

Multipoint measurement of microtremor & seismic motion of slope using small accelerometers

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Abstract. The authors have developed a real-time monitoring system. The monitoring sensors are in small size, power-saving, low-cost. The sensor unit embedded with 1D micro seism accelerometer and 3D MEMS (Micro Electro Mechanical Systems) accelerometer (seismic motion / vibration) and have been verifying its field performance since 2019. In the microtremor measurement, compared the result of acceleration Fourier amplitude spectrum with speed Fourier amplitude spectrum of conventional microtremor speed sensor at the same site, almost the same results of predominant period were obtained. The measured results of the Mj 6.9 earthquake in Miyagi prefecture (March 20, 2021) will also be introduced as a case study. The developed microseism sensor units were applied to the field test of slope over two years, the result is that it can withstand long term measurement with an accuracy comparable to conventional seismometer.

Keywords: Microtremor, Seismic Motion, Geo-ground Monitoring.

1 Introduction

Many research activities have been carried out based on the methods for determining and analyzing ground types and velocity structures by utilizing microtremors and seismic motions so far. Furthermore, a method to estimate the velocity structure from the horizontal and vertical spectral ratios of seismic observation records at one point on the ground surface based on the diffuse field theory for plane waves was proposed as a past study using seismic motion (Kawase et al. 2011). In addition to the above existing methods, the multipoint measurement technology proposed by the authors can be used to evaluate the geo-ground characteristics in the local area, therefore, microtremor and seismic motion observation of the geo-ground are applied as an effective mean. The authors have developed a real-time monitoring system that is in small size, power-saving, low-cost unit embedded with 1D accelerometer and 3D MEMS accelerometer (seismic motion / vibration) and have been verifying its field performance since 2019. In the microtremor measurement comparing the Fourier amplitude spectrum results obtained by the new type of a 1D micro seism accelerometer with the conventional microtremor sensor at the same place, almost the same results were obtained. The field observation results of some earthquakes will be introduced as case studies. It was

confirmed that comparing the observation result of the embedded 3D MEMS accelerometer with the result of the conventional seismometer, it is possible and comparable to measure both the waveform and Fourier amplitude spectrum characteristics in a wide band by using the 3D MEMS accelerometer, which is comparable to the seismometer. Sensor units were set up at multiple points on the field slope, and observations were continued more than two years. Furthermore, because of verifying the embedded accelerometer's accuracy, it was found that it can withstand long-term measurement with an accuracy comparable to that of a seismometer as described above. Based on the above results, it is considered that multi-point and reliable seismic technology and the use of the results will lead to the strengthening of disaster response capabilities when tackling ground disasters that are generally uncertain and difficult to predict.

2 Microseism and Vibration Monitoring System

2.1 Outline of microtremor and seismic motion sensors system

This system, as shown in Fig.1, is consist of 1D accelerometer and 3D MEMS accelerometers (see Table 1), and combines microtremor, seismic motion observation according to the purpose of micro seism, earthquake, and vibration measurement while correcting the time using GNSS (Global Navigation Satellite System), real-time monitor the geo-ground, slopes, or civil engineering structures. In microtremor and seismic motion monitoring, spectrum analysis is performed at any time, the predominant period is calculated, and the calculation results are transferred to the monitoring center by wireless in LoRa (Long Range, which is a proprietary low-power wide-area network modulation technique) or FSK (Frequency-Shift Keying) mode.

Recently, some research for determining and analyzing geo-ground types and s-wave velocity structures by utilizing microtremors and seismic motions have been carried out. For example, Okimura et al. (2007) have proposed a method of observing microtremors of the foundation ground, calculating the predominant period of the ground from the results, and determining the types of ground. In addition, as a past study utilizing seismic motion, for example, Kawase et al. (2011) proposes a method to estimate the velocity structure from the horizontal vertical spectral ratio of seismic observation records at one point on the ground surface based on the diffuse wave field theory for plane.

