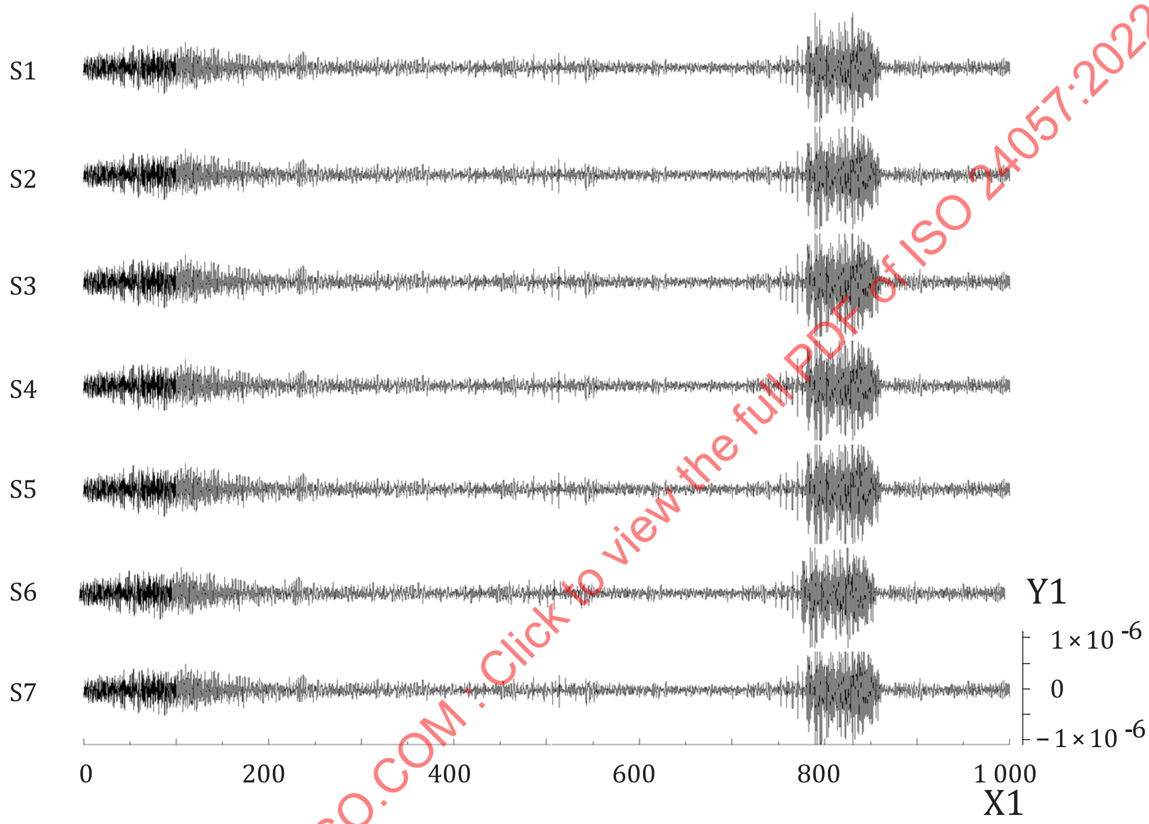
1 high frequency microtremors
2 low frequency microtremors
S1 sensor 1
S2 sensor 2
S3 sensor 3
S4 sensor 4
S5 sensor 5
S6 sensor 6
S7 sensor 7
R1 array radius 1
R2 array radius 2

Figure A.1 — Schematic figure of the array measurement of microtremors, with environmental and artificial conditions in the field, and propagation of high and low frequency microtremors in subsurface

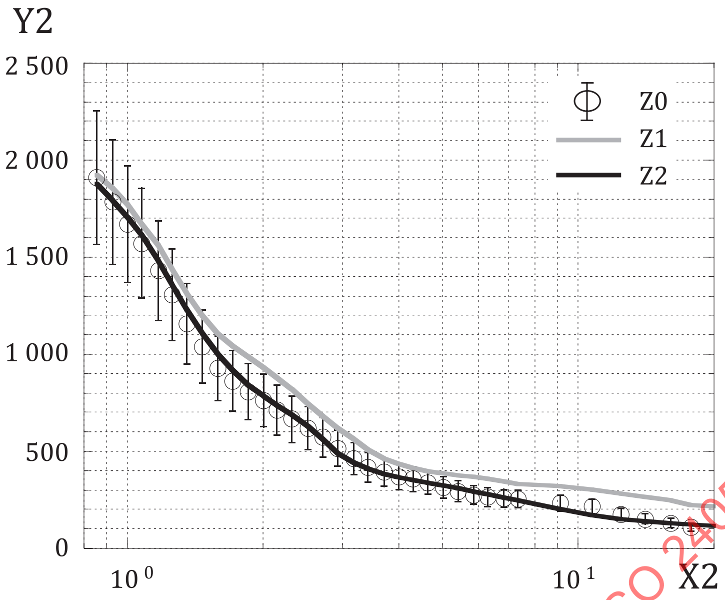
Annex B
(informative)

Example of microtremor records and analysis results

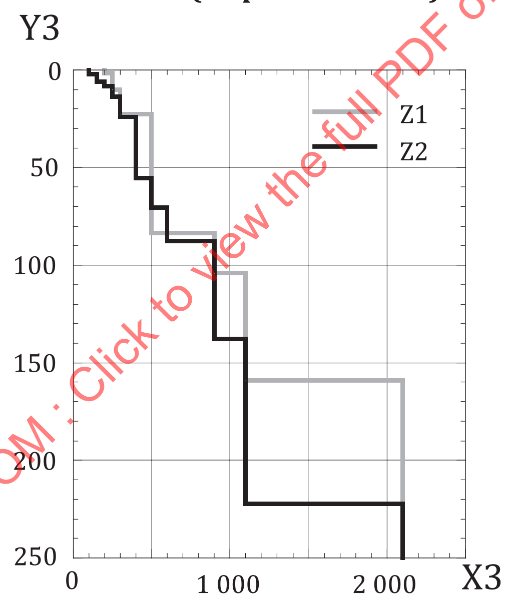
Example of microtremor records and analysis results for the array measurement of microtremors is shown in Figure B.1.



