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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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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

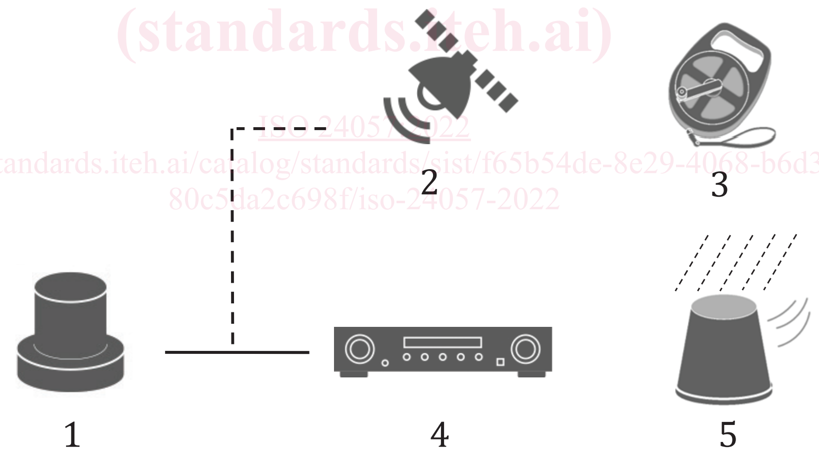
Symbol	Name	Unit
U	Displacement	m
V	Velocity	m/s
A	Acceleration	m/s^2
r	Radius of circular array	m

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].

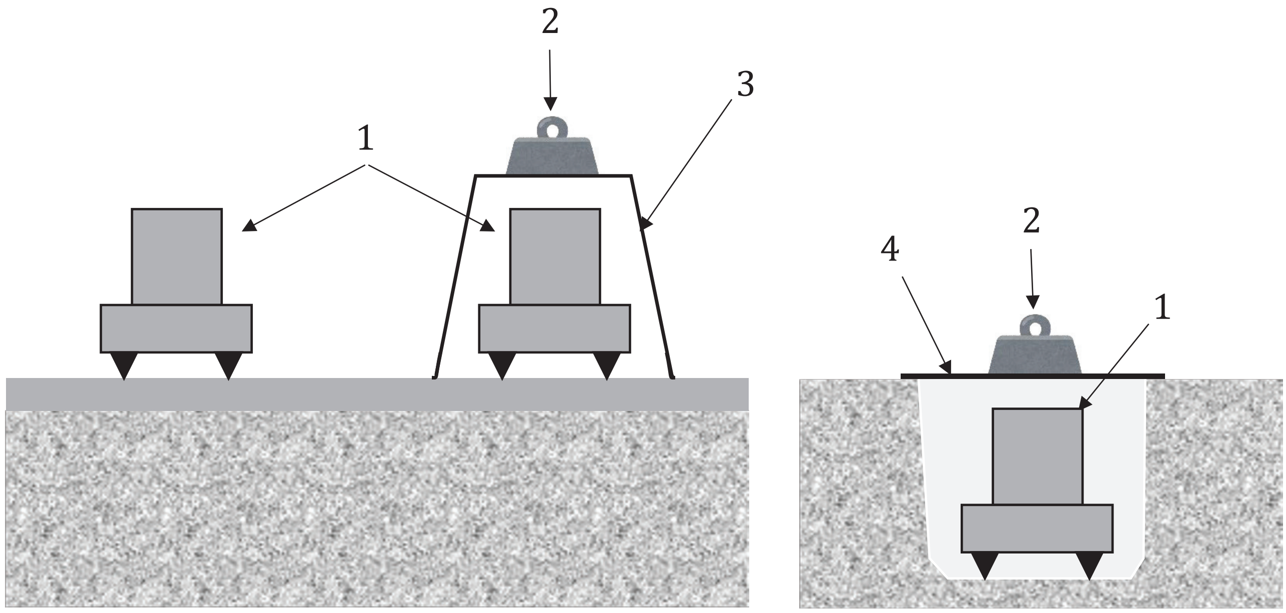
4.6 Protective products

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.

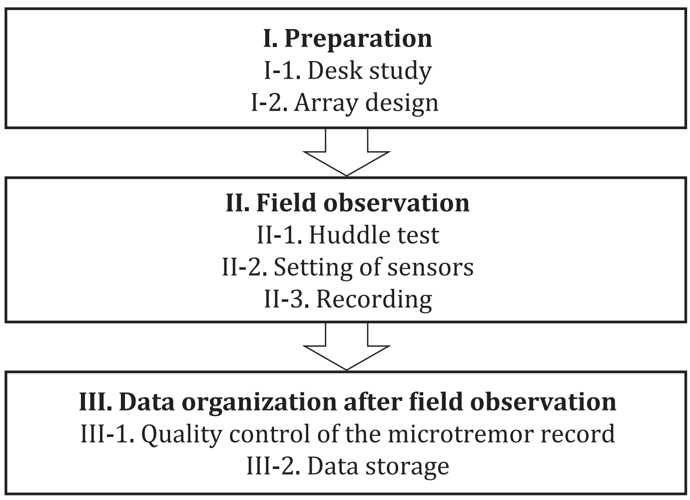


Figure 3 — Typical flow chart of a survey procedure of array measurement of microtremors

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.