Considering the above methods, the evaluation using microtremor observation and seismic observation of the geo-ground are effective and useful, the multi-point monitoring system becomes necessary and important. The ground characteristics can be evaluated in planar evaluation by using such method, furthermore the multi-point measurement technology is proposed by authors, a real-time measurement system embedded 1D accelerometer and 3D MEMS accelerometer (microtremor / seismic motion meter) have been developed. The sensors are compact, power-saving, and the verification field test has been carried out since 2019.

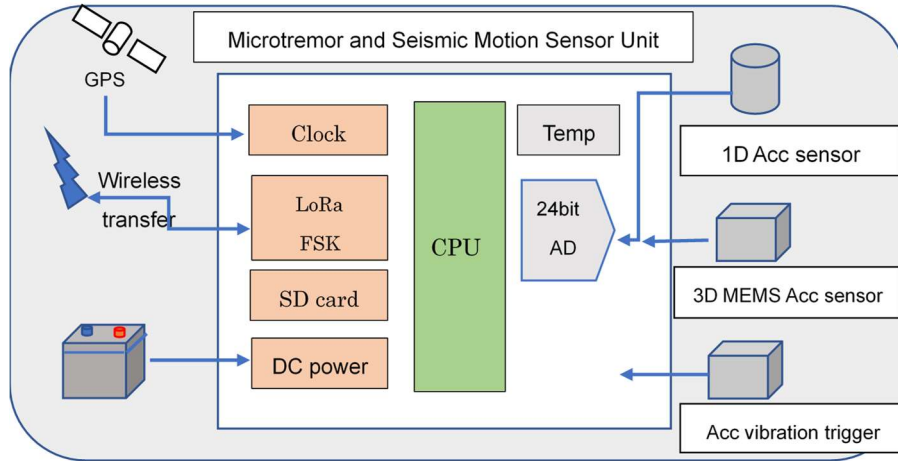


Fig. 1. Wireless (LoRa+FSK) compatible Microtremor/Seismic motion measurement sensor.

2.2 Accuracy verification of a new type of microseism accelerometer.

Table 1 shows the specifications of the 1D accelerometer and 3D MEMS accelerometers embedded in the measurement system. The 1D accelerometer has high sensitivity ($10V / G$) and low electrical noise level ($10\text{Hz}: 0.09\mu\text{g} / \sqrt{\text{Hz}}$), so it is used to microseism measurement. The results of comparing the 1D accelerometer with the conventional seismometer (velocity type) were shown in Fig.3-Fig.4 for the purpose to explain the verification accuracy at the microtremor signal level.

Table 1. The detail of specification.

	Microtremor/Seismic Acceleration	MEMS Seismic Accelerometer
Acceleration range	$\pm 0.5G$	$\pm 2G/\pm 4G/\pm 8G$ selection
Measurement	1D Acceleration	3D Acceleration
Sensitivity	$10V/G, 0.5\text{mg}/\mu$ strain 24Bit A/D Converter	$400\text{mV}/G@ \pm 2.5G$ range 24Bit A/D Converter
Electric noise	$2\text{Hz}: 0.28\mu\text{g}/\sqrt{\text{Hz}}$ $10\text{Hz}: 0.09\mu\text{g}/\sqrt{\text{Hz}}$ $100\text{Hz}: 0.03\mu\text{g}/\sqrt{\text{Hz}}$	$25\mu\text{g}/\sqrt{\text{Hz}}$
Frequency response	$0.3\text{-}1300\text{Hz} (\pm 3\text{ dB})$ $0.05\text{-}450\text{Hz} (\pm 3\text{ dB}),$ Selection	3 dB upper limit 1500Hz
Note	Wireless transfer of acceleration power spectrum area ratio Fourier spectrum is automatically calculated from acceleration wave Microseisms power spectrum area ratio and predominant frequency are automatically calculated.	

