Technical Commentary

N8510 Optical Fiber Strain Sensing System

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Summary

With the optical fibers stretched as sensors throughout road slopes, tunnels, embankments, bridges, etc., the strain rates in these optical fibers can be measured to determine the degree of damage or deterioration of these civil engineering structures. A disaster countermeasure and crisis management system that uses these "optical sensing" technologies to ensure the safe and secure living environment has recently sprung into wide use. This time, we developed the N8510 Optical Fiber Strain Scanning System, which enables distributive, long distance measurement of strain on the optical fibers.

This paper introduces strain distribution measurement technology using optical fibers, and an example of using the N8510 to monitor slope collapse.

1. Introduction

In Japan, many disasters such as urban structure collapse, roadside slope landslides, and tunnel rockslides occur due to earthquakes and typhoons. Protecting people's lives and property from these disasters absolutely requires the construction of a disaster prevention and risk management system that senses beforehand the points likely to be damaged by disasters and the possible degree of damage. Optical sensing technology has drawn attention for use in monitoring applications, in the construction and civil engineering fields to ensure a safer and more secure living environment. The central government is currently promoting the wide use and evolution of various disaster prevention and risk management systems for construction and civil engineering structures to which the optical sensing technology is applied, such as road slope monitoring systems, river and embankment monitoring systems, and tunnel displacement monitoring systems as shown in Fig. 1[1].

This paper first presents an overview of optical fiber sensing. It then enters into details about optical sensing technology which uses Brillouin scattered light and Brillouin Optical Time Domain Reflectometry (BOTDR). Lastly, it describes the N8510 Optical Fiber Strain Sensing System, which is based on BOTDR, gives examples of measurement and enters into details of a simulation using the N8510 to monitor slope collapse.

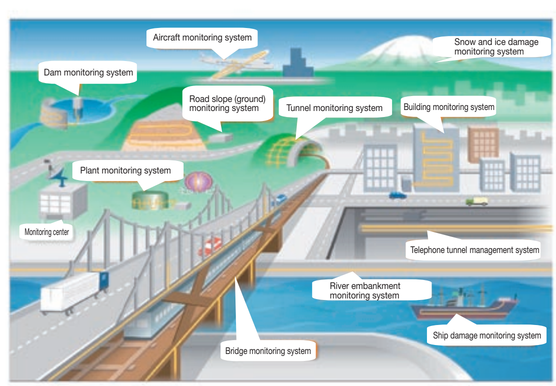


Fig.1 A disaster prevention/crisis management system based of optical fiber sensing technology

2. Optical Fiber Sensing

Many of the buildings and large structures that form the Japanese infrastructure were constructed between the post World War II period and high economic growth period of the early 1970s are about 30 to 40 years old. Japan suffers from many natural disasters such as earthquakes and landslides, and must monitor the degree of deterioration or damage of these old buildings and large structures to maintain and manage the sound infrastructure in order to maintain the safety and security of people's lives.

Conventionally, with the aim of maintaining and managing the sound infrastructure, many electric sensors such as extensometers and electric strain gauges have been used for monitoring to determine the degree of structure deterioration or damage. These electric sensors are compact and easy to bury and enable high-speed and high-sensitivity sensing, while they are difficult to apply to wide areas and large objects for monitoring because distribution measurement is impossible. They also have the disadvantages of the sensors requiring power supply and being susceptible to electromagnetic induction. Their long-term durability and reliability as sensors may have also been perceived as problems. Optical fiber sensors have the following advantages that compensate for the disadvantages of electric sensors.

- Distributed strain measurement is possible.
- They are not affected by lightning.
- Corrosion resistance is high because of their glass material construction.
- Measurement is possible over long-distance sections on the order of several kilometers.
- The existing optical fiber cables for communication can be used as transmission lines.

In sum, optical sensing technology using optical fibers has features that cannot be implemented by electric sensors, and has drawn attention as sensing technology for monitoring purposes. Disaster prevention and risk management systems that use optical-fiber-based optical sensing technology to ensure the safety and security of the environment in which we live have recently sprung into wide use.