a) Vertical component of microtremor records measured in the double concentric equilateral triangle array by seven sensors



b) Dispersive characteristics (dispersion curve) of the microtremors



c) S-wave velocity profile

Key

X1 time (s)
X2 frequency (Hz)
Y2 phase velocity (m/s)
X3 S-wave velocity (m/s)
Y3 depth (m)
Y1 velocity (m/s)
Z0 observed
Z1 calculated [initial]
Z2 calculated [final]

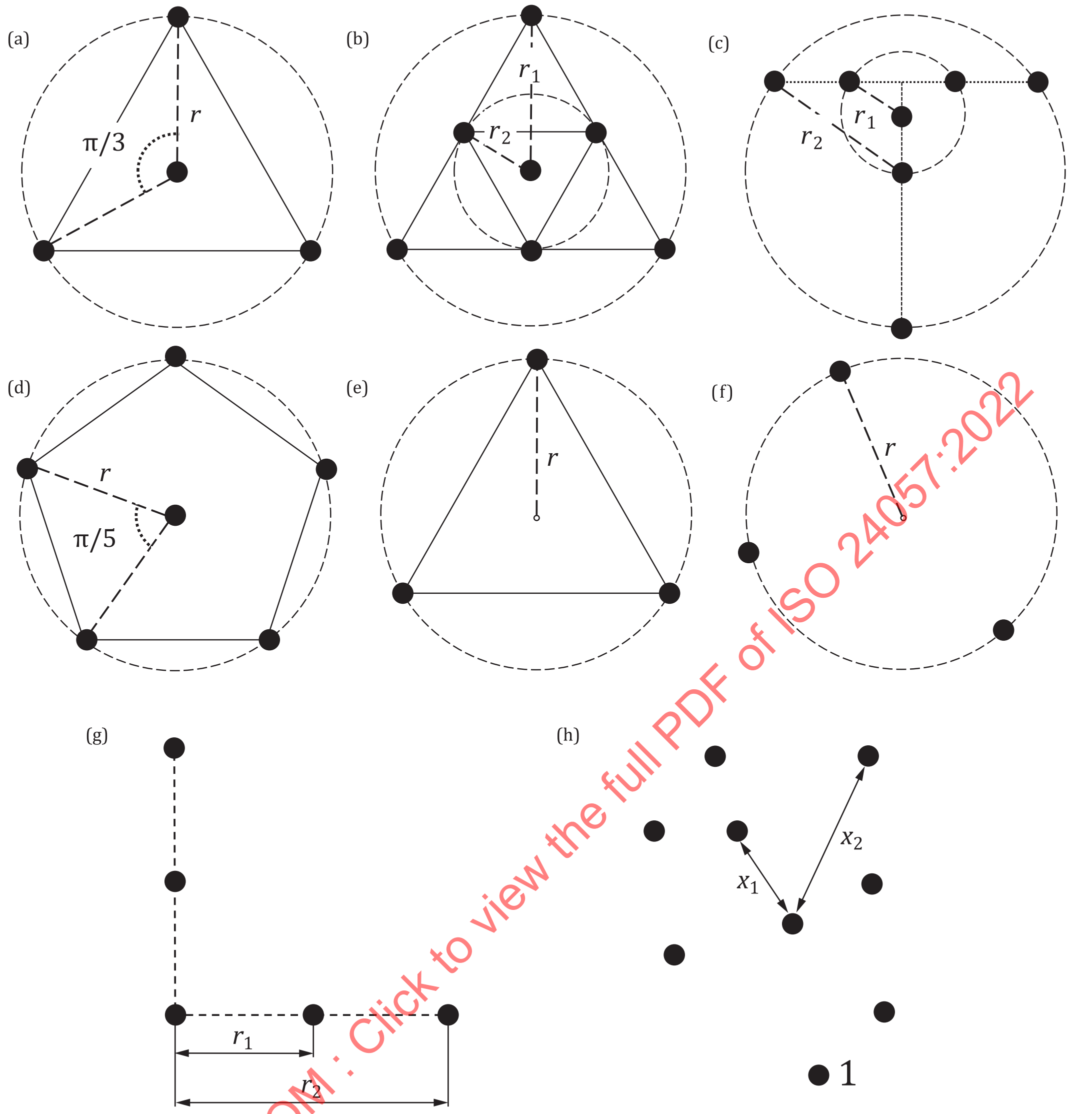
Figure B.1 — Example of microtremor records and analysis results for the array measurement of microtremors

Annex C
(normative)

Array design

C.1 Array configuration

Examples of the array configurations are shown in Figure C.1. The line segment *r* and *x* in Figure C.1 indicate radius of the circles and aperture of two sensors.



Key

1 sensor

(a) Equilateral triangle array

(b) Double concentric equilateral triangle array

(c) T-shape array

(d) Equilateral pentagon array

(e) Centreless equilateral triangle array

(f) Irregular type centreless triangle array

(g) L-shape array

(h) Irregular shape array

Note that array configuration of (b) and (c) are multiple type of (a).

Figure C.1 — Array configurations

The array configuration with no preferential direction [circular configuration shown in Figure C.1 (a), (b), (c), (d)] should be recommended because source locations of microtremors are generally unknown. However, L-shape (g) and other flexible configurations may be adopted where an accessibility to site is limited.