Figure 2 shows the situation of a conventional seismometer and a new type of microseism accelerometer installed in the same place in Tokyo. The verification test field site is near national roads and railway, to avoid the time when the vibration was highly irregular, and comparing test was carried out during the quiet midnight time.



Fig. 2. (a) Conventional seismometer for comparison. (b) New type microseism accelerometer

Figure 3 shows the Fourier amplitude spectrum results calculated for a total of 8 waveforms by selecting the part of the recording (vertical movement component) based on the seismic speed waves of conventional seismometer with relatively little noise contamination. Figure 4 shows the Fourier amplitude spectra of the seismic acceleration wave records obtained by new type of microseism accelerometer observed at the same location. In the range of the period of 0.1 to 1 second, a peak of predominant period was observed in 0.3 to 0.4 seconds, and the comparison results of predominant period of the conventional seismometer and the new type of microseism accelerometer were almost the same. Based on the results of this preliminary study, the new type of seismic accelerometer was applied to our sensor unit (see Table 1). For purpose of covering wide range measurement of acceleration, another type of acceleration meter of 3D MEMS is embedded to the sensor unit, and measurements were carried out in the verification fields shown following.

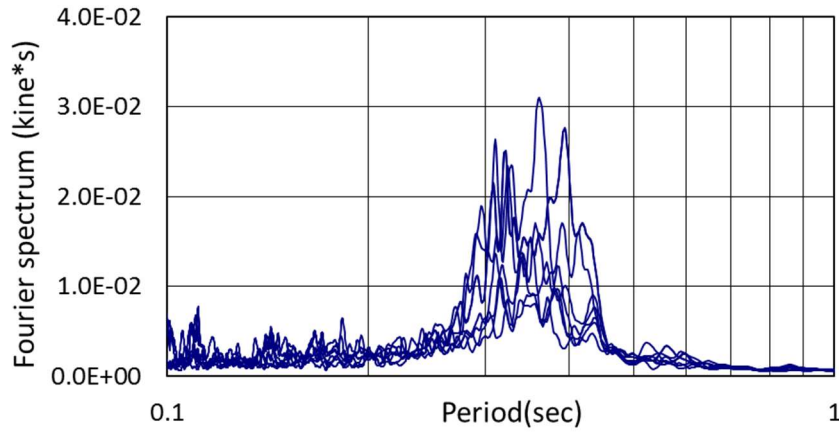


Fig. 3. Fourier spectrum of conventional seismometer

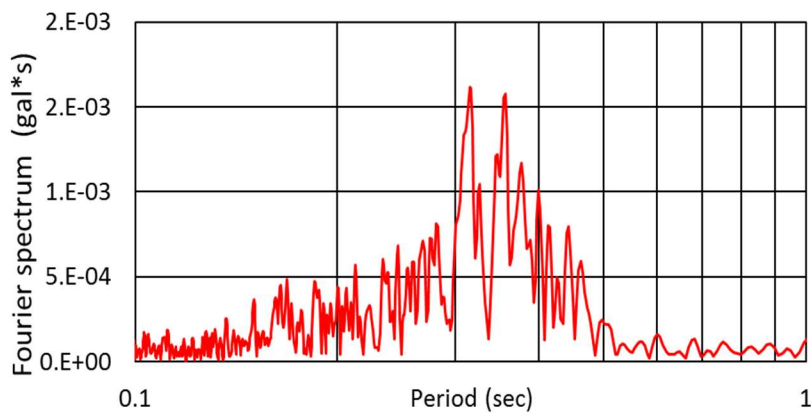


Fig. 4. Fourier spectrum of new type of microseism accelerometer

3 Verification field test and its results

3.1 Outline of test slope field

The test field site is a natural slope located at the boundary between the Ninomiya formation and the Fudoyama gravel layer in the southern part of the Oiso Hills, where is in the eastern part of Odawara city. The loam layer is deposited on the surface layer of the slope, while in the flat part near the slope, the solid gravel layer and mudstone are layered alternately under the embankment with a thickness of about 8 m that created

the valley topography. Accumulation has been confirmed by a boring survey at this site. The outline of the slope to be tested is shown in Fig. 5 to Fig. 7.

