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Health Monitoring for Large Structures using Brillouin Distributed Sensing

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Abstract Brillouin time-domain analysis in optical fibres is a novel technique making possible a distributed measurement of temperature and strain over long distance and will deeply modify our view about monitoring large structures, such as dams, bridges, tunnels and pipelines. Optical fibre sensing will certainly be a decisive tool for securing dangerous installations and detecting environmental and industrial threats.

Keywords: optical fibre, Brillouin-based techniques, distributed sensing, temperature monitoring, reinforcing pipes, tunnel deformation, leakage detection

1. Introduction

Developed societies require more and more information for their safety and for their economic development. Recent disasters due to landslides, fires in tunnels and collapses of bridges are a source of serious concern on the part of the public which seeks for more safety and for an efficient prevention of these frequent recurrences of dangers.

Sensing in adverse environment and extreme conditions requires dedicated techniques. Quite recent technologies like fibre optics may offer novel valuable solutions and give rise to a strenuous research effort. Optical technologies are an essential actor owing to their tremendous capability to transmit and process a high density of information. Optical fibres are a key component for these technologies and their potential for optical processing and for collecting information as sensing probe is still widely unexplored. The development and the popularity of telecommunications have entirely screened the fact that optical fibres may be efficiently used for sensing purposes.

In this paper we present applications of a novel technique using optical fibres to monitor large structures for safety purpose. The fibre is used as sensing element and can provide distributed measurements of quantities like temperature or strain. In other words a value of temperature and/or strain can be obtained for any point along the fibre. This is made possible by using a nonlinear optical effect in the fibre called Stimulated Brillouin Scattering (SBS).

2. Principle and physical aspects

Optical fibre sensors based on stimulated Brillouin scattering have now clearly demonstrated their excellent capability for long-range distributed strain and temperature measurements (Thèvenaz

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et al., 1998). The Brillouin interaction causes the coupling between optical and acoustic waves when a resonance condition is fulfilled. It turns out that this resonance condition is strain and temperature-dependent, so that determining the resonance frequency directly provides a measure of temperature or strain.

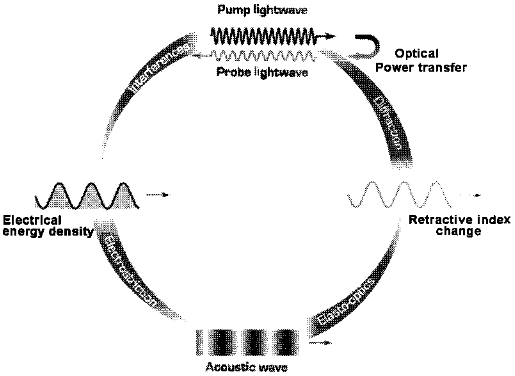


Fig. 1 Description of the stimulated Brillouin scattering. This resonant interaction involves 2 optical waves propagating in opposite directions and 1 acoustic wave and results in a power transfer from one lightwave to the other thanks to 4 different processes.

The resonance frequency is an intrinsic property of the material that may be observed in any silica fibre. This is very attractive since the bare fibre itself acts as sensing element without any special fibre processing or preparation. Standard optical cables may thus be used, resulting in a low cost sensing element that may be left in the structure. Since the optical effect only depends on the fibre material, it is absolutely stable in time and independent of the instrument. Different measurements performed over a long term period are thus fully comparable.

Brillouin scattering results from the scattering of light by sound waves, as depicted in Fig. 1. Thermally excited acoustic waves (acoustic phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light is diffracted backward on this moving grating, giving rise to frequency shifted Stokes and anti Stokes components. This process can be stimulated when the interference of the laser light and the Stokes wave reinforces the acoustic wave through electrostriction. Since the scattered light undergoes a Doppler frequency shift, the frequency difference, called Brillouin shift ν_B, depends on the acoustic velocity and is given by

$$\nu_B = \frac{2 n V_a}{\lambda_o} \qquad (1)$$

where V_a is the acoustic velocity within the fibre, n is the refractive index and λ_o the vacuum wavelength of the incident lightwave. The Brillouin shift is observed in the 12-13 GHz range around a 1300 nm wavelength and in the 10-11 GHz range at 1550 nm, mostly depending on the core doping concentration. This Brillouin shift is therefore fibre-dependent and may be seen as a fingerprint of the fibre.

