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UNDERGROUND TUNNELING MONITORING BASED ON SENSITIVE OPTICAL FIBRE CABLE AND BRILLOUIN REFLECTOMETRY

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Abstract

A new methodology combining Brillouin Optical Time Domain Reflectometry (B-OTDR) in single mode optical fibres and a special cable design is proposed to monitor settlements during tunnelling work, especially with Tunnelling Boring Machine (TBM), in urban environment. The challenge is to avoid confinement losses, which remain an important risk for public works, leading to additional delays and costs and to higher insurance costs. In this particular application, usual surface instrumentations cannot be set up because of high building density in many overcrowded cities, but the tunnelling has the special challenge to require that the ground surface remains undisturbed. Sensing optical fibre cables currently developed in this project result from an industrial manufacturing, and their designs take into account the flexibility and the robustness required both for the installation in Horizontal Directional Drilling (HHD) hole and for storage on drums. Different cable configurations have been studied based both on a single fibre (axial strain) or three fibres (bending measurements).

INTRODUCTION

The development of communication on a world-wide scale requires the enlargement of and the creation of new transportation networks. Tunnelling is, in spite of high costs, the only alternative in areas with high density populations. Urban tunnelling has the special challenge of requiring that the ground surface remains undisturbed. This means that ground subsidence must be avoided.

Subsidence Risk

The loss of confinement in an urban area remains a major risk leading to important delays and costly additional works. As quoted from a reinsurer point of view [1]: *Past experience shows that the occurrence of spectacular loss events during the construction of tunnels cannot be avoided. Although the insurance industry has suffered disastrous results over the years through providing contractors' all risks insurance for tunnel risks, it will continue to be one of the main risk carriers for such projects in the future.* Nine examples of spectacular tunnel losses between 1994 and 2003 are given by the reinsurers. Seven of them deal with ground subsidence, one tunnel was flooded during construction and the last one got a endured fire.

As stressed in the study, the repair work often differs significantly from the original construction method. Thus, for instance, *repairing a ten-metre long stretch of collapsed tunnel that initially costs 500 k€ to construct may involve complicated and expensive repair measures that in unfavourable circumstances could lead to cost 50 times more, in which case it would cost 25 M€ to restore the works to the condition they were in immediately before the collapse*.

Tunnel Construction With Tunnelling Boring Machines

Risks exist for all the tunnelling techniques: explosives, cutter machine or Tunnelling Boring Machine (TBM). This project deals with TBM and the normal method is to maintain the soil pressure during and after the tunnel construction. The TBM fulfils the following functions:

- Its cutter head excavates the ground, maintaining a pressure equivalent to the ground pressure.
- It brings the excavated materials from the confined zone to the tunnel at the atmospheric pressure. The slurry is brought outside the excavation.
- It sets up the lining as an assembly of concrete rings.
- As the cutter head has a bigger diameter than the concrete rings, the TBM fills the free space between the lining and the excavated ground by injecting grout behind the last set-up ring.

These four functions are essential to prevent the development of ground subsidence.

The aim of our consortium is to detect any loss of confinement at an early stage, providing the opportunity to come back to normal conditions by an adjustment of TBM operation parameters. It will avoid taking costly and time-consuming mitigation measures, for instance injections from the surface.

CLASSICAL SETTLEMENT DETECTION AND PROPOSED SOLUTION

The best way to detect a loss of confinement is to identify any ground movement right above the excavation from the TBM front face up to the last erected concrete rings over a maximum span of 50 meters.

Existing Solutions

Many settlement devices are already available to achieve this goal. They are mainly based on vertical boreholes. The simplest device consists in a rod anchored at a given depth. The monitoring is realized by following the vertical motion of the emerging rod with an optical prism. The reading must be done from a distant location to take into account any subsidence of the ground level at the rod place. Vertical boreholes can also be instrumented at different depths. Settlement gauges are installed along the borehole to detect deformation at several levels. These systems present important drawbacks:

- In most situations, the borehole cannot be performed at the vertical of the TBM axis due to existing constructions such as building, network, etc.
- When the borehole location is out of the tunnel axis, the deformation measurements need a correction based on a simple subsidence model leading to an unknown error.
- The settlement devices are equipped with electronic components requiring power supply, data acquisition and communication links for each borehole.
- To be efficient, boreholes must be disposed along the TBM axis, every 10 meters, so the cost of monitoring becomes prohibitive. This is the reason why the settlement devices are limited to optical prisms on the surface at the ground level or on buildings located along the tunnel axis. It is also common to fix inclinometers on vertical walls to detect any tilt of buildings.

