Optical fiber sensors for geo-hydrological applications

Luca Schenato, Raniero Beber, Giulia Bossi, Matteo Mantovani, Gianluca Marcato, Alessandro Pasuto, Giacomo Titti

Geo-Risk Management Group, Research Institute for Geo-Hydrological Protection, National Research Council, Corso Stati Uniti 4, I-35127 Padova,
e-mail: luca.schenato@cnr.it

What is an optical fiber?

... a strand of glass that is as thin as a human hair:

1. Core 8–9 μm diameter (SMF): where the light is confined

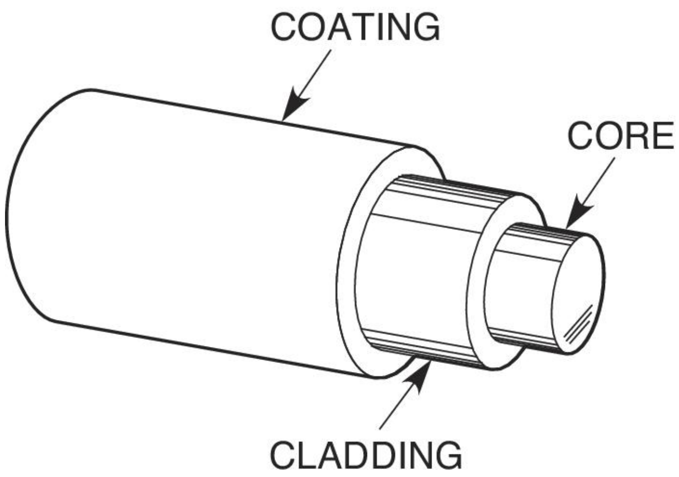
2. Cladding 125 μm diameter: assures the confinement

3. Buffer/coating ~250 μm diameter: first mechanical protection

4. Jacket: variety of sheath with opportune mechanical/chemical/thermal properties

ULTRA WIDEBAND LONG RANGE COMMUNICATION

OPTICAL FIBER



Source: Newport corporation

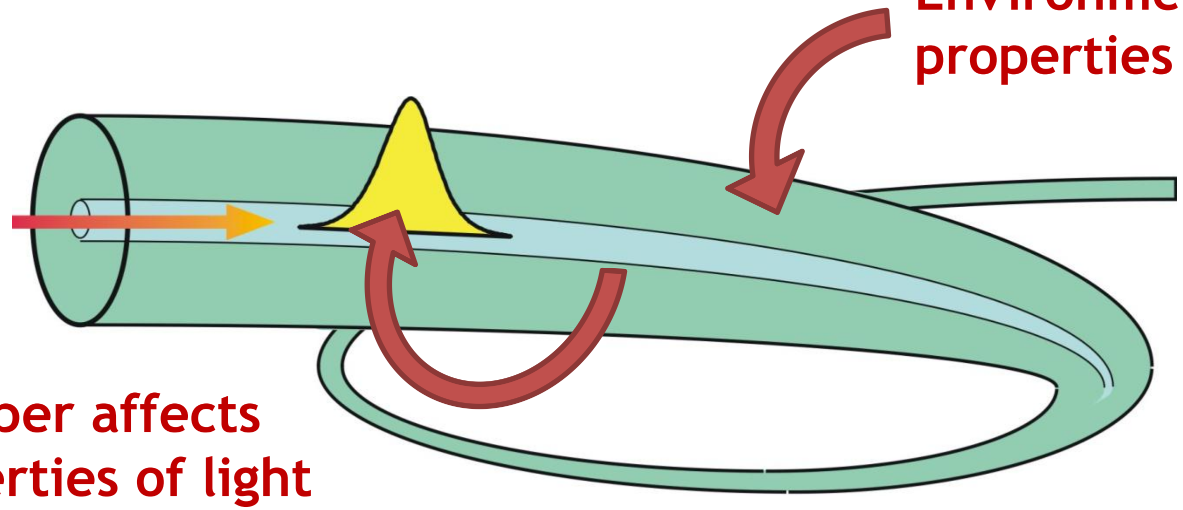
The optical fiber

	Optical Fiber	Coaxial cable
Attenuation	0.2 dB/km	>80 dB/100 m @ 5 GHz
Bandwidth	>50000 GHz	<5 GHz
Lifetime	30 years	5 years
Cost	<0.1 €/m	>0.6 €/m
Weight	0.06 kg/km	1000 kg/km
Diameter	0.25 mm	>1.5 mm
EMI	Immune	NOT Immune

- More than 1 billion of km of optical fiber has been deployed around the world
- Phone services, Internet and related services (VOD, OTT, IoT, cloud, SaaS, PaaS, ...) would not exist without the optical fiber technology

AND THEN???

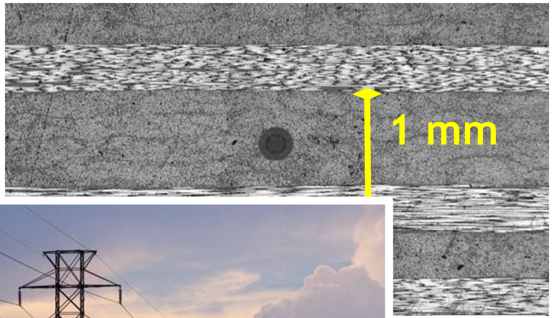
How a fiber can be a sensor?



1. The properties of light propagating in the fiber depend on the optical properties of the fiber.
2. Optical properties of the fiber depend on some extent to the external environment (temperature, strain, etc.).
3. Variation of the external environment may affect the properties of propagating light.

THE OPTICAL FIBER IS THE SENSOR !

The optical fiber...