For sensing purpose the effect of stimulated Brillouin scattering is observed somehow differently: two lightwaves, propagating in opposite directions within a single mode fibre and showing an optical frequency difference equal to the Brillouin shift ν_B will also similarly generate an acoustic wave through electrostriction. The moving grating sustained by this acoustic wave will diffract light from the upper frequency lightwave, called pump, to the lower frequency lightwave, called probe. This power transfer is equivalent to an amplification process from the probe point of view, and the net gain experienced by the probe reads:

$$I_S = I_o \, e^{g_B(n) I_P L} \qquad (2)$$

where the intensities are I_o for the incident probe, I_S for the probe after amplification and IP for the pump, respectively, and $g_B(\nu)$ is an equivalent gain coefficient called Brillouin gain spectrum and L the interaction length. The actual amplification experienced by the probe only depends on the pump intensity, so that the strongest effect is obtained using intense pump light, the probe power being maintained as low as possible to avoid significant pump depletion.

The strong attenuation of sound waves in silica determines the shape of the Brillouin gain spectrum. Actually, the exponential decay of the acoustic waves results in a gain $g_B(\nu)$ presenting a Lorentzian spectral profile:

$$g_B(\nu) = g_o \frac{\left(\Delta\nu_B/2\right)^2}{(\nu-\nu_B)^2+\left(\Delta\nu_B/2\right)^2} \tag{3}$$

where $\Delta\nu_B$ is the full width at half maximum. This FWHM width ranges from 35 MHz at 1300 nm to 25 MHz at 1550 nm in standard single mode fibres, these figures being significantly increased for more special fibres.

The Brillouin gain spectrum peaks at the Brillouin frequency shift ν_B, and the peak value is given by the Brillouin gain coefficient g_o:

$$g_B(\nu_B) = g_o = \frac{2\pi n^7 p_{12}^2}{c_o \lambda_P^2 \rho_o V_a \Delta\nu_B} \tag{4}$$

where p_{12} is the longitudinal elasto-optic coefficient, ρ_o is the density, λ_p is the pump wavelength and c_o is the vacuum velocity of light. In most fibres the peak gain value g_o lies in the $2-3\times10^{-11}\frac{\mathrm{m}}{\mathrm{W}}$ range.

The acoustic velocity is directly related to the medium density which is temperature and strain dependent. As a result the so called Brillouin frequency shift carries the information about the local temperature and strain of the fibre as shown in Fig. 2 (Niklès et al., 1997).

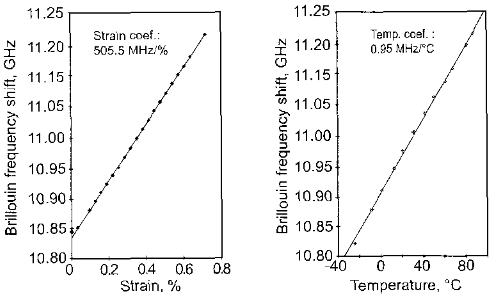


Fig. 2 Strain and temperature dependence of the Brillouin frequency shift of standard telecommunication optical fibres

Brillouin-based techniques bring the following advantages over other distributed techniques:

- The technique makes use of standard low-loss single-mode optical fibre offering several tens of kilometres of distance range and a compatibility with telecommunication components.
- It is a ***frequency based technique*** as opposed to Raman-based techniques which are intensity based. Brillouin based techniques are consequently inherently more accurate and more stable on the long term, since intensity based techniques suffer from a higher sensitivity to drifts.
- Brillouin scattering can be optically ***stimulated*** leading to a much greater intensity of the scattering mechanism and consequently a more acceptable signal-to-noise ratio.

The frequency difference between pulse and probe can be scanned for precise and global mapping of the Brillouin shift along the sensing fibre. At every location, the maximum of the Brillouin gain is computed and the information transformed to temperature or strain using the calibration coefficients of Fig.2. The probe signal intensity can be adjusted to acceptable levels for low noise fast acquisition whatever the measurement conditions and fibre layout, thus solving the main problem which is generally associated with distributed sensing based on spontaneous light scattering.