Optical Fibre Sensor Solution

To perform a real-time monitoring, the original approach proposed by the consortium consists of very early settlement detection the nearest to the tunnel vault, before any effect on the surface and based on instrumented horizontal directional drilling (HDD). This technology from the petroleum industry allows carrying out a drilling along a chosen axis (see fig. 1a and 1d). The borehole trajectory is done parallel and above the future tunnel axis. The challenge is to equip the drilling with measurement cables.

The proposed solution, is to introduce a curvature sensing cable (based on Brillouin optical fibre measurement technology as described below) between the tunnel and the surface (typically 2 m above the vault) and along the total length of the future tunnel (see fig. 1c). Any occurring settlement will be detected by a curvature change on the cable (see fig. 1d). The settlement z(x) can then be calculated by a double integration of the curvature ρ(x) as follows:

$$\rho(x) = \frac{\frac{\partial^2 z}{\partial x^2}}{\left(1 + \left(\frac{\partial z}{\partial x}\right)^2\right)^{3/2}} \approx \frac{\partial^2 z}{\partial x^2} \text{ at first order} \qquad (1)$$

Optical Fibre Brillouin Optical Time Domain Analyser (B-OTDA)

The optical fibre sensor technology selected is based on the strain measurement with Brillouin reflectometry. Several papers [2, 3] described both the spontaneous and stimulated Brillouin scattering phenomena in optical fibres due to a nonlinear effect resulting from an interaction between acoustic phonons (generated by the vibration of the silica) excited in the medium and an incident light. When the fibre is strained or when its temperature changes, the acoustic wave velocity is modified and the Brillouin frequency shift changes proportionally. In standard single mode optical fibre the Brillouin frequency shift with respect to strain (respectively temperature), is about 500 MHz/%, (respectively 1 MHz/°C).

In order to measure strain or temperature distribution of an optical fibre, a pulse light (respectively a pulse light and a continuous pump light) is launched into the fibre, and the power of spontaneous (respectively stimulated) Brillouin backscattered light is sampled in the time domain at a designated rate, generally at very high frequency. The localization of an event along the optical fibre length is defined using the propagation time of the incident and backscattered light, which is called Optical Time Domain Reflectometry (OTDR) in telecommunications.

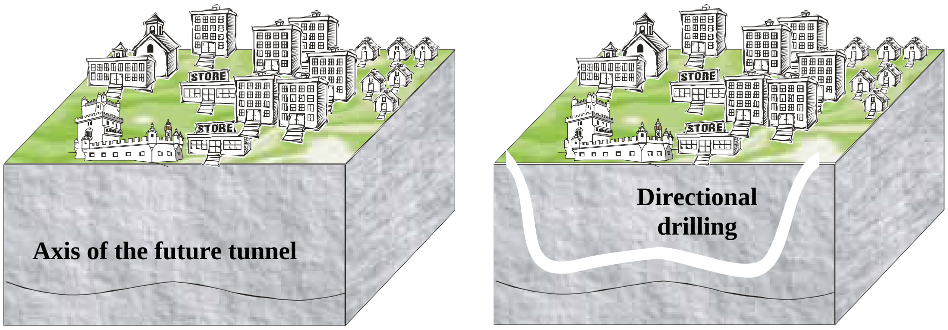
The great interest of the B-OTDA measurement is the capability of continuous and distributed measurement along a standard single mode fibre over several tens of kilometres or more [4, 5]

Instruments are now commercially available. Five companies (two in Europe and Asia and one in Canada) provide such interrogation units. For all of them, the basic measurement is the Brillouin frequency shift which is converted in strain or temperature.