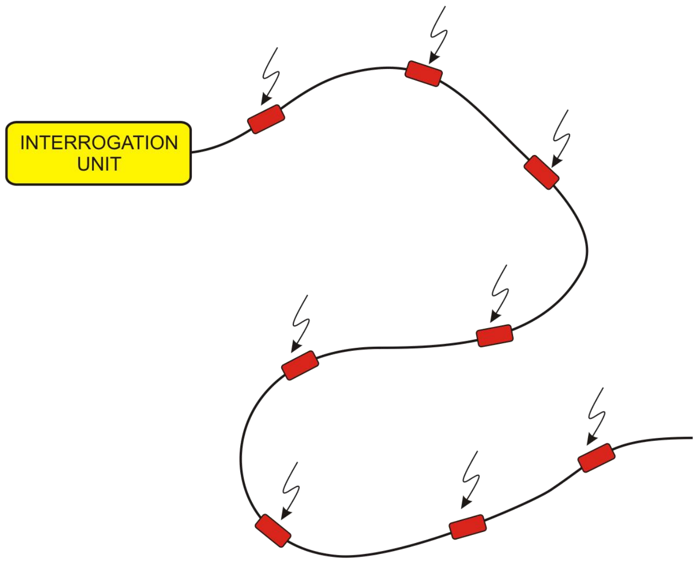


1. is intrinsically sensitive to several physical fields (most notably **temperature** and **strain)**
2. is small, lightweight and passive (can be easily embedded)
3. operates from few to several hundreds of K (ideal for harsh environments)
4. is immune to electromagnetic interference
5. allows signal propagation over huge distances (beyond tens of km) and remote "powering"
6. **enables sensors multiplexing:**
   - **tens of concatenated sensors**
   - **distributed sensors**

!

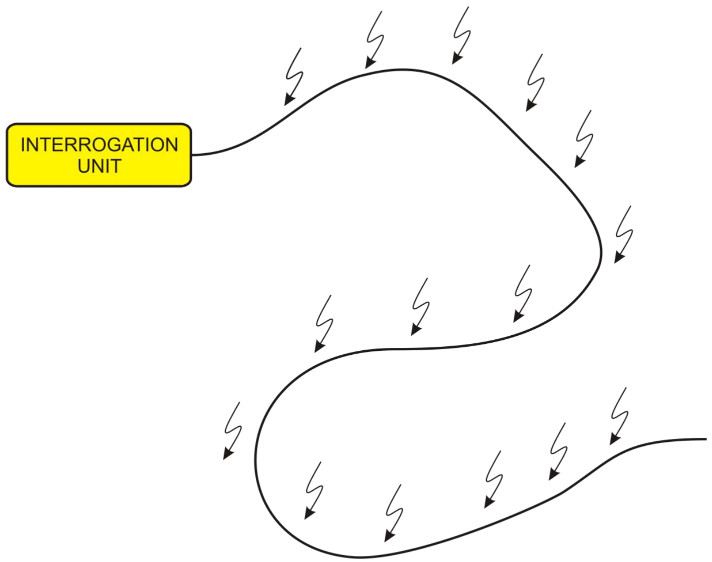
Fiber optic sensors (FOSs)

Single-point (quasi-distributed) sensors



- Typically, Fiber Bragg gratings (FBGs)
- Tens of sensors concatenated ("localized") along a single cable, several chilometer long.
- Typically, addressed by wavelength selection.