The localization of the temperature or strain information along the fibre is possible by using a pulsed pump signal. The interaction of the probe with the pump is recorded as a function of time and the time information can be converted into distance. An actual temperature profile of the fibre can be computed by using calibration curves (Fig. 2). Thanks to the high speed of light, fibre lengths of several kilometres can be scanned within a fraction of second, yielding several thousands of measurement points. The spatial resolution is set by the pump pulse width or the equivalent distance occupied by half of optical pulse within the fibre (for instance a 10 ns pulse yields a 1 metre spatial resolution along the fibre).

The spatial resolution obtained with this technique is 1 meter for a 30 km range. The physical limit for spatial resolution is just below 1 meter and results from the acoustic properties of silica. This configuration of the sensor is thus definitely dedicated for long range measurements with meter resolution and is not suitable for centimeter resolution. It must be pointed out that a novel and very inventive configuration was recently reported by K. Hotate *et al*, based on a correlation technique, that achieved measurements with a 1 cm spatial resolution, but the range is also reduced to less than 1 km, accordingly.

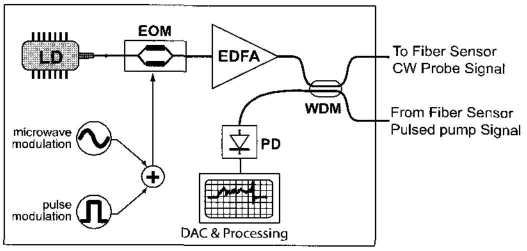


Fig. 3 Schematic setup of the DiTeSt instrument developed for the measurement of Brillouin frequency shift in optical fibres. The monitoring configuration requires a so-called double-ended configuration where both fibre ends are connected to the instrument.

The accuracy on the determination of the Brillouin shift ν_B depends on the amplification contrast and the probe signal intensity. In standard fibres an accuracy of 0.5 MHz is observed. This approximately corresponds to a 0.5 K temperature resolution and to a 1×10^{-5} strain resolution. The Brillouin shift accuracy can be improved to 200 kHz, corresponding to a 0.2 degC temperature and 4×10^{-6} strain resolutions, respectively, at the expense of either a worse spatial resolution or a longer measurement time.

An innovative instrumental configuration has been developed for temperature/strain monitoring based on the measurement Brillouin frequency profiles of optical fibre (Niklès et al., 1995). The company Omnisens in Switzerland has integrated this technique into commercially available instruments called DiTeSt. The used schematic configuration of the optics is shown in Fig. 3.

Advanced modulation techniques and wavelength-demultiplexing components developed for telecommunication applications offer ideal solutions for the generation and the control of both pump and probe signals. The operation wavelength was selected to match the lowest attenuation (typically around 0.2 dB/km at a 1.55 micron wavelength) of standard singlemode telecommunication fibres. The system main original feature is the presence of a single laser source (LD) that is modulated through a Mach-Zehnder electro-optic modulator (EOM). This electro optic modulator is used on the one hand for pulsing the CW light forming the pump signal and on the other hand for the generation and frequency tuning of the probe signal through the modulation of the laser light. A dedicated Er3+ doped optical amplifier (EDFA) is used to boost the optical signal intensities and wavelength- demultiplexing components are used to route the signals in the sensing fibre. When the probe signal returns from the sensing fibre its intensity as a function of time is recorded with a fast photodetector (PD) and digital acquisition card.

The Brillouin time domain analysis was first developed to detect local strains in telecommunication cables, which may cause early failure due to fibre breaking. It turned out that this application has gained little interest, the manufacturing quality of telecom cables making the optical fibre to show practically no strain.

But the special threadlike geometry of the optical fibre makes it an excellent candidate for monitoring large structures and installations. This property clearly opens new opportunities for a better control of the natural or built environment. The distributed nature of the sensing element offers the possibility to densely control a structure over its entire length, surface or volume, which would be impossible using point sensors.