C.2 Array size

The maximum and the minimum analysable wavelengths of Rayleigh waves are empirically estimated from the radius of the circle (the aperture of two sensors) by Formulae (C.1) and (C.2). Accordingly, the minimum and maximum analysable wavenumbers are calculated by Formulae (C.3) and (C.4). The ratio of the maximum analysable wavelength of Rayleigh waves to a radius of the circle is generally several to tens depending on the power of microtremors, the array configurations, and the analysis methods. The ratio of the minimum analysable wavelength of Rayleigh waves is two, based on the Nyquist wavenumber. The maximum analysable wavelength for a radius of the circle differs depending on analysis methods, and the maximum analysable wavelength by the SPAC and the CCA methods is generally longer than the one by the F-K method. In case of a miniature array, the analysable wavelength by the CCA method is generally longer than the SPAC method.

$$\lambda_{max} = N_{max} \cdot r \tag{C.1}$$

$$\lambda_{min} = N_{min} \cdot r \tag{C.2}$$

$$k_{min} = \frac{1}{\lambda_{max}} \tag{C.3}$$

$$k_{max} = \frac{1}{\lambda_{min}} \tag{C.4}$$

where

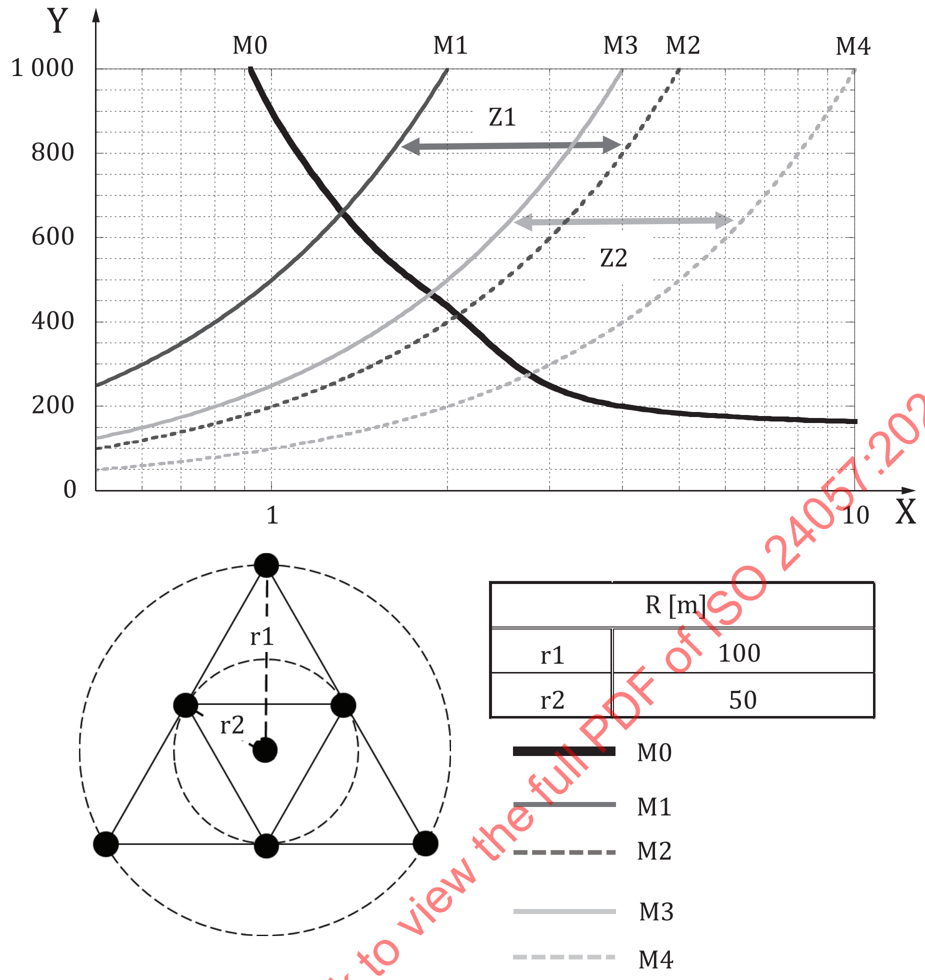
λ_{max}	is the maximum analysable wavelength of Rayleigh waves;
λ_{min}	is the minimum analysable wavelength of Rayleigh waves;
N_{max}	is the ratio of the maximum analysable wavelength of Rayleigh waves to a radius of the circle;
N_{min}	is the ratio of the minimum analysable wavelength of Rayleigh waves to a radius of the circle;
r	is the radius of the circle in the array;
k_{min}	is the minimum analysable wavenumber;
k_{max}	is the maximum analysable wavenumber.

Figure C.2 shows the maximum and minimum analysable wavelengths with respect to the frequency for two different radii in the array (r1, and r2). The solid line and the dot line indicate the maximum and the minimum analysable wavelengths when N_{max} and N_{min} are 5 and 2, respectively.

A frequency range of interest corresponding to the depth of S-wave velocity profile to be investigated should be determined by the maximum and minimum analysable wavelengths in a theoretical dispersion curve based on an S-wave velocity profile collected in the desk study.

When the frequency range defined by arrays with certain radii cannot fully cover the frequency range of interest, additional arrays with different radii shall be included in array design. The frequency range defined by an array and adjacent-sized arrays should be overlapped.

When a prior information on S-wave velocity profile near the site is not available, the maximum array size may be one to two times to the maximum depth to be investigated and the minimum array size may be equal to the desired spatial resolution of the S-wave velocity profile near the surface.



R [m]	
r1	100
r2	50

Key

X	frequency (Hz)	M0	fundamental mode
Y	phase velocity (m/s)	M1	K min (r1)
R	array radius (m)	M2	K min (r2)
Z1	frequency range of array (r1)	M3	K max (r1)
Z2	frequency range of array (r2)	M4	K max (r2)