3. Principle of Optical Fiber Strain Sensing Using Brillouin Scattering Phenomenon

Optical sensing technology which uses optical fibers includes strain sensing technology which applies the Brillouin scattering phenomenon that is one of various types of nonlinear phenomena related to optical fibers. Details of this phenomenon are as follows.

When coherent light enters an optical fiber, the incident light is partially scattered in the optical fiber and returns to the incident end. This light is referred to as backscattered light. Fig. 2 shows frequency distributions of backscattered light. Backscattered light includes Rayleigh scattered, Brillouin scattered, and Raman scattered light. The scattering frequency depends on the type of scattered light.

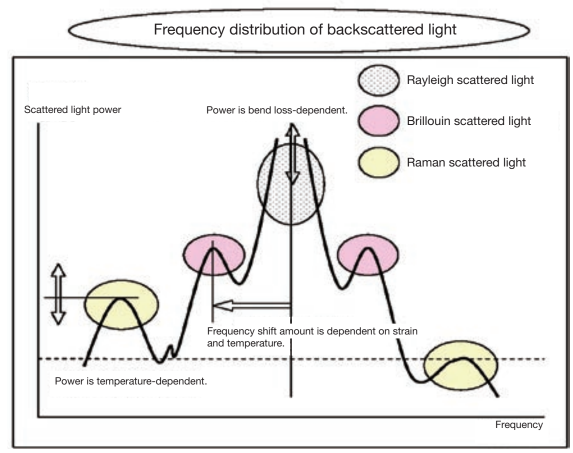


Fig.2 Spectrum of the backscattered light of optical fiber

Of backscattered light, the scattered light generated by nonlinear interaction between acoustic lattice vibrations and exciting light (incident light) is referred to as Brillouin scattered light. Brillouin scattered light has a power that is about 20 dB smaller than Rayleigh scattered light. Its power spectrum patterns are known to have a Lorentz type profile, which is expressed by equation (1)[2].

$$g_B(\nu) = \frac{(\Delta\nu_B/2)^2}{(\nu-\nu_B)^2 + (\Delta\nu_B/2)^2} \cdot g_{B0} \quad \cdot\cdot (1)$$

In equation 1, $g_B(\nu)$ represents a Brillouin scattering power spectrum, ν represents frequency, $\Delta\nu_B$ represents full width at half-maximum width of the Brillouin scattering power spectrum, and g_{B0} represents the peak value of Brillouin scattering power spectrum. As shown in Fig. 3, Brillouin scattering power spectrum $g_B(\nu)$ takes on the maximum value g_{B0} at frequency $\nu = \nu_B$. ν_B is a frequency difference between the exciting light (incident light) frequency ν_0 and the peak frequency $\nu_0 + \nu_B$ of the Brillouin scattering power spectrum, and is referred to as frequency shift. Frequency shift ν_B is known to vary, depending on strain or temperature.

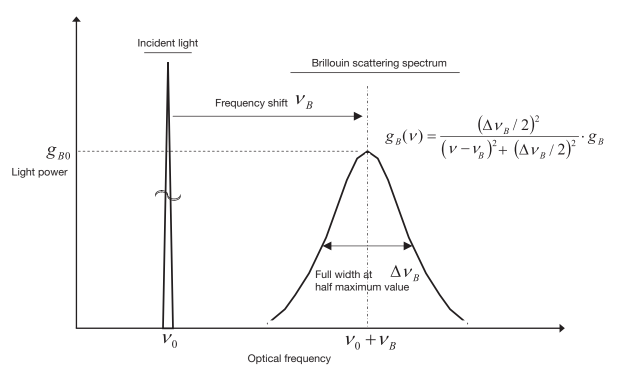


Fig.3 Spectrum of the brillouin backscattered light

Frequency shift is expressed by equation (2).

$$\nu_B = \frac{2n\upsilon_A}{\lambda} \quad \cdots\cdots\cdots\cdots\cdots \quad (2)$$

In equation (2), n represents the refractive index of the optical fiber, υ_A A represents the acoustic wave speed in the optical fiber (m/s), and λ represents the wavelength of incident light (nm). Generally, frequency shift ν_B for Brillouin scattered light in a silica-based single-mode fiber is about 11 GHz (when wavelength λ = 1550 nm), and full width at half-maximum value $\Delta\nu_B$ when the light is excited by continuous light is 30 MHz to 50 MHz. If the light is excited by pulsed light of 10 ns, the full width value at half maximum $\Delta\nu_B$ is known to broaden to about 100 MHz to 200 MHz.