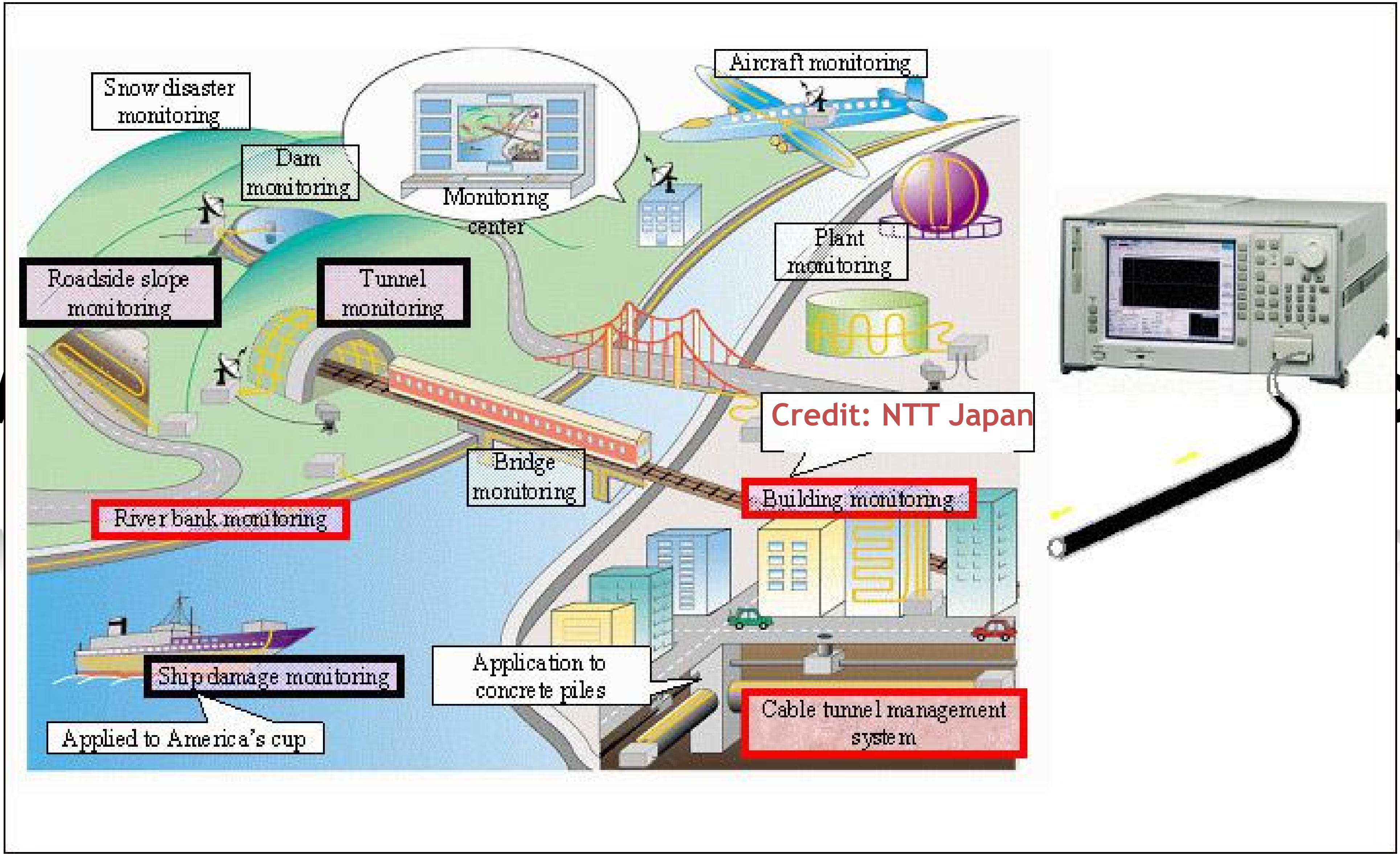
Distributed sensors



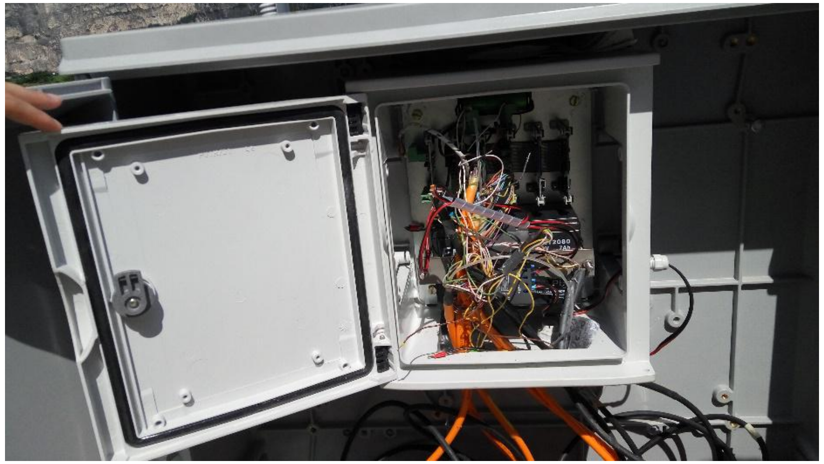
- The fiber is a single sensing element.
- Arbitrary sections can be addressed by sending single optical pulses.
- Spatial resolution around 1 m (but may be smaller).
- Thousands of sensing points/km!

Using an "image": I want to «measure» this landslide…

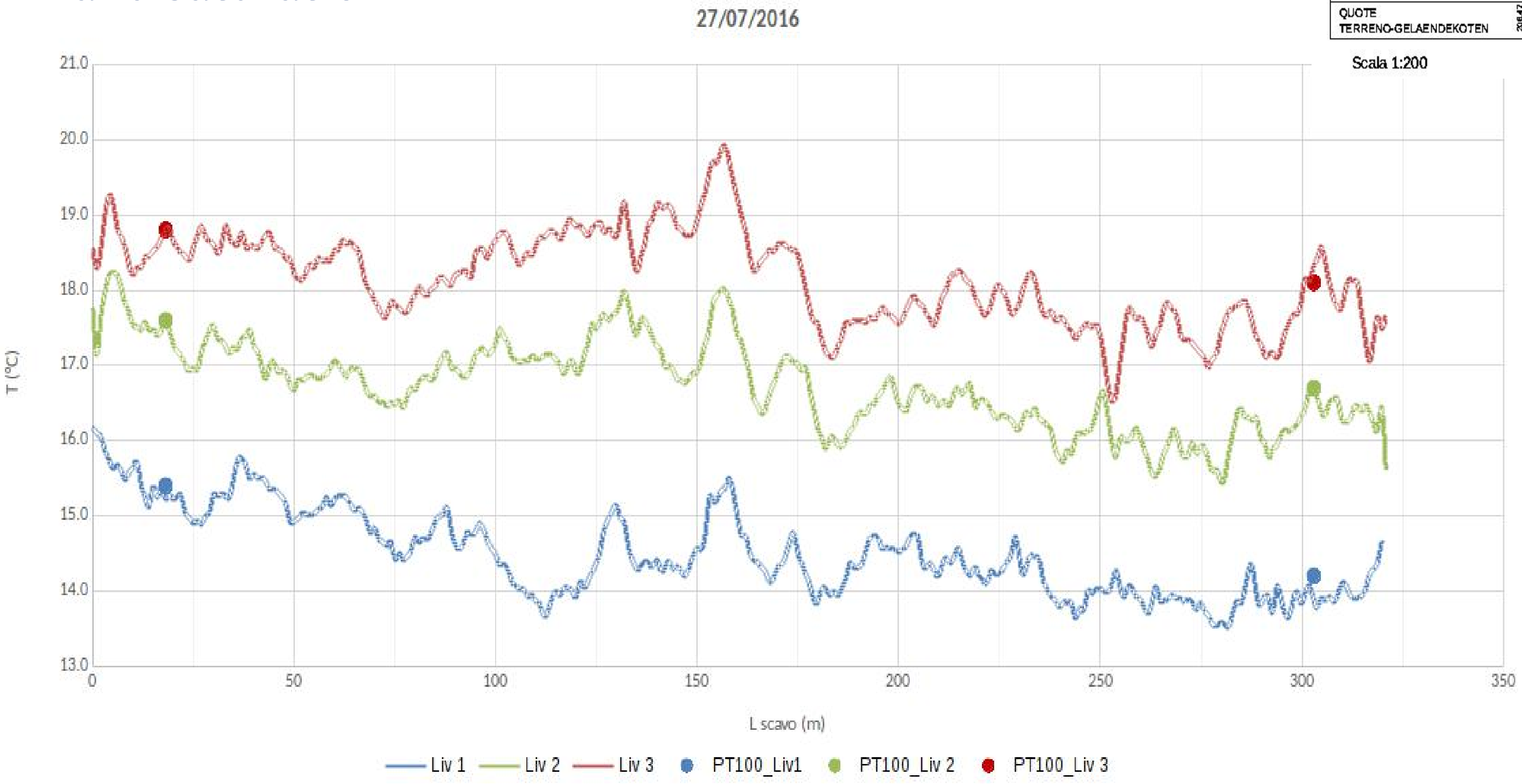
Schenato, L. A Review of Distributed Fibre Optic Sensors for Geo-Hydrological Applications. Appl. Sci. 2017, 7, 896.