Figure C.2 — Array configurations

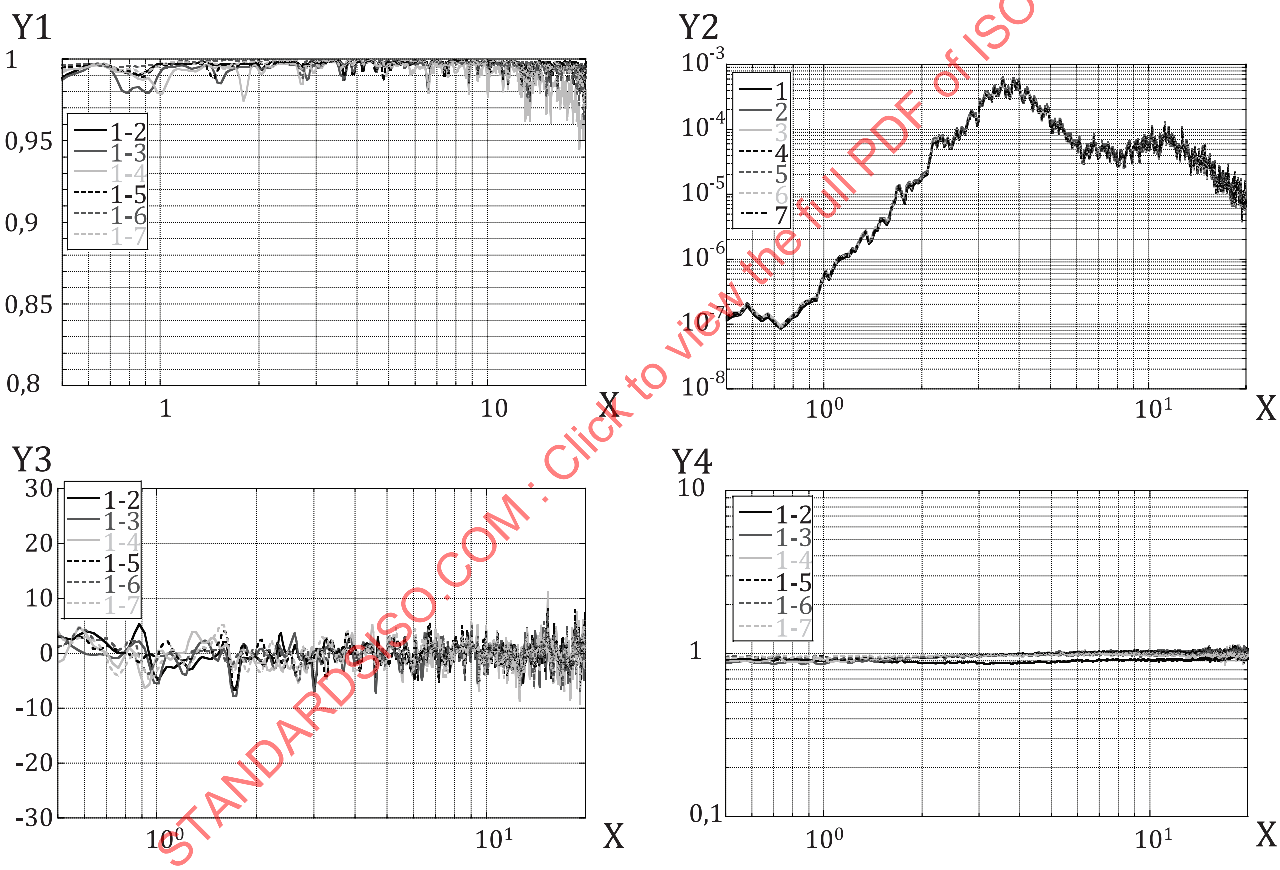
Annex D
(informative)

Frequency characteristics of sensors in huddle test

The consistency of frequency characteristics of sensors to be used in the array measurement of microtremors is confirmed by a huddle test.

To confirm the consistency of frequency characteristics of sensors, coherency, phase difference, power spectrum, and amplitude spectrum ratio are generally used as shown in Figure D.1.

As a high coherency and a small phase difference values between any pairs of sensors, for instance, the coherency of more than 0,95 and/or the phase difference of within ±5 degrees are recommended for the frequency range of interest.



Key

X frequency (Hz)
Y1 coherency
Y2 power spectrum
Y3 phase difference (degree)
Y4 amplitude spectrum ratio

NOTE The number in the key represents the number of sensor or sensor pair.

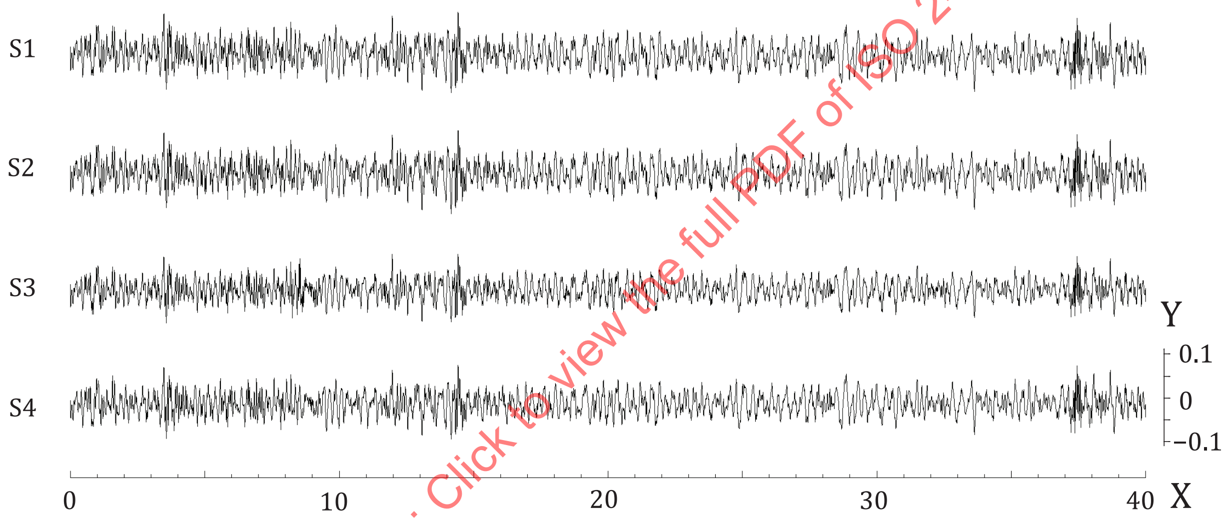
Figure D.1 — Example of huddle test (coherency, phase difference, power spectrum and amplitude spectrum ratio)

Annex E
(informative)