5 set of 3D MEMS accelerometers and 1D microseism accelerometer were installed on the slope, and a conventional strong motion seismograph for comparison and verification was installed in place (nearby to No5). The verification test has been continued since 2019. The interval (horizontal distance) between adjacent sensors is 24 m to 35 m, and the angle of inclination of the slope is approximately 25 to 35 degrees. After installation, more than 10 waves of seismic observation records were obtained in this test field.

A microtremor array investigation using a conventional micro seismometer (velocity) was carried out near No. 5, and it was found that the S wave velocity near the surface layer was about 450 m/s. In addition, in the horizontal vertical spectral ratio of microtremor, a peak considered to be predominant in horizontal motion in the Rayleigh wave basic mode has been confirmed around 1 second in the period.

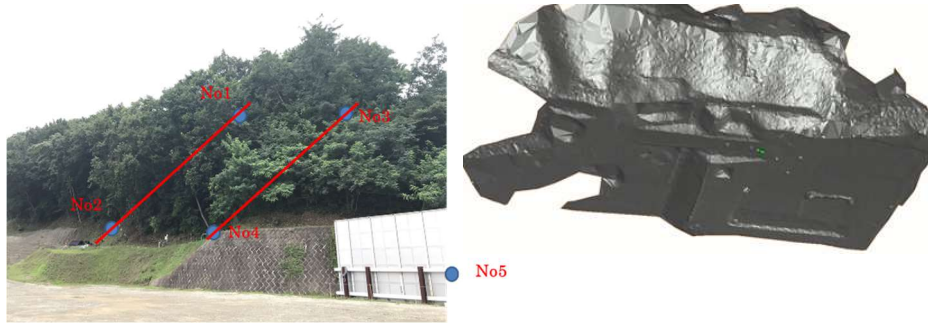


Fig. 5. (a) Measurement slope and sensor arrangement (plan view, the numbers in the figure are sensor numbers). (b) Measurement results of slope topography using a 3D laser scanner (looking from east to west).