Typical performances are:

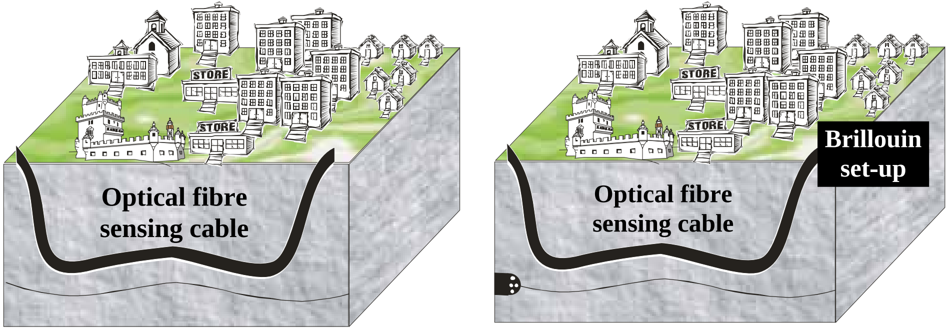
Strain / temperature accuracy:	20 µm/m (1°C)
Repeatability:	+/- 10 µm/m (+/- 0.5°C)
Spatial resolution	1 m

Over sampling	0.1 m
Acquisition time	few minutes
Measurement range	up to 25 km
Strain (temperature) ranges	+/- 1.25 % (+/- 600°C)



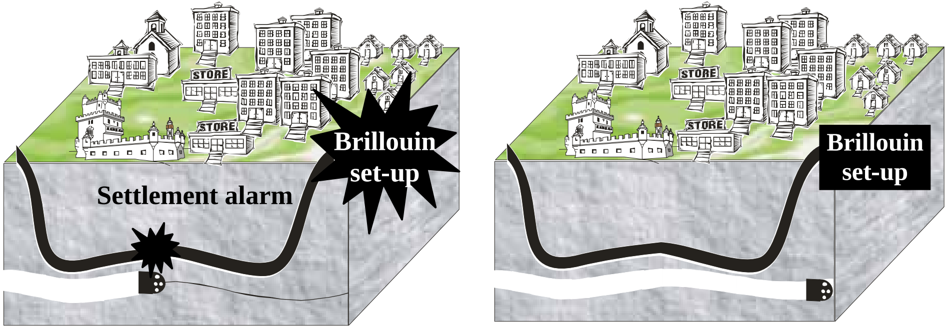
a: Scheme of the future tunnel profile

b: Boring of directional drilling



c: Insertion of optical fibre sensing cable

d: Connection to Brillouin set-up and start of principal tunnel boring



e: Ground settlement detected by the cable

f: End of the principal tunnel boring

Figure 1: Principle of settlement detection method based on optical fibre sensing cable embedded in a borehole above the tunnel.

CONCEPTION AND DESIGN OF THE BENDING CABLE

Numerical Soil Movement Model

In order to define the cable design and to adapt its sensitivity, numerical simulation of soil settlements have been carried out. Tunnel calculations are classically based on the convergence-confinement method approaches also called soil/tunnel interaction methods where the loading of lining is obtained in a relationship with the distance to the tunnel face. Soil deformations around the TBM have been modellised at different levels. Typical settlement results for an 8-m diameter TBM and for soft soil are represented on Figure 2 where the TBM front is localized at 40 m. The final settlement at the surface reaches 18 mm and **33 mm** at level 2 m above the tunnel vault, confirming the interest of an in-depth measurement. From model, it has been observed that the irregularities are smoothened by rising the surface. For that purpose, it is recommended to place the sensing cable at least 2 m over tunnel vault. At this location, the cable is close enough to the TBM location to provide a representative idea of happening phenomenon above the cutter head, but not too close to reduce local variation impact.