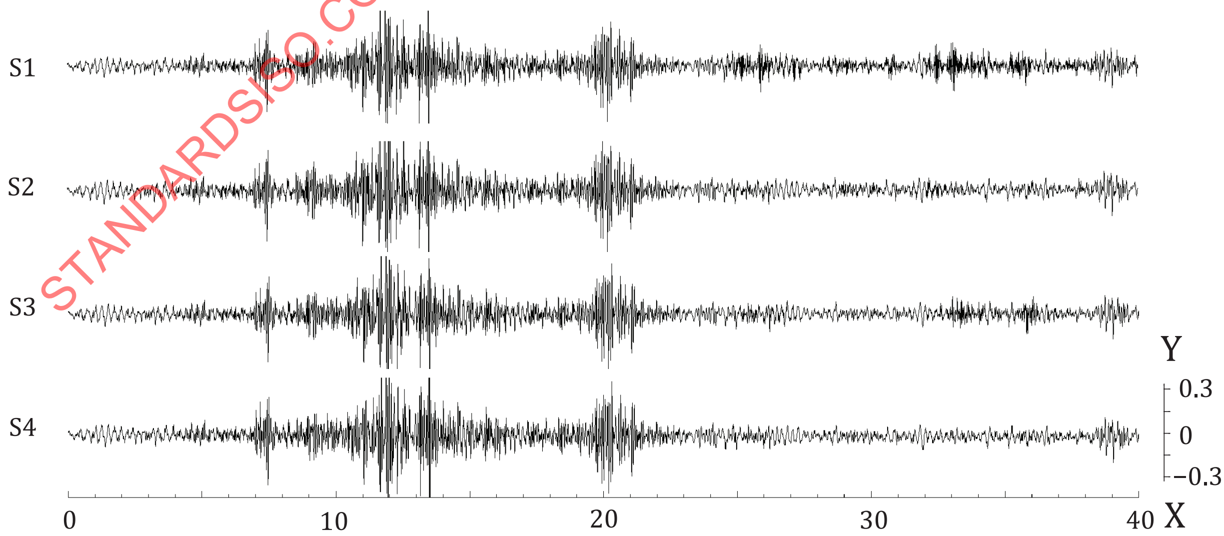
Examples of good and poor quality microtremor records

Waveforms and power spectra of good and poor quality microtremor records are shown in Figures E.1 and E.2, respectively. In Figure E.1, in the case of good quality, the correlation of the waveforms between the sensors is high, whereas in the poor quality, the correlation of the waveforms between the sensors is low.

In Figure E.2, in the case of good quality, the power spectrum of each sensor exceeds the sensor's instrumental noise level, whereas in the case of poor quality, it is close to the instrumental noise level.



a) Good quality



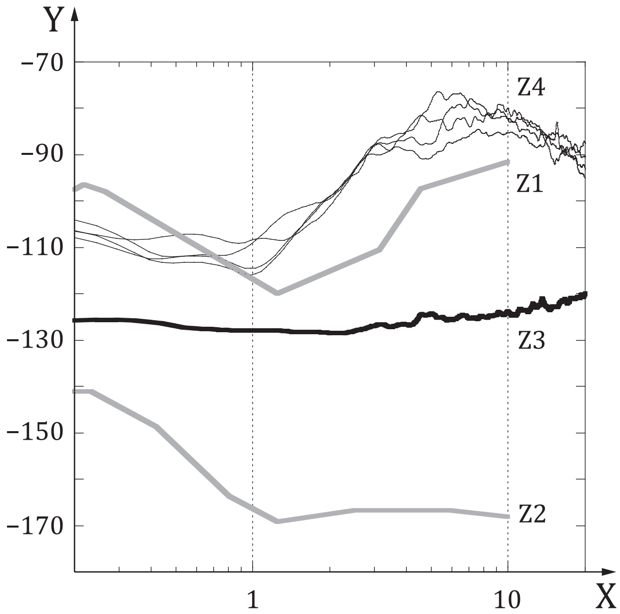
b) Poor quality

Key

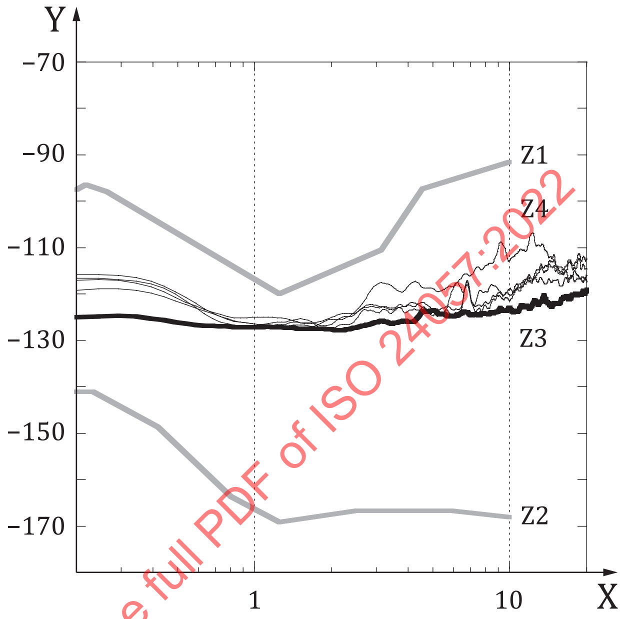
X time (s)

Y acceleration (m/s^2)

Figure E.1 — Examples of waveforms of the microtremor records measured by four sensors



a) Good quality



b) Poor quality

Key

X frequency (Hz)

Y acceleration power (dB re m^{2}s^{-3})

Z1 NHNM[10]

Z2 NLNM[10]

Z3 self-noise

Z4 power spectrum

NOTE A comprehensive standard model of microtremors recorded by broad band sensors (NHNM, NLNM)[10] is shown for a reference.