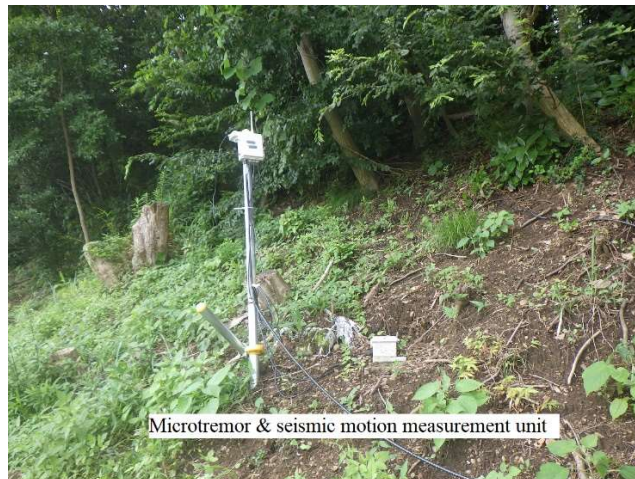


Fig. 6. Outline of sensor installation status

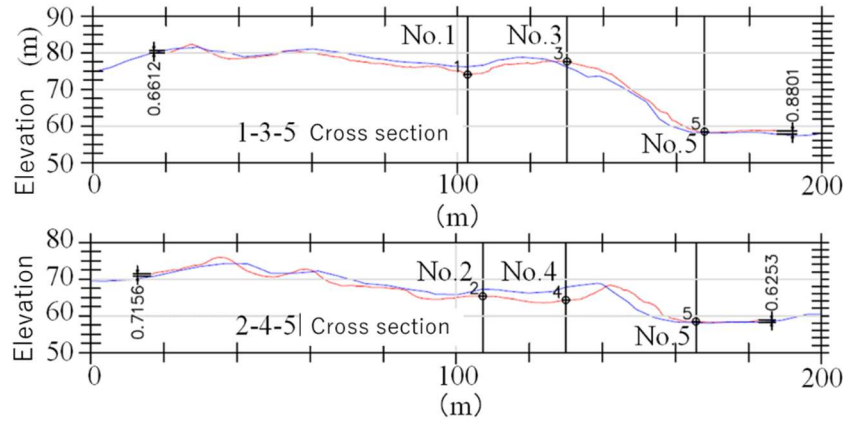


Fig. 7. Comparison of sensor installation position and measurement cross section

3.2 Typical comparing results based on earthquake measurement

Fig. 8 shows the relationships of Fourier spectrum, and earthquake waves of conventional seismograph, and new MEMS microseism sensor. The two types of microseism sensors almost got the same result from the monitoring of earthquake of Miyagi Prefecture Mj6.9, Japan, 20/Mar/2021.

The graph of Fig. 8(a) shows the relationship between the Fourier spectrum and the vibration period of the two types of sensors during an earthquake, the results of two curves almost overlap and match. Fig. 8(b) shows the relationship between the seismic acceleration waveforms of the two types of sensors and the seismic motion time during an earthquake, as a result, the measurement waveforms of the two types of sensors naturally overlap.

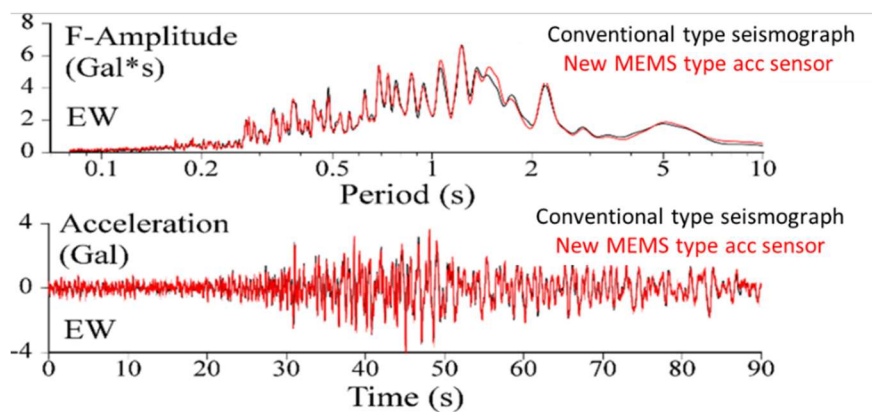


Fig. 8. Accuracy verification of earthquake measurement by using 3D MEMS acceleration sensor (Mj6.9, Earthquake of Miyagi prefecture Japan,20/Mar/2021).

To investigate the geo-ground amplification characteristics of the slope, the observation results obtained at No. 2 installed on the flat part of bottom of slope, and No. 1 installed on top of slope for the earthquake (seismic magnitude scale is Mj5.0) in central Chiba prefecture on May 6, 2020. The recorded acceleration Fourier amplitude spectrum is shown in Fig. 9. It was found that the period around 0.15 seconds is predominant due to the ground structure of the slope of the mountain body.

In the future, the observation records for estimating the S-wave velocity structure of the slope of the mountain body is planned to utilize.

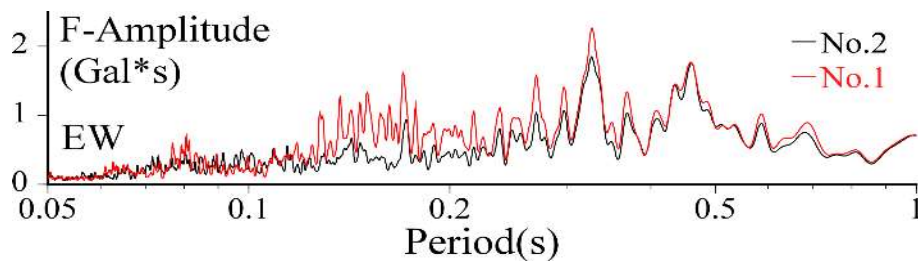


Fig. 9. Spectrum comparison (Mj5.0, Earthquake in central Chiba prefecture, Japan, 6/Jun/2020).