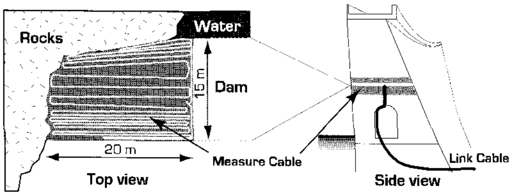


Fig. 4 View of the concrete slab and of the mat-like installation of the measuring cable for concreting temperature monitoring, during the raising of Luzzone dam in the Swiss Alps

We had the opportunity these past few years to perform many measurements on different sites. In all cases the sensor demonstrated its capability to perform the required measurements, in few cases at the expense of a special installation or packaging of the fibre.

3. Concrete temperature monitoring in a dam

The first application reported here was performed in 1997 in a real environment and uses the optical fibre as a temperature probe. The equipment was used to monitor the concrete setting temperature in large structures.

This monitoring is of prime importance in critical works, since the density and the importance of microcracks are directly related to the maximum temperature experienced by the concrete during the setting chemical process.

A major dam at Luzzone in the Swiss Alps was recently raised to increase the power capability of the associated hydroelectric plant. This raising was actually achieved by gradually stacking new concrete slabs of 15 m × 10 m average size for a 3 m thickness, as shown in Fig. 4. A small optical telecommunication cable was installed during the concreting over the

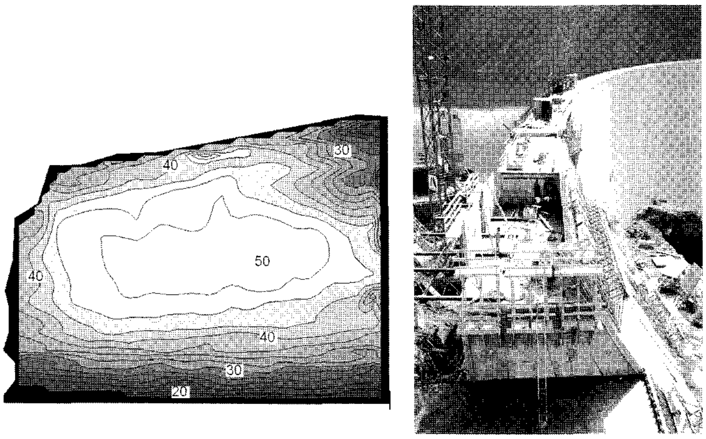


Fig. 5 Temperature of a 20 x 13 x 3m concrete structure in a dam, performed 30 days after concreting. Isotherms are shown in degree centigrade. On the right is shown the tested structure, at the very front of the picture.

central layer of the largest slab, so that the embedded cable makes a dense horizontal mat, necessary to obtain a two-dimensional temperature distribution of the whole slab area. Fig. 5 shows the temperature distribution over the slab 30 days after concreting. It can be clearly seen that the temperature rises up to 50 degC in the central area. Periodic measurements showed it took about 6 months to cool down this region. The outer areas of the slab rapidly stabilize at the ambient temperature, so that an observer is totally unaware that the concrete is still fairly hot in the central region of the dam.

4. Secure tunnelling using smart reinforcing pipes

Construction of tunnels in unstable soils may lead to severe safety issues. Numerous tragedies during the construction process were reported in the past. This issue is particularly present in Eastern Asia and techniques based on the installation of reinforcing bars are now commonly used.

The possibility to use the reinforcing tools as sensing elements turned out to be very attractive, since it offers the opportunity to inform on the soil movements during the construction in real time. Brillouin local analysis of strain turns out to be very convenient for this application, since the fibre may be installed to replace many points sensors and thus to fully inform on the deformations experienced by the reinforcing pipes. In addition the fibres from different pipes may be serially connected, so that the entire site may be controlled in a single measurement process.

The fibre was placed longitudinally along the pipe and at each cardinal point on the section, as shown in Fig. 6. In case of moving unstable soils the pipe is subject to flexure and fibres placed on opposite sides of the pipe experience symmetric and opposite strains (elongation compression). This makes possible to subtract any offset due to temperature and residual strains resulting from the installation.