Figure E.2 — Power spectrums corresponding to the good and poor quality microtremor records

Annex F
(informative)

Methods for phase velocity analysis

F.1 F-K method (Frequency wavenumber method)

In the F-K method, frequency-wavenumber power spectral density function is calculated to estimate the phase velocity and a direction of microtremors propagating in an array. Two methods have been devised for data from an array with non-uniform distances between neighbouring sensors. One is the frequency-domain beam-forming method (BFM)[8] and another is the maximum likelihood method (MLM)[3]. The MLM has higher resolution in F-K power spectra than BFM, and most widely used within the context of analysis of array measurement of microtremors[7]. Representations for BFM and MLM according to Okada[9] are shown below:

In BFM, estimated power spectrum is written as a weighted average of the true power spectrum P(k_x,k_y,ω) [see Formula (F.1)].

$$\hat{P}\left(k_x,k_y,\omega\right)=\int\int_{-\infty}^{\infty}W\left(\kappa_x-k_x,\kappa_y-k_y\right)P\left(k_x,k_y,\omega\right)d\kappa_x d\kappa_y \tag{F.1}$$

$W(\kappa_x, \kappa_y)$ is called “array response” and is unique to the distribution of sensors.

In MLM,

$$P'\left(k_x,k_y,\omega\right)=\left\{\sum_{i=1}^{N}\sum_{j=1}^{N}\phi_{ij}\left(\omega\right)exp\left[ik_x\left(x_i-x_j\right)+ik_y\left(y_i-y_j\right)\right]\right\}^{-1} \tag{F.2}$$

$\phi_{ij}(\omega)$ is an element of the matrix $\Phi(\omega)$ and (x_i, y_i) is the position coordinates of the sensor;

$\Phi(\omega)$ is the inverse matrix of the Fourier transform of the covariance matrix $\sigma_{\tau,i,j}$;

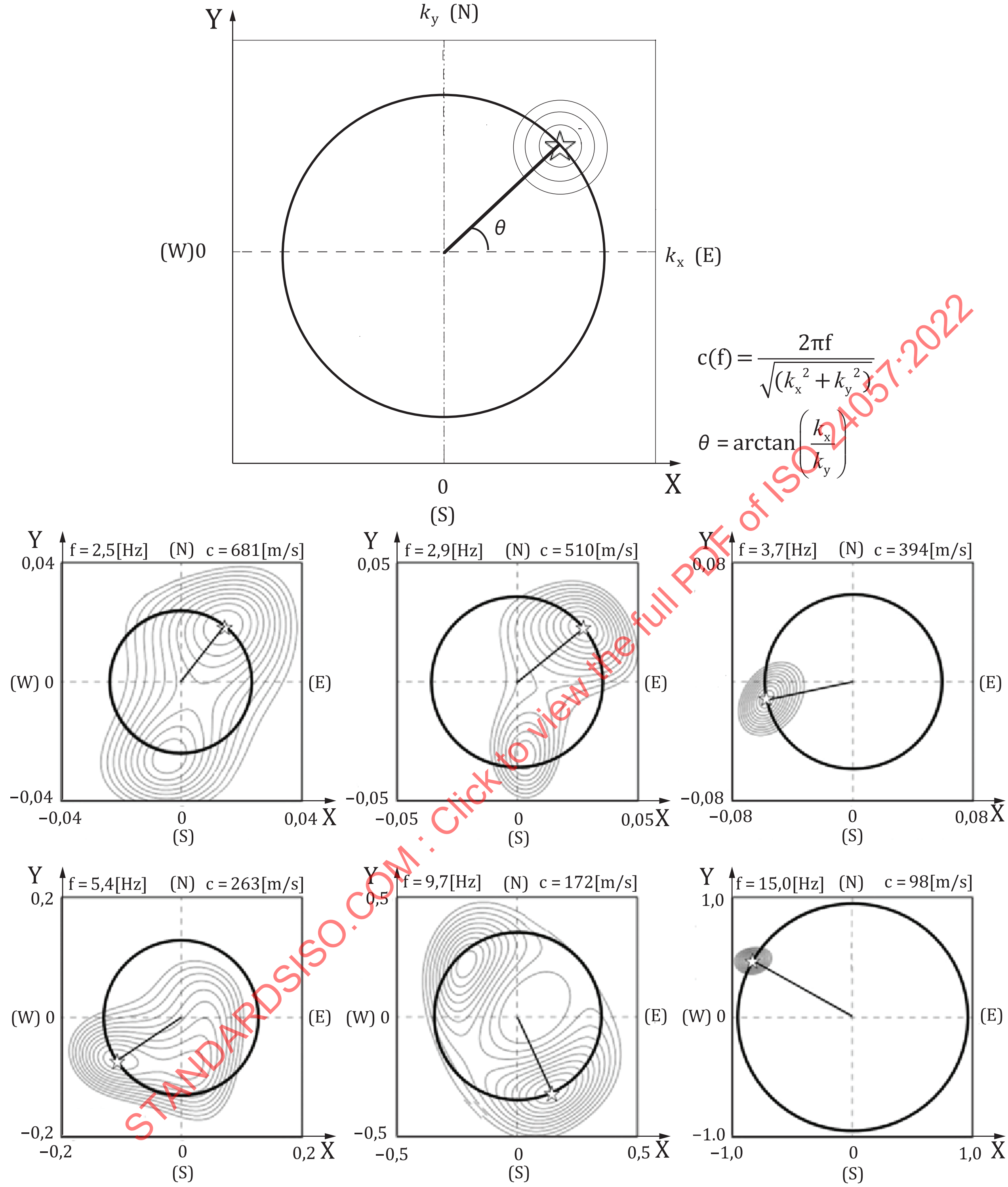
$\sigma_{\tau,i,j}$ $=\mathrm{E}\left[X_{t,i}\cdot X_{t+\tau,j}\right]$ where E stands for an ensemble average and $X_{t,i}$ stands for microtremors at sensor *i*.

The phase velocity and a direction of microtremors corresponding to the peak wavenumber of F-K spectrum given by k_x, k_y is calculated by Formulae (F.3) and (F.4).

$$c(f)=\frac{2\pi f}{\sqrt{{k_x}^2+{k_y}^2}} \tag{F.3}$$

$$\theta=\arctan\left(\frac{k_y}{k_x}\right) \tag{F.4}$$

Example of F-K power spectrum is shown in Figure F.1.