In Fig. 10, the acceleration Fourier amplitude spectrum of the microseisms observed by the new type of micro-seismic accelerometer is compared with the observation result by the conventional micro-seismic sensor. With a period of about 0.2 seconds or less, the amplitude characteristics of the two types of microseisms accelerometers in good agreement, and it was found that the new type of accelerometer can constantly observe microseismical wave with the same accuracy as the conventional microseism sensor. To improve the observation accuracy on the long-period monitoring, authors are studying the use of another small accelerometer and the improvement of measurement method and waveform processing method.

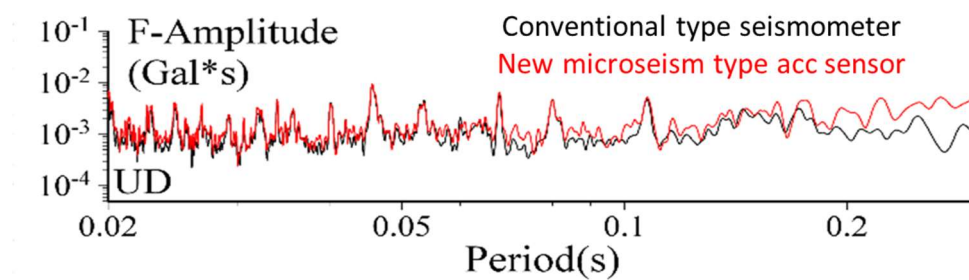


Fig. 10. Accuracy verification of new type microseism acc sensor with conventional microseism sensor

3.3 Ground vibration results of slope due to mechanical vibration in multipoint measurement

At the verification test slope field, 5 set of sensor units were installed here for multi-point measurement of seismic response evaluation of ground vibration and seismic motion. This sensor network system includes the functions of wireless data transmit, microtremor monitoring, and earthquake monitoring, at the same time, the system supports multi-point monitoring measurement based on GPS time synchronization.

Fig. 11 shows that the micro seism and vibration monitoring system can sensitively monitor the micro acceleration vibrations of road roller by 5 devices installed for multi-point measurement on the slope. From left to right, the graphs show the measured acceleration vibration results of MEMS seismic sensors no.1 to no.5. From top to bottom, the graphs show three direction results of mechanical vibration waveforms, that are north-east direction, south-west direction, and up-down direction. Fig.12 shows the acceleration Fourier spectrum results. It turned out that the developed sensor sensitively measured the mechanical acceleration even in very small vibration.