If a strain occurs in a structure and the laid optical fiber becomes stressed in a longitudinal direction, the acoustic wave speed υ_A in the media changes with change in its density. At this time, frequency shift ν_B for Brillouin scattered light also changes. Equation 2 indicates the basic concept of using Brillouin scattered light for such strain sensing. When strain ε is applied, frequency shift $\nu_B(\varepsilon)$ is given as the function of strain ε by equation (3).

$$\nu_B(\varepsilon) = \nu_B(0) + (d\nu_B/d\varepsilon)\cdot\varepsilon \quad \cdots\cdots \quad (3)$$

In equation $d\nu_B/d\varepsilon$ represents the ratio of variation of frequency shift to variation of strain (strain sensitivity coefficient) and $\nu_B(0)$ represents the frequency shift without strain. Sensitivity coefficient $d\nu_B/d\varepsilon$ in equation (3) becomes a fixed value determined by the optical sensor, and strain ε can be specified by measuring frequency shift with strain $\nu_B(\varepsilon)$ and frequency shift without strain $\nu_B(0)$. Strain sensitivity coefficient $d\nu_B/d\varepsilon$ in a silica-based single-mode fiber is about 500 MHz/%, and if frequency shift $\nu_B(\varepsilon)$ is measured at an accuracy of 5 MHz during multiple repetitive measurements for an extended period of time, for example, the degree of structure deterioration or damage can be monitored at a strain accuracy (measurement reproducibility) of 0.01%.

As previously stated, a power spectrum width of Brillouin scattered light is form 100MHz to 200MHz, This extension of power spectrum width of Brillouin scattered light reduces the measurement accuracy of frequency shift $\nu_B(\varepsilon)$ For this reason, during strain measurement using an actual Brillouin scattering phenomenon, frequency shift ν_B is obtained from a Lorentz function-type approximate computation for power spectrum waveform data to improve the measurement accuracy of strain ε.

4. Optical Fiber Distributed Strain Measurement Technology

Frequency shift for Brillouin scattered light changes according to the strain locally placed on the optical fiber. In other words, as shown in Fig. 4, if the strained and unstrained sections coexist in the longitudinal direction of one optical fiber, the amount of frequency shift differs between the sections, and is proportional to the amount of strain from the property of the previously described Brillouin scattering. Thus, continuous measurement of frequency shift at each distance position of the optical fiber enables the specification of the position and amount of strain on the optical fiber.

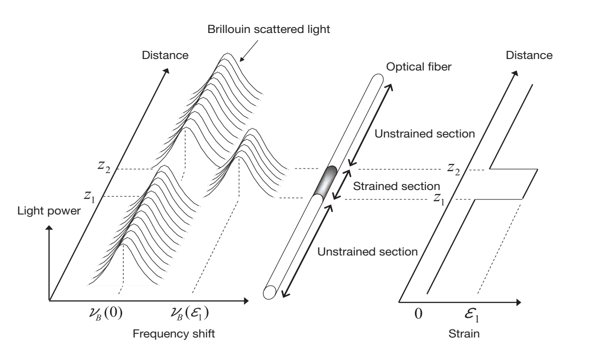


Fig.4 Distributed strain measurement using the brillouin backscattered light

Pulsed light is allowed to enter the optical fiber, frequency shift at each distance position of optical fiber is calculated from power data of Brillouin scattered light detected at the incident end, and strain on the optical fiber is measured in a distributed manner. The measurement method that enables distributed strain measurement at a long distance is referred to as Brillouin Optical Time Domain Reflectometry (BOTDR). Fig. 5 shows a block diagram of the N8510 Optical Fiber Strain Sensing System based on this BOTDR technology.