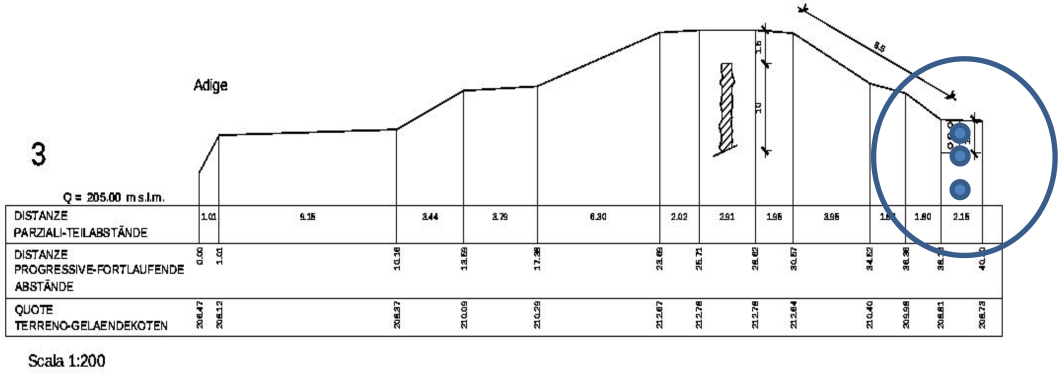

Snow disaster monitoring
Dam monitoring
Monitoring center
Aircraft monitoring
Plant monitoring
Roadside slope monitoring
Tunnel monitoring
Credit: NTT Japan
Bridge monitoring
Building monitoring
River bank monitoring
Application to concrete piles
Ship damage monitoring
Cable tunnel management system
Applied to America's cup