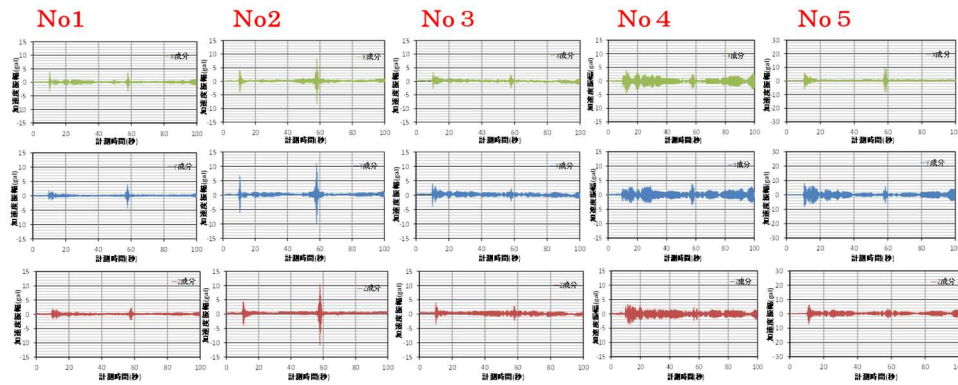


Fig. 11. Mechanical vibration waveform of slope ground by road roller vibration

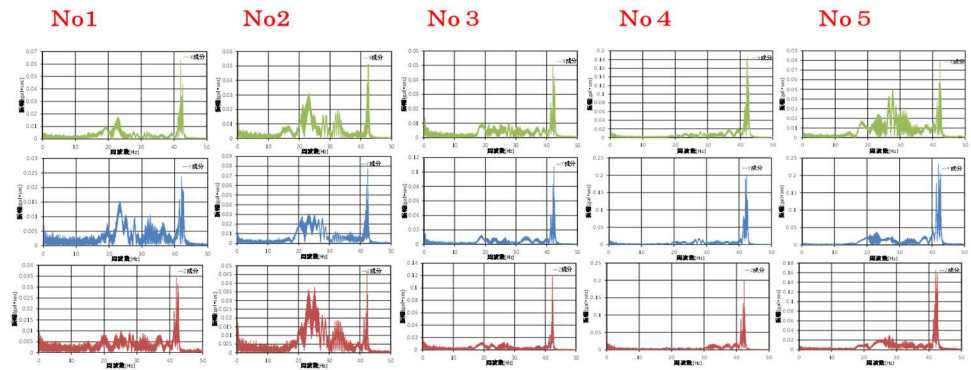


Fig. 12. Mechanical vibration Fourier spectrum (gal*sec) of 5 sensors by road roller vibration.

Based on acceleration Fourier spectrum results in Fig.12, predominant frequency is found to be around 42Hz. It was presumed that the frequency of the engine vibration of stopped road roller was picked up (Miura et al. 2009). Therefore, it is considered that the response dominant frequency of the slope ground due to the road roller vibration of the road roller is between 20Hz and 30Hz.

3.4 Seismic slope motion results of earthquakes in multipoint measurement

Fig. 13 shows that the microseism and vibration monitoring system can sensitively monitor the earthquake (Mj5.1) happened in Southern Ibaraki prefecture (12/Apr/2020 00:44) using five devices installed on the slope. From left to right, graphs show the observed earthquake acceleration wave results of MEMS seismic sensor no1 to no5. From top to bottom, the graphs show the measured acceleration waveforms (gal) of NW, SW, UD directions. The result of K-NET Odawara station (KNG013) where is 5km far away from slope was also showed in right. The K-NET is a strong-motion seismograph networks managed by NIED (National Research Institute for Earth Science and Disaster Resilience, Japan). Based on the results comparing acceleration wave of developed seismic sensor unit with K-NET, it showed that the shape of the acceleration waveform is almost the same, it indirectly explained that the developed seismic sensor can measure earthquakes sensitively.