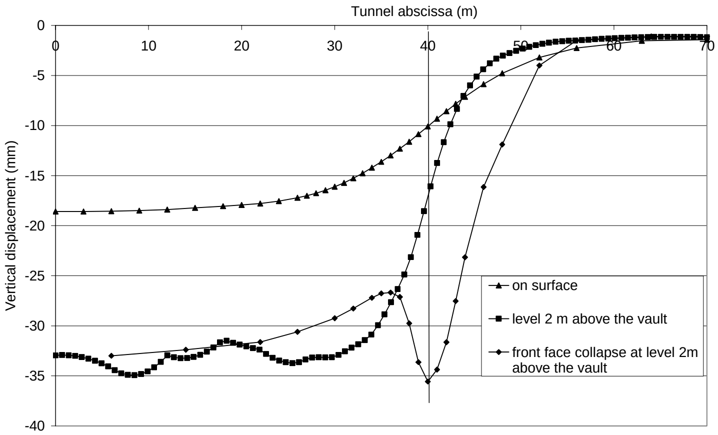


Figure 2: Standard settlement curve and front face collapse modelled at the surface and 2 m above the tunnel vault.

The sensing cable will detect soil movements around the TBM during construction progress, in order to detect both standard displacement curve induced by boring as shown in previous analysis and during abnormal situations. Two types of abnormal situations could occur when boring:

- The first one deals with a too large soil settlement. In this case, the sensing cable will measure the same shape of vertical displacement as for standard situation, but with higher amplitude.
- The second abnormal situation is an initiation of a face collapse mechanism which is due to a too low face pressure (see figure 2, third curve).

Cable Design

We can consider that the cable is fixed at the two external points. Since no sliding is allowed between cable and soil, the cable will experience an axial strain due to bending. We can show that the axial strain $\varepsilon_a=\Delta L/L$ (see fig. 3) calculated for the previous settlement curve with the equation 2 is less than 7 µm/m. Such value remaining lower than the Brillouin set up resolution is not detectable.

$$\varepsilon_{a\,i} = \frac{\int_{x_i}^{x_{i+1}} \sqrt{(1+\left(\frac{\partial z}{\partial x}\right)^2}\, dx - \left(x_i - x_{i+1}\right)}{\left(x_i - x_{i+1}\right)} \qquad (2)$$

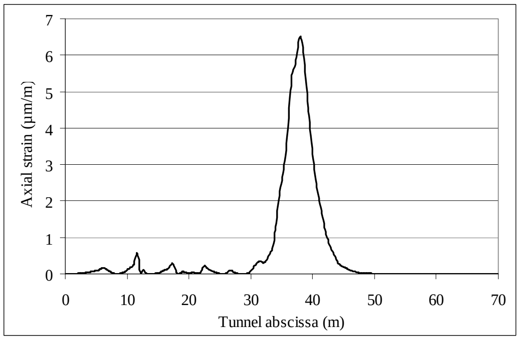


Figure 3: Axial strain calculated at 2 m above

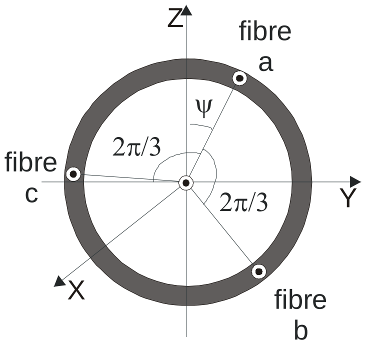


Figure 4: Scheme of the 3D cable

the vault

For this reason, another cable concept has been proposed based on the strain measurement due to the settlement. Let us consider a curved cable, of diameter ϕ equipped with three fibres as represented on Figure 4. There is no strain due to curvature on the plane surface (X,Y). When the cable is curved in the plane XZ (ψ represents the angle due to the cable twist with respect to Z axis), the upper part of the cable is under compression whereas its lower part is under traction. The local strain at the fibre depends on the distance between the fibre and the neutral axis. If the cable does not twist along its length (ψ = 0°), only the upper fibre located at z = ϕ/2 would be necessary with an additional fibre strain free to achieve temperature compensation represented in the centre.

But, in real conditions of directional drilling, the cable can twist and the rotation of the sensing fibre to the neutral axis will move along the cable, inducing a change on curvature strain sensitivity. That is why proposed is a sensing cable whose measurement is independent of the cable orientation in the ground, based on the measurements provided by three fibres placed at 120° with respect to each others.