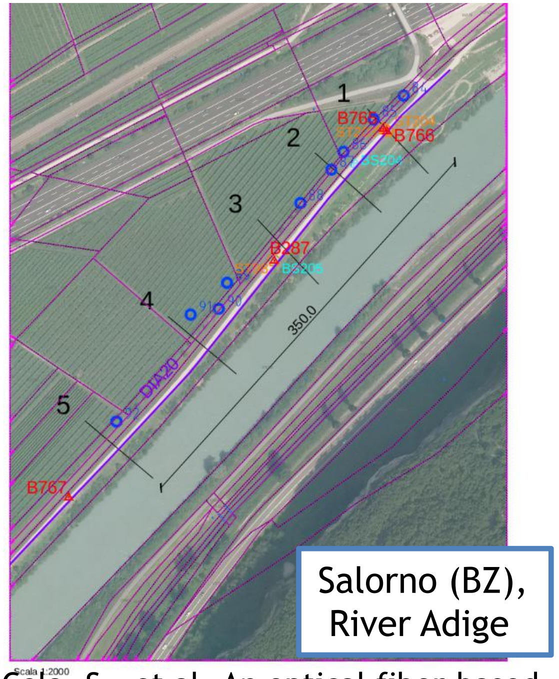
Distributed temperature sensing in soil



The temperature profile is given by the soil properties and saturation





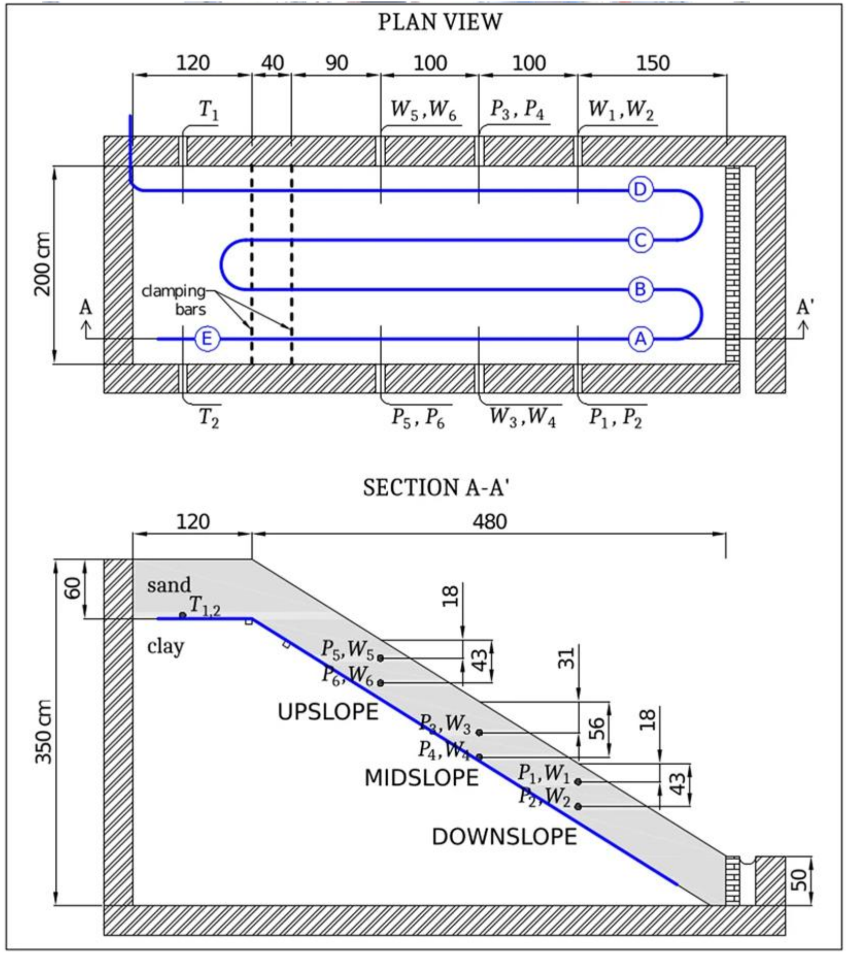


Cola, S., et al. An optical fiber-based monitoring system to study the seepage flow below the landside toe of a river levee (2021) Journal of Civil Structural Health Monitoring, 11 (3), pp. 691-705.

>500 sensing point/km

(No other physical contact sensors can achieve that resolution)

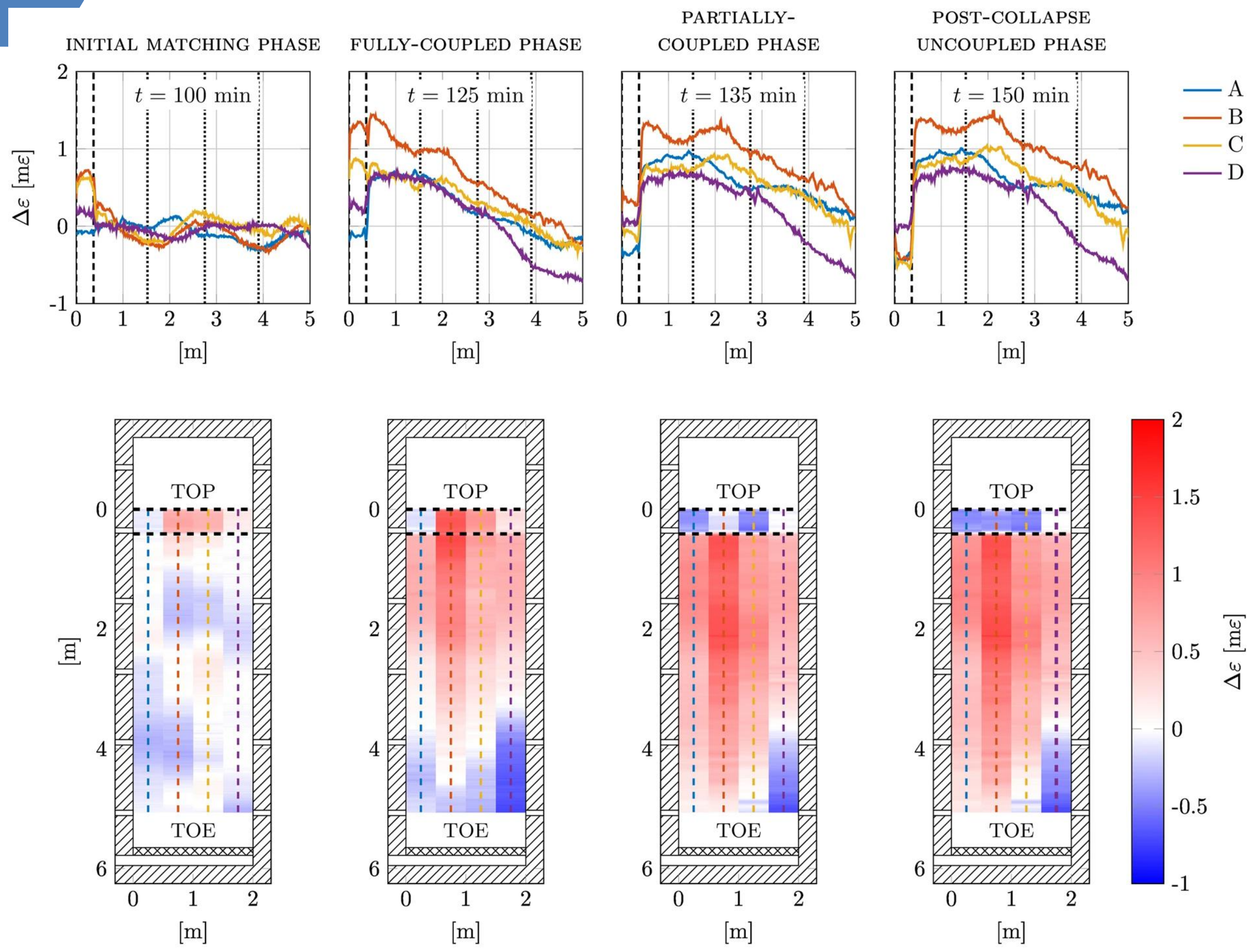
Distributed strain sensing in soil



(b)

Time-space map of the strain field at the sliding surface with a spatial resolution along the fiber of 1 cm.