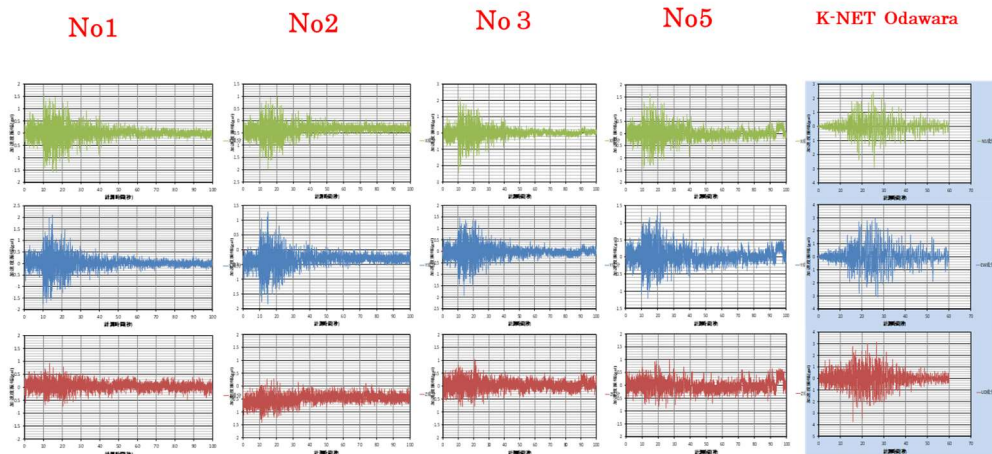


Fig. 13. Earthquake waveform of slope ground by seismic observation (12/Apr/2020 00:44, Southern Ibaraki prefecture Mj5.1, Seismic intensity 4, and K-NET (KNG013 Odawara))

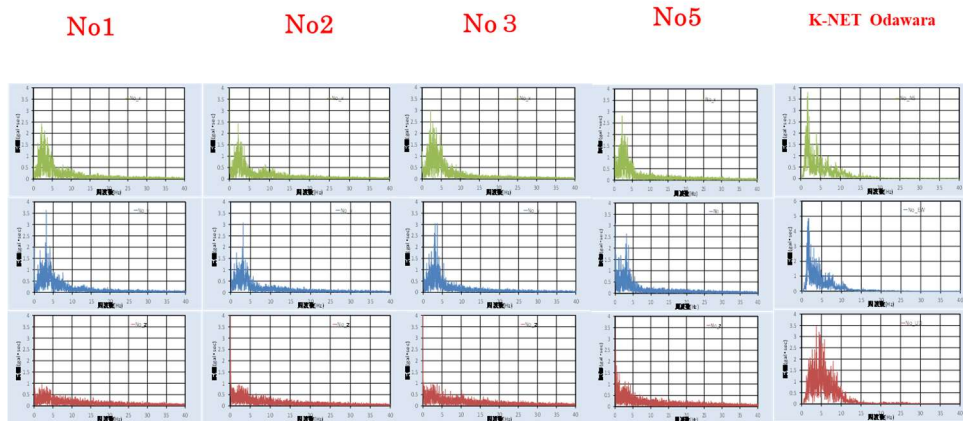


Fig. 14. The Fourier spectrum of slope ground by seismic observation (12/Apr/2020 00:44, Southern Ibaraki prefecture Mj5.1, Seismic intensity 4, and K-NET (KNG013 Odawara))

Fig. 14 shows the Fourier spectrum results of measured the earthquake by seismic sensor no.1 to no.5. The result of K-NET Odawara station (KNG013) is showed in right. Since the installation of these seismic sensors, the earthquakes occurred in the Kanto region of Japan were mostly monitored. By long-term certification experiment for more than 2 years, the new type of microseism and vibration monitoring system developed by authors has been found to withstand long-term measurements with comparable .

4 Conclusion

Compared to conventional microtremors and seismometers, the new type of sensor developed has been found to withstand long-term measurements with comparable reliability. Based on the above results, it is considered that multi-point and reliable seismic technology and its application will lead to the strengthening of disaster response capabilities when tackling ground disasters that are generally uncertain.

When making efforts to deal with geo-ground disasters that are generally uncertain and difficult to predict, authors believe that the spread of small, inexpensive, and reliable sensing technology and the use of the results will lead to the strengthening of disaster response capabilities. For example, table 2 shows the candidates for deploying the measurement system. If its implementation and dissemination accelerate, it is expected that it will contribute to the achievement of SDGs (Sustainable Development Goals) through the reduction of ground disasters.

Table 2. Future perspective for usage of the new type of measurement systems.

Measurement technology	Fields of application
Microseisms / Vibration measurement	Evaluation of ground shaking
	Estimating the velocity structure of the ground and establish a ground model
	Estimating the depth distribution of the support layer of ground
	Safety monitoring of slopes and rockfalls
	Detection of secular change of geo-ground structure, real-time damage diagnosis
	Estimating the location of the slope failure
	Verification of effects after measures such as ground improvement

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