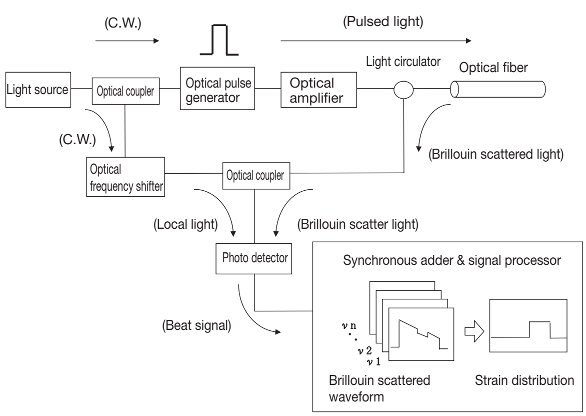


Fig.5 Block diagram of N8510 BOTDR

This section explains the operating principles of the N8510. A light signal (C.W.) from a light source is branched by the optical coupler, and one signal is supplied to the light pulse generator and another signal is supplied to the optical frequency shifter. First, the light signal pulsed by the optical pulse generator is amplified to a pulse peak power of about +25 dBm by the light amplifier for entry to the optical fiber. Brillouin scattered light generated in the optical fiber sensor by this light pulse returns to the incident end of the optical fiber for entry to the optical coupler through the light circulator.

The local light (C.W.) generated by the optical frequency shifter is then allowed to enter the optical coupler in the same way as Brillouin scattered light. The local light and Brillouin scattered light multiplexed by the optical coupler undergo optical-electric conversion and are detected as electric beat signals. The optical power detection method to detect an electric beat signal that provides a difference frequency from these two light signals with different optical frequencies is referred to as optical heterodyne detection. This detection method enables highly sensitive detection of weak Brillouin scattered light.

The obtained electric beat signals are accumulated by the synchronous adder and saved as Brillouin scattered waveforms (vertical axis: optical power and horizontal axis: distance). The power spectrum waveform of Brillouin scattered light at each distance position is obtained from multiple Brillouin scattered waveforms measured repetitively while allowing the optical frequency shifter to slightly change the local optical frequency. The amount of frequency shift is calculated for the obtained power spectrum waveform by approximation calculation of the Lorentz function, and converted to the amount of strain, using equation (3).

The N8510 that we developed uses the following technologies to achieve a highly efficient strain measurement performance.

(1) Optical switch (optical pulse generator) with high pulse extinction ratio/low chirp characteristics

Brillouin scattered light is more highly sensitive to continuous light than pulsed light, and its power spectrum shape is subject to the chirp effects of pulsed light. The N8510 uses a newly developed optical switch (optical pulse generator) that has a high pulse extinction ratio and low chirp characteristics based on Advantest's proprietary optical device technology to enable highly accurate detection of the power spectrum shape of Brillouin scattered light and achieve a wide dynamic strain measurement range.

For details about the newly developed optical switch for optical pulse generation, see the technical paper, Complementary 2-Stage Distributed Coupling Optical Switch Module that Achieves High Extinction Ratio and Low Chirp in Probo No. 27.

(2) Optical heterodyne detection using local optical frequency shift method

Accurate detection of weak Brillouin scattered light with a frequency shift of about 11 GHz for the frequency of incident pulsed light requires a highly sensitive detection method that enables a stable frequency sweep. The N8510 achieves highly accurate detection of Brillouin scattered light at a spacial resolution of 1 m and high strain measurement reproducibility through optical heterodyne detection, using the optical frequency shift method and stabilization control over local light power

The distributed strain measurement technology based on this BOTDR technology enables measurement of strain on the optical fiber for several kilometers at a distance resolution of 1 m at a measurement reproducibility of less than ±100 $\mu\varepsilon$ (±0.01%), for example, and has been adopted to monitor road slopes and large structures.