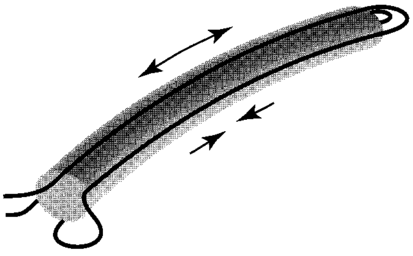


Fig. 6 Schematic view of the smart reinforcing pipe used for strengthening the soil during excavation. The fibre is placed at the four cardinal points of the pipe section and experiences strain whatever the direction the pipe is deformed by soil movements.

The fibre optic sensor system was tested in the Ulsan Kangdong tunnel in South Korea, that is a section of a national road under construction. The system is used to predict the behaviour of the tunnel section during and after excavation.

During tunnelling, most of the tunnel deformation is observed within 1 day after tunnel excavation. The smart pipe thus offers a key advantage with respect to conventional techniques as far as safety is concerned, since it informs immediately after installation.

As a result of the fibre placement the response to strain of the smart reinforcing pipe is symmetric with respect to the centre line. This is clearly shown in Fig. 7, which is a typical measurement of the response of a smart reinforcing pipe during excavation in the Ulsan-Kangdong tunnel.

From these strain data, the stress and displacement of the reinforcing pipe are calculated, giving important information to predict issues about the tunnel safety. As shown in Fig 7, large variations of the pipe deformation occurred just after tunnel excavation, within 2 days. Then the strain response remains steady, meaning that the tunnel deformation has stopped and the tunnel may be considered as safe.

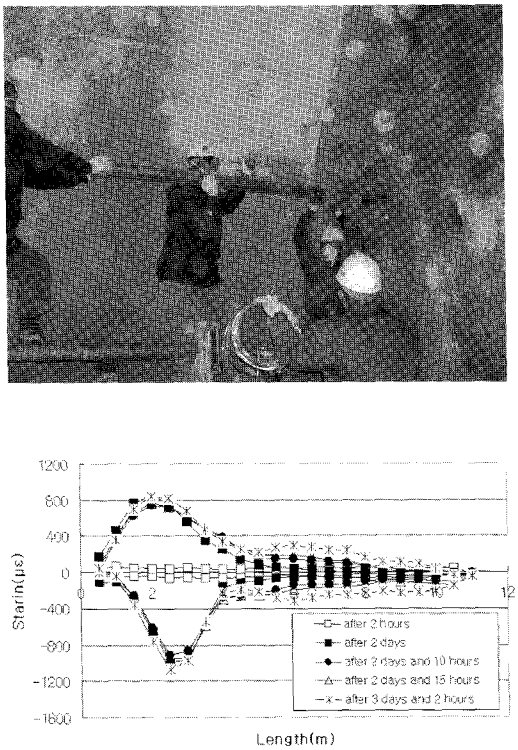


Fig. 7 Top: Installation of a reinforcing pipe containing fibres as strain sensor in the Ulsan Kangdong tunnel Bottom: Distribution of strain along the smart reinforcing pipe for 2 fibres placed on opposite sides, showing a symmetric deformation. The deformation process stops after 2 days and remains steady.

5. Pipeline leakage detection

The next application is based on distributed temperature sensing using Brillouin analysis and demonstrates that the long range capability of this technique may lead to a very efficient and cost effective solution.

In 2002 the construction of a natural gas storage facility some 1500 m under the ground surface was started in the area of Berlin in Germany. Using mining technology the building of underground caverns for gas storage in large rock salt formation requires hot water and produces large quantities of water saturated with salt, the so called brine. In most cases the brine cannot be processed on site and must be transported by a pipeline to the location where it can either be used for chemical processes, or injected back safely into the ground. Because the brine can be harmful for the environment, it was a mandatory request that the pipeline is monitored by a leakage detection system.