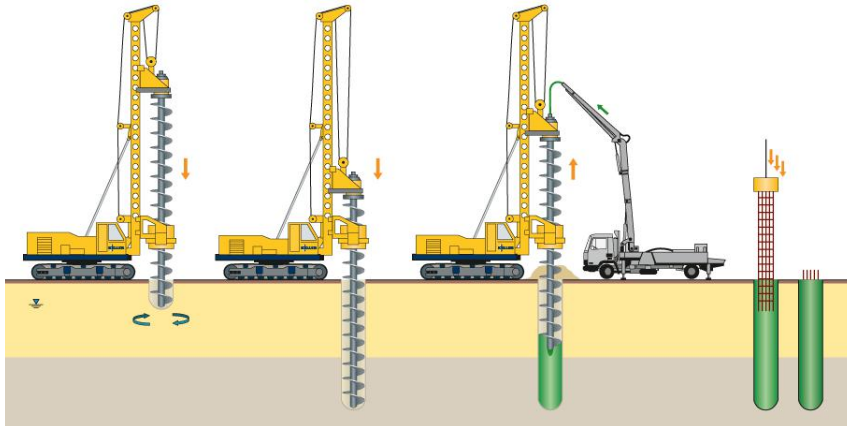
Distributed strain sensing in soil

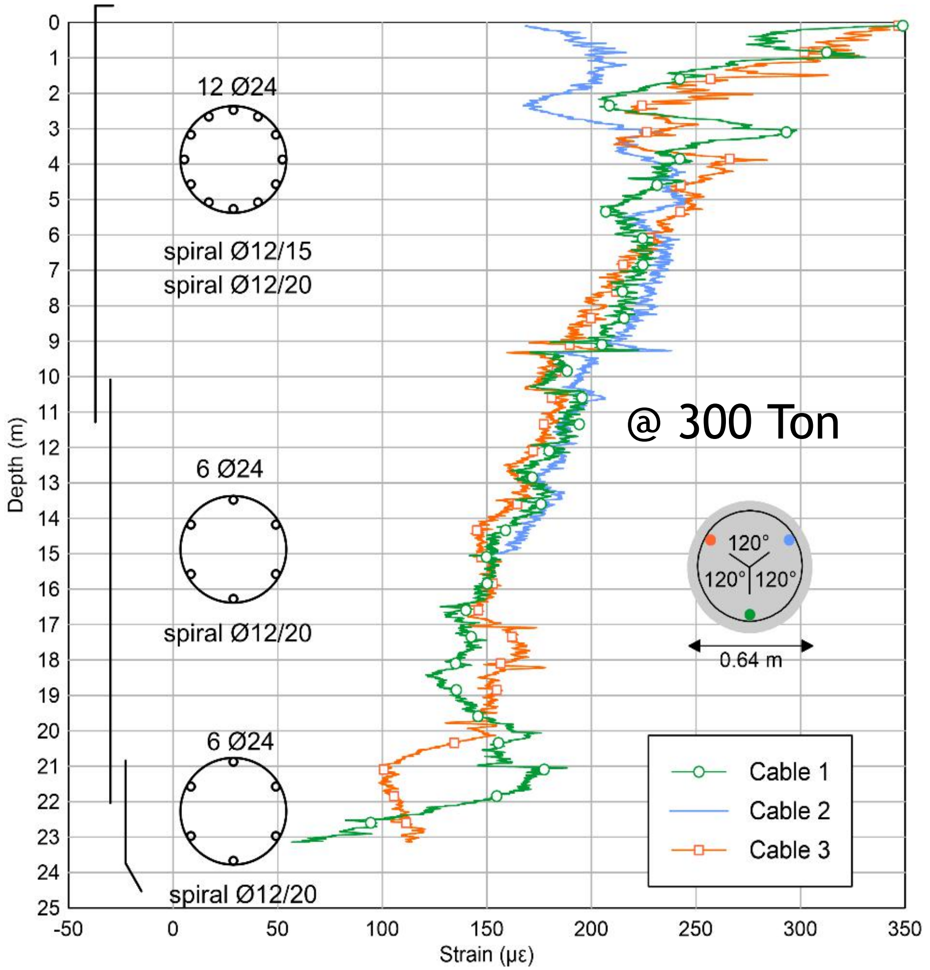


Schenato, L., et al., Distributed optical fibre sensing for early detection of shallow landslides triggering (2017) Scientific Reports, 7 (1), art. no. 14686

Time-space map of the strain field at the sliding surface with a spatial resolution along the fiber of 1 cm.

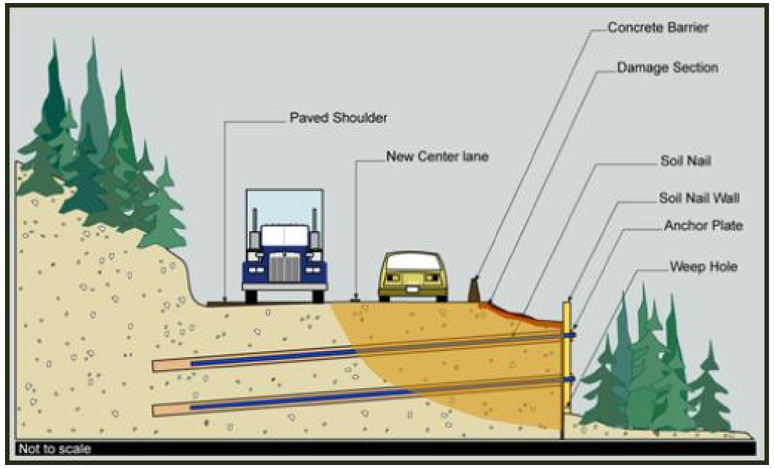
Distributed strain measurement in geotechnical structures