In the ground, each optical fibre is submitted to both axial strain ε_a (residual strain of the cable pulling during installation and common lengthening due to curvature) and ψ-oriented bending induced strain (different for each fibre).

$$\varepsilon_{fa} = \varepsilon_a + \frac{\phi}{2\rho}\cos\psi \qquad (3)$$

$$\varepsilon_{fb} = \varepsilon_a + \frac{\phi}{2\rho}\cos\left(\psi + \frac{2\pi}{3}\right) \qquad (4)$$

$$\varepsilon_{fc} = \varepsilon_a + \frac{\phi}{2\rho}\cos\left(\psi - \frac{2\pi}{3}\right) \qquad (5)$$

From equation 3 to 5, where ρ is the local curvature radius, it is possible to deduce the axial strain ε_a (common on the three fibres), the maximal curvature strain $\varepsilon_{c\,\max}$, and ψ the orientation of the cable in the ground, as follows:

$$\varepsilon_a = \frac{\varepsilon_{fa} + \varepsilon_{fb} + \varepsilon_{fc}}{3} \qquad (6)$$

$$\varepsilon_{c\max} = \sqrt{\frac{1}{3}\left(\varepsilon_{fb} - \varepsilon_{fc}\right)^2 + \left(\varepsilon_{fa} - \varepsilon_a\right)^2} \qquad (7)$$

$$tg\ \psi = \frac{\varepsilon_{fb} - \varepsilon_{fc}}{\sqrt{3}\left(\varepsilon_{fa} - \varepsilon_a\right)} \qquad (8)$$

The greater the fibre distance from the (XY) plane, the higher the bending strain. Consequently, the bending sensitivity can be adjusted with the cable diameter. However, the cable cannot be too large to satisfy all the conditions of use and storage for several hundreds of meters length. Let us consider an upper limit of 1 percent in strain, a cable of diameter 30 mm has to be stored on a drum of diameter 3 m.

Brillouin Bending Cable Demonstrator

For such sensing application, we are looking for a good strain transduction, so standard telecom optical cables are not convenient because fibres inside their structure remain strain-free. That brought us to design and manufacture a specific cable. The cable manufacturing procedure has been divided in two steps: an elementary wire (0.9 mm diameter) containing one optical fibre embedded in a transducing material and the final 3D structure with three elementary wires extruded or mechanically fixed around the structure. This includes two qualification steps.

Several elementary optical wires, from different processes (different materials and production lines), have been manufactured and the strain transduction between material and fibre has been characterized up to 0.8% on an axial tensile bench. This kind of test is very severe for optical wire because only a short length of the cable is fixed and all the shear stresses are applied on a short surface (fig. 5). Figure 6 represents the frequency Brillouin shift of the optical wire *versus* the applied tensile strain, as well as the variation to the linearity. We can point out the very good linearity of the curve representative of the strain transduction of the material. The slope of the curve (488.15 MHz/%) is close to that of a bare fibre 504.70 characterized in same conditions.

Considering the global design of the 3D sensing cable, we have qualified the strain transductions between the coating material and different substrates (aluminium and polymers) which can be used for the cable structure.

For the 3D cable, the attachment of three elementary wires will be continued on a cylindrical body of diameter ϕ, to measure the strain due to the bending of the cable. This bending can be reproduced with a four-point bending set-up. The advantage of such a bench is that the curvature remains constant between the two loading points which induces on the fibre a constant strain between them (figure 7).