5. Features of the N8510

The previously-mentioned various disaster prevention and risk management systems for buildings and civil engineering structures conduct monitoring while using the optical channel selector to change multiple optical fiber sensors in most cases because there are multiple measurement points. Because monitoring all measurement points requires huge amounts of time, the technical problem has conventionally been the enhancement of measurement speed through improved device performance.

As previously described, the N8510 uses Advantest's proprietary optical device technology and highly sensitive operating sensing technology based on optical heterodyne detection to achieve higher strain measurement performance. The measurement time required for monitoring at strain measurement reproducibility of less than ±400 $\mu\varepsilon$ (±0.04%), for example, is about one fourth the conventional one. If the conventional measurement time is taken, this system also can do monitoring at strain measurement reproducibility of less than ± 100 $\mu\varepsilon$ (±0.01%). Thus, the N8510 ensures efficient monitoring that has been a conventional problem and enables quicker identification of dangerous points than before.

Fig. 6 is an external view of the N8510, and Table 1 lists the specifications of the N8510. The features of the N8510 are summarized as follows.

Features of the N8510

◎High strain measurement performance

- Strain measurement reproducibility: ±100 $\mu\varepsilon$ (±0.01%)
- Dynamic strain measurement range: 3.5 dB (at spacial resolution of 1 m)

  The newly developed optical switch for pulse generation with high pulse extinction ratio and low chirp characteristics, and an optical heterodyne detection method were adopted to achieve a wide dynamic strain measurement range. This significantly improves the basic performance related to strain measurement such as measurement distance, measurement time and measurement reproducibility.

◎High reliability

The mechanical drive is eliminated to achieve the high reliability required for continuous tests for an extended period of time.

◎Large-volume, high-speed data processing

An internal large-capacity memory was installed and a new signal processor was optimally designed to ensure high-speed and batch measurements of distance data items at up to 100,000 points. This enables distributed strain data over distance range of 10 km and at spacial resolution of 1 m to be obtained in one measurement.

Table.1 Specification of N8510

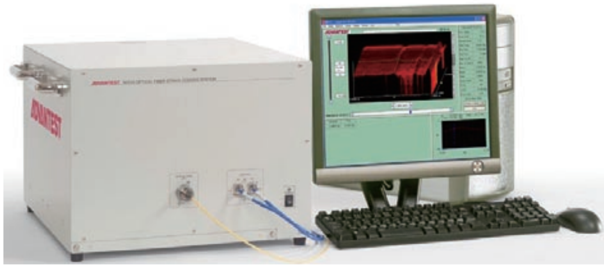
Measurement specification	Measurement function	Strain distance distribution, Brillouin scattering spectrum, Brillouin scattering loss distribution				
	Range of distance to be set	1, 2, 3, 10, 20, 40, 80 km				
	Range of refractive index to be set	1.00000 to 1.99999 (0.00001 steps)				
	Distance resolution	0.05, 0.10, 0.20, 0.50, 1.00 m				
	Number of measurement points	Up to 100,000 points				
	Measurement frequency range	10 to 12 GHz				
	Measurement frequency interval	1, 2, 5, 10, 20, 50 MHz				
	Average setting count	2^{10} to 2^{24} times				
	Pulse width	10, 20, 50, 100, 200 ns				
	Strain unit	μ, ε, %				
Performance	Measurement wavelength	1.55 μm range				
	Strain measurement range*1	10 $\mu\varepsilon$ to 15000 $\mu\varepsilon$				
	Strain measurement reproducibility*2	< ±100 $\mu\varepsilon$				
	Strain measurement linearity*3	±4 x 10^{-3}				
	Pulse width	10 ns	20 ns	50 ns	100 ns	200 ns
	Dynamic range*4	3.5 dB	7.5 dB	11.5 dB	14.5 dB	16.5 dB
	Distance measurement accuracy	±(5.0 x $10^{(-5)}$ x measurement distance (m) + 0.2 m + 2 x scan resolution (m)) The setting error caused by refractive index is excluded.				