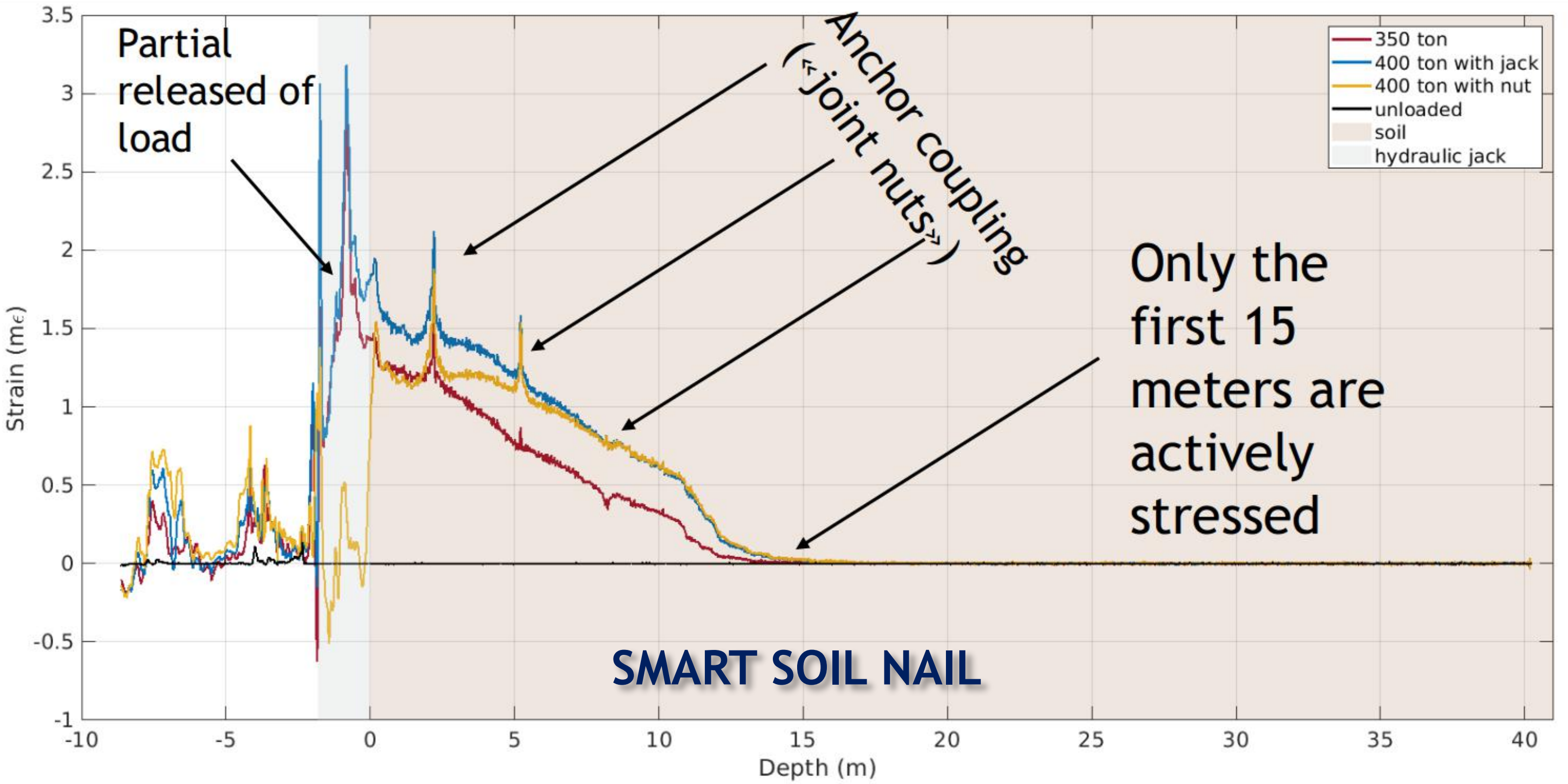




Bersan, S., et al., Distributed strain measurements in a CFA pile using high spatial resolution fibre optic sensors (2018) Engineering Structures, 160, pp. 554-565