In the Berlin project a 55 km pipeline was built and a Brillouin-based optical fibre sensor was selected as a leakage detection system (Niklès et al., 2004). In order to cover the whole pipeline distance, it was decided to use two DiTeSt analyzers although one instrument would have been theoretically able to cover the whole distance with its two channels. However the installation of the fibre cable required some 60 splices (that correspond to a additional loss of up to 3 dB) which reduces the distance range of the instrument accordingly and justified the use of two instruments. The selected sensing cable is a customized version of a standard armoured telecommunication fibre optics cable for underground applications. The cable includes the optical fibres used for temperature monitoring as well as fibres for data communication between the instruments and the control room and additional spare fibres.

During the construction phase the fibre cable was first placed in the trench and buried in the sand some 10 cm underneath the pipeline. The position of the cable with respect to the pipeline is important in order to guarantee that all leakages are detected. The position of the sensing cable is a trade off between the maximum contrast in the case of a leakage and the assurance to detect leakages occurring from every point of the tube circumference.

The overall pipeline configuration together with the temperature monitoring system configuration is schematically depicted in Fig. 8. Both DiTeSt instruments are installed in dedicated buildings (gate II and gate V respectively). Each instrument is responsible for the monitoring of half of the total distance and an optical switch is used to select the section to be monitored, so that the longest fibre section is 16,85 km. The central communicate with the instrument through an optical LAN using spare fibres in the sensing cable. The temperature profiles measured by both DiTeSt instruments are transferred every 30 minutes to the central PC and further processed for leakage detection.

A dedicated software runs continuously on the central PC and controls the complete monitoring system. It performs the leakage detection through a comparison between recorded temperature profiles, looking at abnormal temperature evolutions and generates alarm in the case of the detection of leakage. The system is able to automatically transmit alarms, generate reports, periodically reset and restart measurements, and requires virtually no maintenance.

The brine is pumped out from the underground caverns and is injected into the pipeline at a temperature of about 35°C. At normal flow rate the temperature gradient along the whole pipeline length is about 8°C. Since the pipeline is buried in the ground at a depth of approximately 2 to 3 meters, the seasonal temperature variations are quite small and the soil

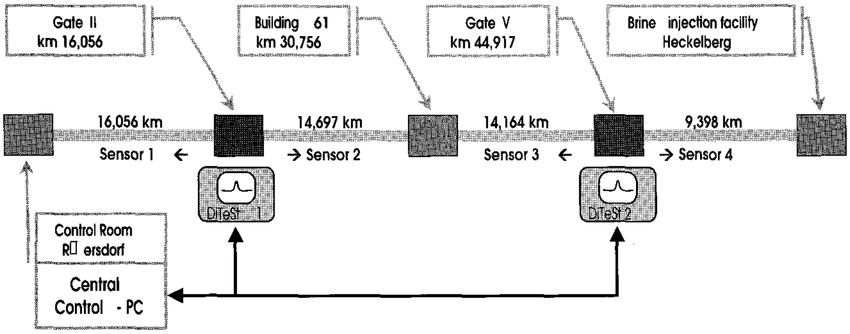
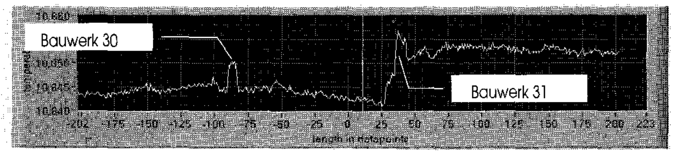


Fig. 8 Schematic representation of the brine pipeline built to evacuate the brine from Rüdersdorf and transport it to Heckelberg where the brine in injected back into the ground. Both DiTeSt instruments have two measurement channels, respectively called sensor 1 to 4. The sensors temperature profiles are periodically transferred to the central PC for further processing and alarm generation.

Temperature profile before leakage



Temperature profile when the leakage is detected

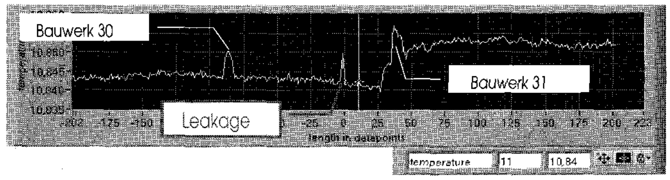


Fig. 9 Measured profiles before and after the leakage occurred at distance 17970 meter from the pumping station, as displayed on the central PC in the control room. The vertical scale corresponds to raw Brillouin frequency shift given in GHz. The observed local temperature increase associated to the leakage was measured to be of around 8°C

temperature was measured to be around 5°C. As a result a substantial temperature increase is associated to every leakage even in the case of low leak rates.