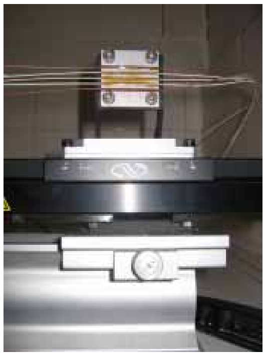


Figure 5: Wire fixation on axial strain bench

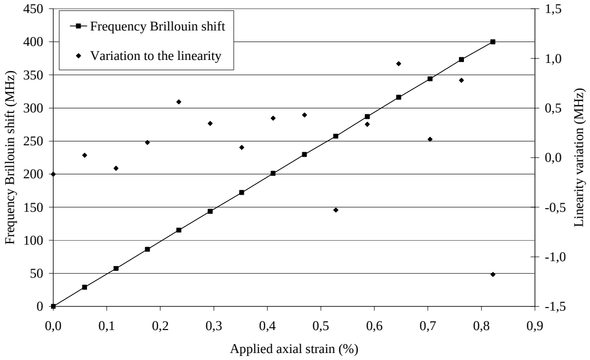


Figure 6: Optical wire axial tensile strain sensitivity

Taking in account that the curvature at any point is the second derivative of the deflection, one may set the relation between $\varepsilon_{c\,\max}$ and the bench parameters:

- L: the length between the two loading points,
- a: the distance between a loading point and a support point,
- $f_{\max}$: the maximal deflection localized in the centre of the framework.

$$\varepsilon_{c\,\max} = \frac{12\,\phi\,f_{\max}}{(3L^2 - 4a^2)} \qquad (9)$$

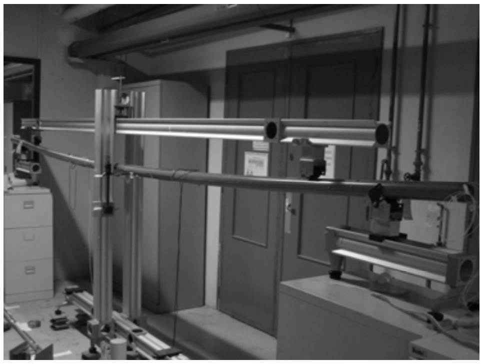


Figure 7: Four-point bending experimental set-up

A 3D demonstrator was performed with a cylindrical structure (Φ =62 mm and 6 m long) for a central deflection in the range of 0 mm to 150 mm. For each optical fibre measurement (figure 8), and from equations 6 and 7, it is possible to determine the measured maximal curvature strain. Finally we can highlight good agreement between strain predicted by four-point bench modelled (equation 9) and experimental results (figure 9).

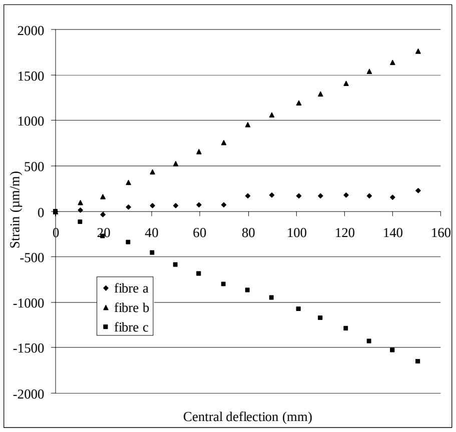


Figure 8: Strain measurements for the three fibres at 120° versus cable deflection.

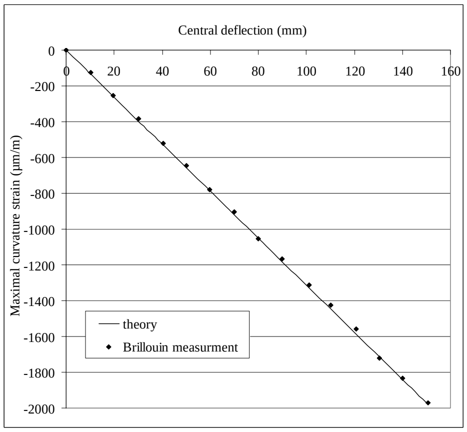


Figure 9: Maximal curvature strain comparison (experiment and model).

CONCLUSION

Feasibility of a bending sensitive cable based on three optical fibres at 120° on a 3D structure is now established. We know how to industrially produce small diameter optical fibre cables (Φ = 0.9 mm) dedicated to axial strain measurements with very good performances up to 1 % strain. Next stage will concern qualification of the 3D industrial prototype on a realistic span covering 100 metres and the detection algorithm.

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