*1 SMF 1.3 μm range zero dispersion optical fiber (ITU-T G.652 compliant)

*2 Standard deviation (2δ) of measured value of strain at any distance during measurement 10 consecutive times at average count of 2^{14} times and a measurement frequency interval of 5 MHz, with an SMF fiber

*3 Strain measurement linearity (except characteristic variation of optical fiber) at average count: 2^{14} times, measurement frequency interval: 5 MHz, and SMF fiber

*4 Optical fiber loss that satisfies strain measurement reproducibility of less than ±100 $\mu\varepsilon$ at average count: 2^{14} times, measurement frequency interval: 5 MHz, and SMF fiber



* This product does not include the personal computer for control (and its accessories) and LAN cable.

Fig.6 N8510 Optical Fiber Strain Sensing System

6. Example of Distributed Strain Measurement

With a strain verifier that can apply an optional strain to a specific section of the optical fiber being built instead of the laid optical fiber sensor, the N8510 was used to measure the strain distribution on this strain verifier. As shown in Fig. 7, the strain verifier consists of an optical fiber for strain measurement, a stain application unit, a fixed unit, and a tension measurement unit, and can apply an optional stain to a specific section of the optical fiber. In this evaluation system, this strain verifier and an optical fiber of about 1 km were used to provide a 1 m long strained section at the distance position about 1 km away from the N8510. During measurement, the amount of strain in the strained section was varied from 0.1% to 0.5% in steps of 0.1%.

Fig. 8 shows distributed strain measurement results of the N8510 using this strain verifier. As evidenced by the measurement results, distributed strain measurement enables measurement of the variation in strain in the strained section (1 m long) about 1 km away from the N8510.

From the measurement results of the N8150 shown in Fig. 8, strain measurement linearity was obtained. Fig. 9 shows the obtained strain measurement linearity. It is clear from Fig. 9 that the measured value of strain also varies linearly with linear variation in the set amount of strain. This measurement provides a favorable result that strain measurement linearity is smaller than ±0.004% with the deviation (maximum value) from an ideal straight line (linear approximate straight line: solid line) equal to 0.0036%.

Strain measurement linearity requires a strict test method because it is a performance index that is critical to ascertaining the variation in the amount of strain exactly. The N8510 thus adopts a highly accurate test method that has not conventionally been available, to assure its performance. This test method provides the frequency shift simulated based on the frequency reference traced to eliminate a strain measurement error caused by characteristic variation in optical fibers as the reference of the amount of strain.