The pipeline construction phase was completed in November 2002 and the pipeline was fully operating in January 2003. In July 2003, a first leakage was detected by the monitoring system. It was later found that the leakage was accidentally caused by excavation work in the vicinity of the pipeline. Fig. 9 shows the occurrence of the leakage and its effect on the temperature profiles as they were displayed on the central PC in the control room. The graphs in Fig. 9 correspond to measured raw data, i.e. Brillouin frequency shifts, as a function of distance. By using the 0.927 MHz/deg temperature coefficient, the local temperature increase due to the leakage is measured to be 8°C. This corresponds to a leak rate as low as 50ml/min. An alarm was immediately and automatically triggered and the flow was eventually stopped.

Taking into account the application requirements in terms of distance range and measurement time, neither Raman nor spontaneous Brillouin scattering techniques were applicable and only a stimulated Brillouin-based system could perform an accurate temperature monitoring in the available time (monitoring of 55 km with 1°C accuracy in less than 10 minutes). To date the leakage detection system has been in operation for two years and two leakages were successfully detected.

On the other hand, leakage detection for water mains is ongoing at Noksan, Pusan, Korea. This project was initiated in June this year 2005 by Pusan Metropolitan city and 4.4 km length of pipeline of which diameter is 900 mm has been under construction. The local government worried about the leakage problem that might be stemmed from the ground subsidence because the territory Noksam is a reclaimed land from the sea to develop a big industrial complex.

Unlike the brine case, where the temperature of the liquid inside keeps relatively high so that the fibre underneath easily picks up the temperature difference in case it leaks, water detection by temperature is not easy due to the lower margin of the temperature difference between in and outside of pipe. It was successfully achieved, however, with specially developed sensor cable which was incorporated with heating wire. As of August 11, 2005, validation test has already been finished. As the figure 10 shows the results of measurement profiles, it is very clear that the water seepage deprived the temperature that had been warmed

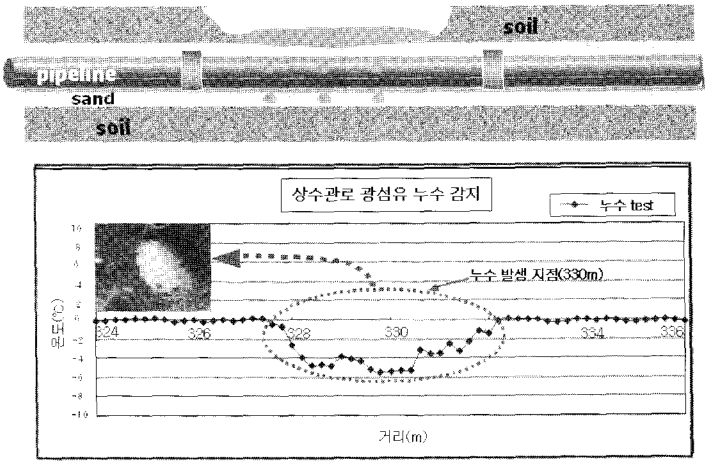


Fig. 10 Measured profiles after water seepage at the marked distance

up by heating wire before water permeated and consequently spot out the location of seepage or leakage.

6. Conclusions

Fibre optics distributed temperature sensing techniques have opened new possibilities in temperature and strain monitoring and gradually have found applications in various domains such as the oil and water mains, tunnel deformation, dam monitoring, etc. Their ability to precisely measure temperature and strain evolution over several tens of kilometres and localize the information with a meter spatial resolution makes them very attractive for safety monitoring applications. Among today's available sensing techniques, Brillouin-based techniques have demonstrated the best performances in terms of distance range, accuracy and detection time.

Furthermore, new configurations have been demonstrated to extend the distance range beyond 100km while maintaining a spatial resolution in the meter range.

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