Key

X wave number in X direction (rad/m)

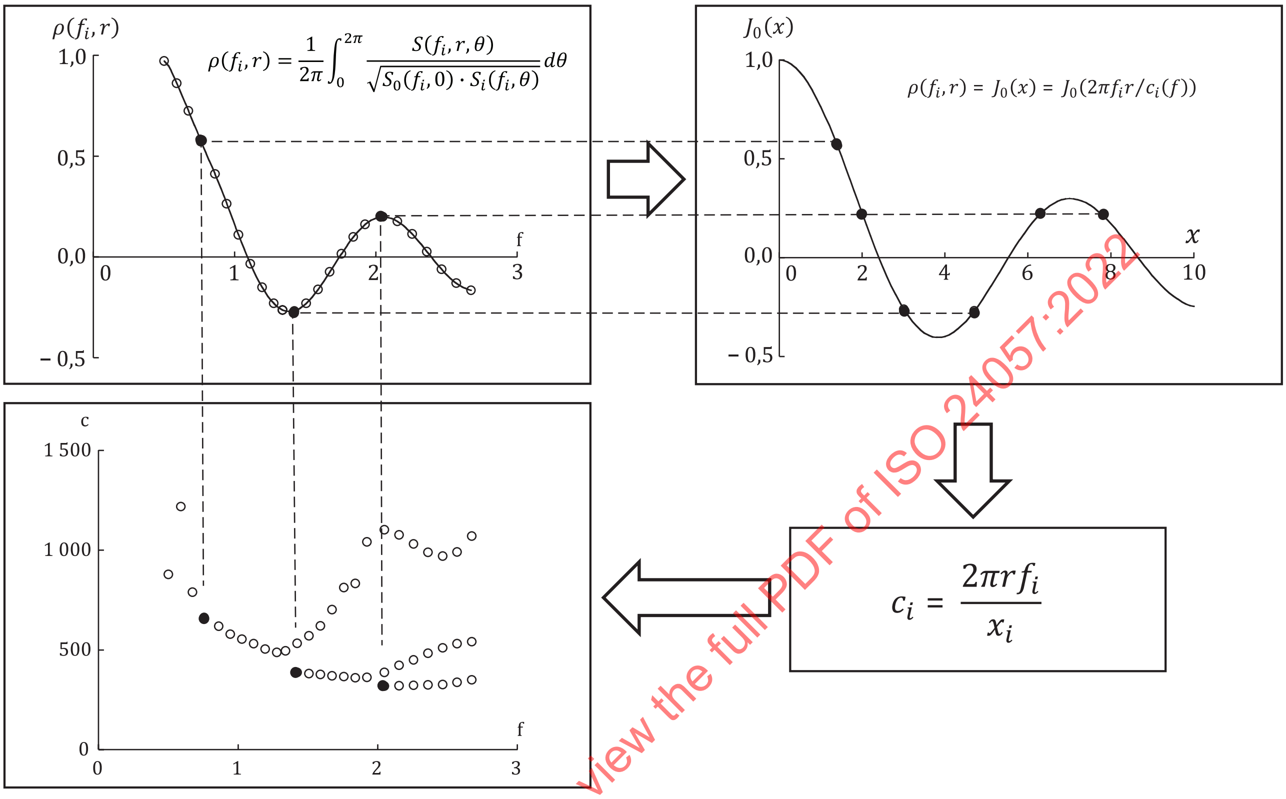
Y wave number in Y direction (rad/m)

Figure F.1 — Example of F-K power spectrum

F.2 SPAC method (spatial autocorrelation method)

The spatial autocorrelation method is based on the theory developed by Aki[1] to determine the relationship between the temporal and spatial spectra of seismic waves.

The spatial autocorrelation coefficient ($\rho(\omega_i, r)$) of microtremor records at a certain radius (r) and a certain angular frequency (ω_i) is obtained by an azimuthal average of the coherency between the records at the centre and the circumference of the circular array given by Formula (F.5).



Key

f frequency (Hz)

ρ spatial autocorrelation coefficient

C velocity (m/s)

Figure F.2 — Procedure for estimating phase velocity by the SPAC method[9]

$$\rho(\omega_i, r) = \frac{1}{2\pi}\int_0^{2\pi} \frac{S(\omega_i, r, \theta)}{\sqrt{S_0(\omega_i, 0)\cdot S_r(\omega_i, \theta)}} d\theta \quad \text{(F.5)}$$

$S(\omega_i, r, \theta)$ is a cross spectrum of the records at the centre and the circumference of the circular array;

$S_0(\omega_0, 0)$ is a power spectrum of the record at the centre;

$S_r(\omega_0, \theta)$ is a power spectrum of the record at the circumference of the circular array.

The spatial autocorrelation coefficient is expressed by the Bessel function of the first kind of zero order (J_0).

$$\rho(\omega, r) = J_0(rk) \quad \text{(F.6)}$$

$$k = \frac{\omega}{c(\omega)} \quad \text{(F.7)}$$

$$\omega = 2\pi f \quad \text{(F.8)}$$

k is an element of the matrix $\Phi(\omega)$ and (x_i, y_i) is the position coordinates of sensors.

A procedure for estimating phase velocity by the SPAC method is described below and is shown in Figure F.2.

1) Input array radius (r_0) of the field observation.

2) Calculation of a spatial autocorrelation coefficient from the observed microtremor records at a frequency (f_0) by using Formula (F.5).

3) Finding of x giving the same value equal to the spatial autocorrelation coefficient ($\rho_{r_0}(f_0)$) from the Bessel function ($J_0(x)$).

$$\rho_{r_0}(f_0) = J_0(x) \tag{F.9}$$

4) Calculation of phase velocity $c(f_0)$ by using Formula (F.10)

$$c(f_0) = \frac{2\pi r_0 f_0}{x} \tag{F.10}$$

5) Repeating the processes 1) to 4) at each frequency to calculating the phase velocity dispersion curve.