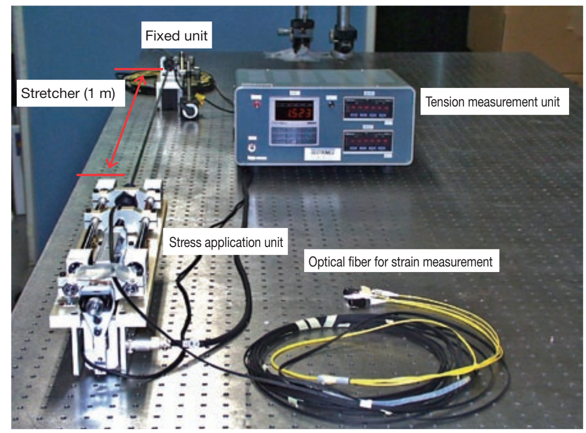


Fig.7 Reference of optical fiber strain

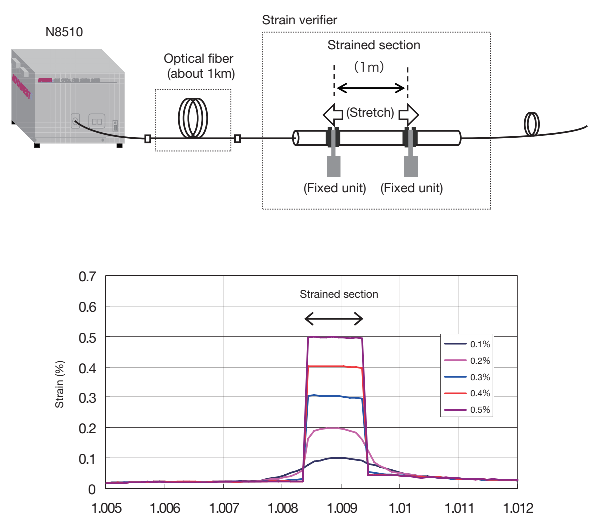


Fig.8 Measurement results of N8510

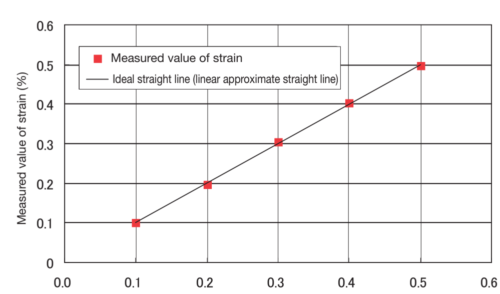


Fig.9 Strain measurement linearity of N8510

7. Slope Collapse Monitoring Simulation

This section introduces the simulation results of monitoring slope face collapse provided by the Public Works Research Institute. This experiment is a monitoring simulation to aim at verifying that soil collapse from road slope due to rain can be sensed beforehand through monitoring, and was performed using the N8510 in the civil engineering building of Tsukuba Central Research Institute, Public Works Research Institute (Tsukuba, Ibaraki Prefecture).

Fig. 10 illustrates the slope face of soil used in this simulation. One optical fiber (total length: about 80 m, was connected to optical fiber sensors (2 m long x 4 units) and run over an artificial slope face of soil of about 5 m square so that it covered the entire slope. The optical fiber is laid so that it is placed under tension due to displacement of slope face of soil, and the parts of 2 m long each of the optical fiber (sensor No. 1 to sensor No. 4) run among the fixed units functioning as the sensors that monitor soil displacement.

With artificial rain allowed to fall onto this slope face of soil, the N8510 was used to monitor the slope face ground displacement (strain) until a landslide occurred.