Distributed strain measurement in geotechnical structures



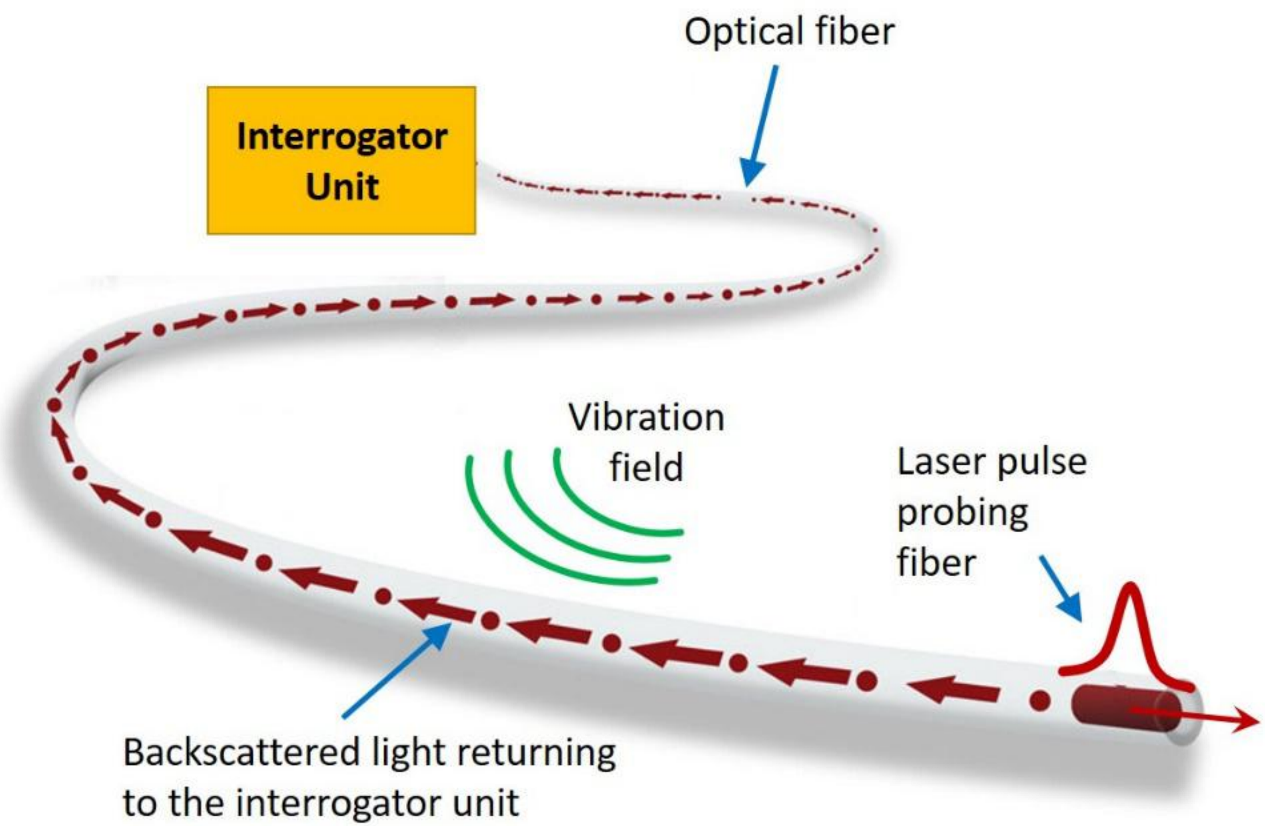


Cola, S., et al., Composite anchors for slope stabilisation: Monitoring of their in-situ behaviour with optical fibre (2019) Geosciences, 9 (5), art. no. 240.

Patent N. 102019000007140 "Sistema Perfezionato per il Monitoraggio di Ancoraggi Geotecnici"

This work was supported by dalla gassa s.r.l

Distributed vibration sensing (Debris Flow)



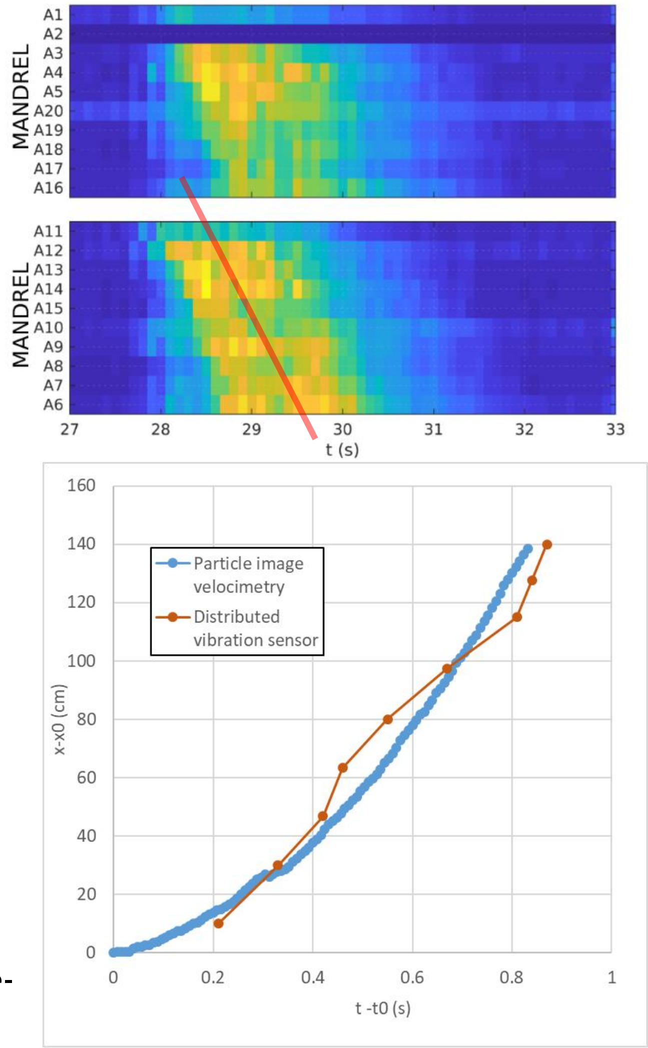
Distance	Tens of km
Spatial resolution	2-10 m
Acoustic bandwidth	limited by the fiber length (p.es. 10 kHz at 10 km)
Sensitivity (ε)	<1 nε (at 1 kHz, 31.6 pε /Hz$^{1/2}$)

Distributed vibration sensing (Debris Flow)

20 pick-up fiber coils, each with 20 sensing points
(about 800 m of fiber and **400 sensing points**) require **1 connector**

Schenato, L., et al., L.: Distributed acoustic sensing of debris flows in a physical model. In: Proc. OFS 2020 (2020).

Mean acoustic energy vs. time and distance



Optical fiber sensors for geo-hydrological applications

"These examples are presented to illustrate the potentially transformative nature of the data that could be obtained using such a system."

Selker, J. S., L. Thévenaz, H. Huwald, A. Mallet, W. Luxemburg, N. van de Giesen, M. Stejskal, J. Zeman,M. Westhoff, and M. B. Parlange (2006), Distributed fiber-optic temperature sensing for hydrologic systems, *Water Resour. Res.*, 42.

… but three expertises are mandatory to successfully run a FOS system into real applications and disclose this transformative nature:

«a photonic expert, a system Integrator and an "expert of the application"» [cit. a wise scientist of the FOS community].

GEO-RISK MANAGEMENT GROUP

luca.schenato@cnr.it