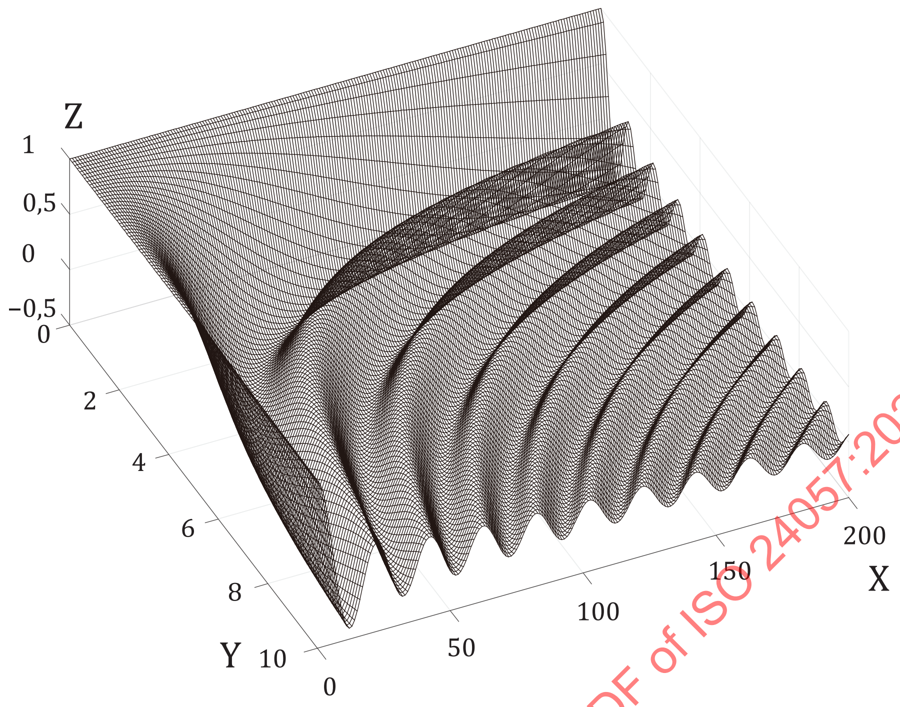
F.3 ESPAC method (extended SPAC method)

The spatial auto correlation coefficient is a function of both frequency and distance as shown in Figure F.3. The phase velocity is calculated from the spatial autocorrelation coefficient against frequency at a constant distance by the SPAC method. In contrast, the phase velocity by the ESPAC method[9] is calculated from the spatial autocorrelation coefficient against distance at a constant frequency.

For instance, the spatial autocorrelation coefficient ($\rho\_f_0(r)$) at a constant frequency (f_0) is given by Formula (F.11), and the phase velocity at the frequency is calculated from Formula (F.12).

$$\rho_{f_0}(r) = J_0(x) \tag{F.11}$$

$$x = \frac{2\pi r f_0}{c(f_0)} \tag{F.12}$$



Key

X distance (m)

Y frequency (Hz)

Z $\rho(f,r)$

Figure F.3 — An example of the spatial autocorrelation coefficient at both frequency and distance

F.4 MSPAC method (modified SPAC method)

SPAC method assumes that arrays are perfectly circular in order to compute the coherency between the records at the centre and the circumference of the circular array. However, this is not always possible for logistical or accessibility reasons. The MSPAC method[2] computes the average coherency value in azimuth and within a ring with radius r_1 to r_2 by Formulae (F.13) and (F.14), so that imperfect shaped circles are used. These formulae are inverted to compute the phase velocity and therefore the dispersion curve. MSPAC also allows to use relative positions between pairs of sensors instead of setting the central sensor as a reference, thus allowing more measurements possible with the same array.

$$\overline{\rho_{r_1,r_2}}(\omega)=\frac{2}{\pi\left(r_2^2-r_1^2\right)}\int_0^{\pi}\int_{r_1}^{r_2}\rho(r,\varphi,\omega)r\,dr\,d\varphi$$

$$=\frac{2}{\pi\left(r_2^2-r_1^2\right)}\int_0^{\pi}\int_{r_1}^{r_2}cos\left(\frac{\omega r}{c(\omega)}cos(\theta-\varphi)\right)r\,dr\,d\varphi \qquad \text{(F.13)}$$

$$\overline{\rho_{r_1,r_2}}(\omega)=\frac{2}{\left(r_2^2-r_1^2\right)}\int_{r_1}^{r_2}rJ_0\left(\frac{\omega r}{c(\omega)}\right)dr$$

$$\overline{\rho_{r_1,r_2}}(\omega)=\frac{2}{\left(r_2^2-r_1^2\right)}\frac{c(\omega)}{\omega}\left[rJ_1\left(\frac{\omega}{c(\omega)}r\right)\right]_{r_1}^{r_2} \qquad \text{(F.14)}$$

F.5 CCA method (centreless circular array method)

CCA method uses a circular array similar to that in the SPAC method, but this method does not require a sensor at a centre of the circular array. In this method, microtremors are measured at any points on the circumference of a circle with radius r. Here is an explanation based on Reference [4].

The simple averaged waveform (d_{ave}) is calculated from microtremor records at each sensor (d_j) as expressed by Formula (F.15).

$$d_{ave}(t) = \frac{1}{N}\sum_{j=1}^{N} d_j(t) \tag{F.15}$$

The weight is added to perform directional averaging to derive the complex waveform. When N sensors are equidistantly placed along the circumference, the weighted average complex waveform (d_{wave}) is expressed by Formula (F.16).

$$d_{wave}(t) = \frac{1}{N}\sum_{j=1}^{N} d_j(t) exp\left(\frac{2\pi i(j-1)}{N}\right) \tag{F.16}$$

where i is an imaginary unit.

The spectral ratio of d_{ave} to d_{wave} (ρ_{cca}) is called CCA coefficient.

$$\rho_{cca} = \frac{d_{ave}}{d_{wave}} \tag{F.17}$$

The spectral ratio for each frequency is associated with the wavenumber of the Rayleigh waves, and described by Formula (F.18).

$$\rho_{cca} = \frac{J_0^2(rk) + \frac{\varepsilon}{N}}{J_1^2(rk) + \frac{\varepsilon}{N}} \tag{F.18}$$

J_m is the Bessel function of the first kind of mth order, N is the number of sensors and ε is NS (Noise-to-Signal) ratio.