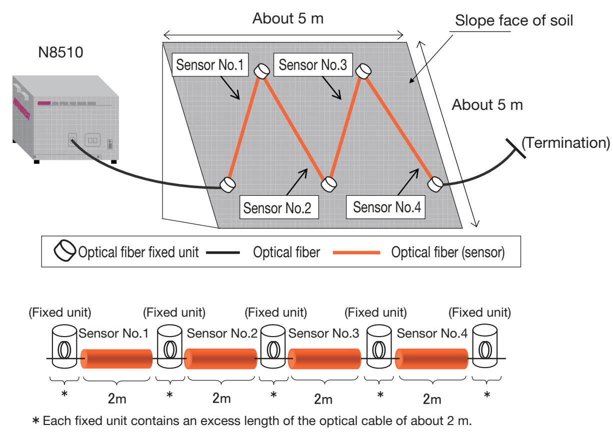


Fig.10 Experiment outline of slope face of soil

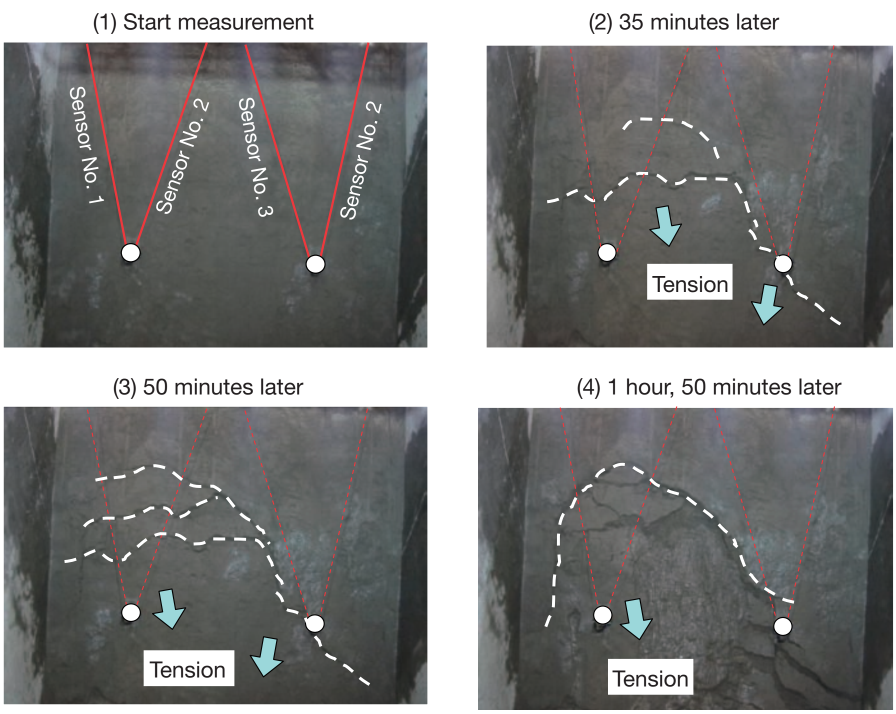


Fig.11 Appearance of slope face of soil during rainfall

Fig. 11 shows the appearance of the collapsing slope face of soil. It is clear that rainfall causes cracks in the slope face of soil and multiple cracks to expand with time. As evidenced by the photo of 35 minutes later in photo 2 of Fig. 11, a crack runs at sensor No. 1 and sensor No. 2 points. It is clear from the photo taken 50 minutes inform the start (photo 3) that the crack has expanded forming multiple cracks. In the photo of 1 hour and 50 minutes from the start (photo 4), the previously described crack has further expanded and the soil under this crack has collapsed along the crack.

Fig. 12 shows the results of monitoring using the N8510 (variation in amount of strain on each optical fiber sensor with time). As evidenced by the appearance of soil collapse shown in Fig. 12, it is clear that the amount of strain on sensor No. 1 and sensor No. 2 shown in Fig. 12 becomes larger with time unlike that on other sensors. In this experiment, the slope face collapsed 1 hour and 50 minutes after rainfall started. It can be perceived from the monitoring result shown in Fig. 12 that a small collapse is a sign that a collapse is in the process of beginning about 1 hour and 20 minutes (35 minutes after rainfall starts) before final collapse of the slope face. This indicates that the abnormal points on the slope face can be specified before collapse by monitoring the strain on the shape of the soil slope face.

In sum, the distributed strain measurement technology using the optical fiber sensors can be used to detect disaster hazard points in an early stage. As a result, safety can be secured by risk management measures such as early countermeasures against disaster hazard points, preparation for disaster, traffic regulation and evacuation notification through collapse prediction[3].

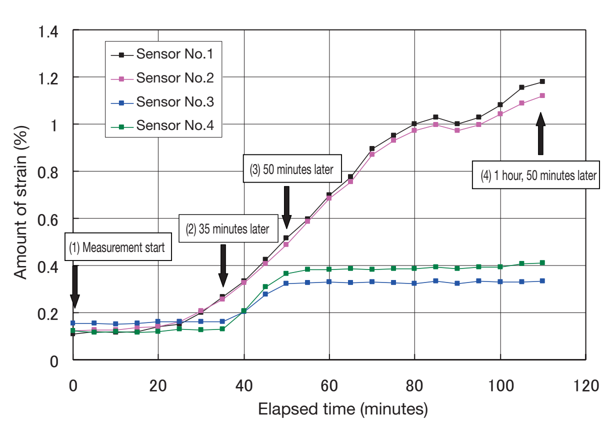


Fig.12 Collapse detection Results in slope face of soil

8. Conclusion

The N8510 Optical Fiber Strain Sensing System was developed to enable long-distance, distributed strain measurement. The N8510 achieves higher strain measurement performance such as dynamic strain range and strain measurement reproducibility, enhanced product reliability that endures continuous measurement operation for monitoring use, and high-speed and batch measurement of distance data items at up to 100,000 points. The simulation results of using The N8510 to monitor slope face collapse indicated that optical sensing technology using an optical fiber enables specification of the collapse points on the slope face beforehand. This product has been jointly developed for market with NTT InfraNet.

9. References

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