Fibradike:

UN SISTEMA A FIBRA OTTICA DISTRIBUITO PER IL MONITORAGGIO DI FILTRAZIONE, EROSIONE INTERNA E ESTERNA DI ARGINI E ALVEI FLUVIALI

Alessio Höttges
Prof. Carlo Rabaiotti

IBU, Institut für Bauingenieurwesen,
OST, Rapperswil, Switzerland

Dr. Massimo Facchini

Iridis Solutions GmbH
Zürich, Switzerland

28 June 2022

Fibradike:

A DISTRIBUTED FIBER OPTIC SYSTEM FOR MONITORING FILTRATION, INTERNAL AND EXTERNAL EROSION OF RIVERBANKS AND RIVERBEDS

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Agenda - FIBRADIKE

1. Project stakeholders
2. Project motivation, applications
3. Technical Requirements
4. Distributed Fiber Optic Systems (DFOS)
5. Evaluation of different sensor designs
6. Technical solution, patent
7. Final sensor
8. Field verification : Borretto, Wallis
9. Upcoming activities

Project stakeholders

Funding

- FOEN Swiss Federal Office for the Environment
- Cantonal Service for Flood protection of the 3rd Rhone (VS)

Partners

VAW from ETHZ	Laboratory of Hydraulics. Hydrology and Glaciology at the ETH Zürich
AIPo	Interregional Agency of the Po river
SOLIFOS AG	Cable production company
IWK at OST	Institute for Materials Technology and Plastics Processing
IRIDIS Solutions	Fiber Optic Specialist
SISGEO	Geotechnical Monitoring Instrumentation Manufacturer Company

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Umwelt BAFU
Office fédéral de l'environnement OFEV
Ufficio federale dell'ambiente UFAM
Uffizi federal d'ambient UFAM

CANTON DU VALAIS
KANTON WALLIS

Laboratory of Hydraulics, Hydrology and Glaciology

ETH zürich

AIPo
Agenzia Interregionale per il fiume Po

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FIBER OPTIC SYSTEMS

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Sensing | Fiber Optics | Photonics | IoT

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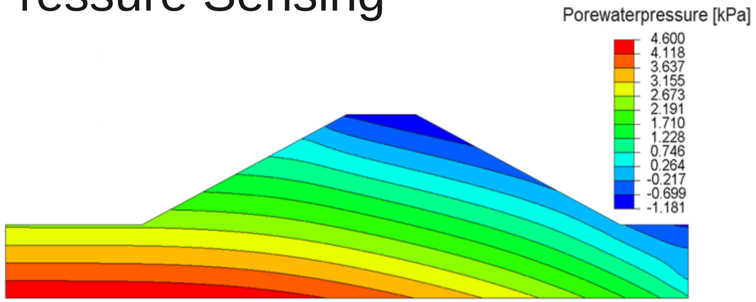
Project goals

- The main objective of the project is to develop a new DFOS monitoring system and methodology for identifying, locating and quantifying in real time
  - ➢ Stability issues of levees
  - ➢ Erosion and scouring of riverbeds and embankments
  - ➢ Interchange between groundwater and river flow

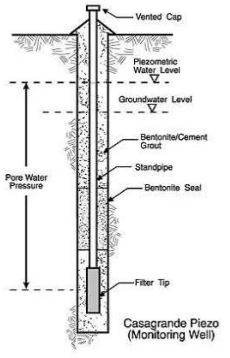

Source: EMSCHER Cooperative/Lippe Association

- The monitoring system and methodology require:
  - ❑ A dedicated, functionalized FO sensing cable for Distributed Pressure Sensing
  - ❑ Definition of ad hoc installation procedures
  - ❑ Choice of appropriate measurement instrumentation
  - ❑ Development of measurement data analysis models



Levee monitoring

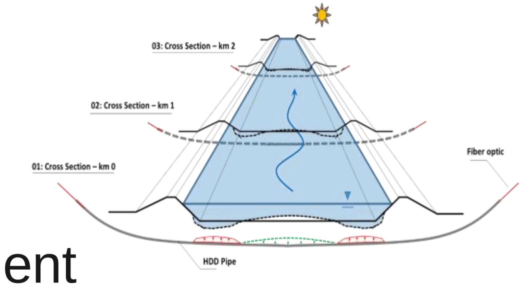
- **Traditional measurement systems**



Standpipe Piezometer

  - Carried out manually
  - Insufficient data for failure prediction
  - Large human resources / time required
  - Hard interpretation
  - Spatially discrete, point measurements

- **Distributed fiber optic sensors as new monitoring system**



  - Automated measurements
  - Direct measurement of physical parameters in the soil
  - Spatially continuous
  - Timely dense data can be fed in AI prediction models

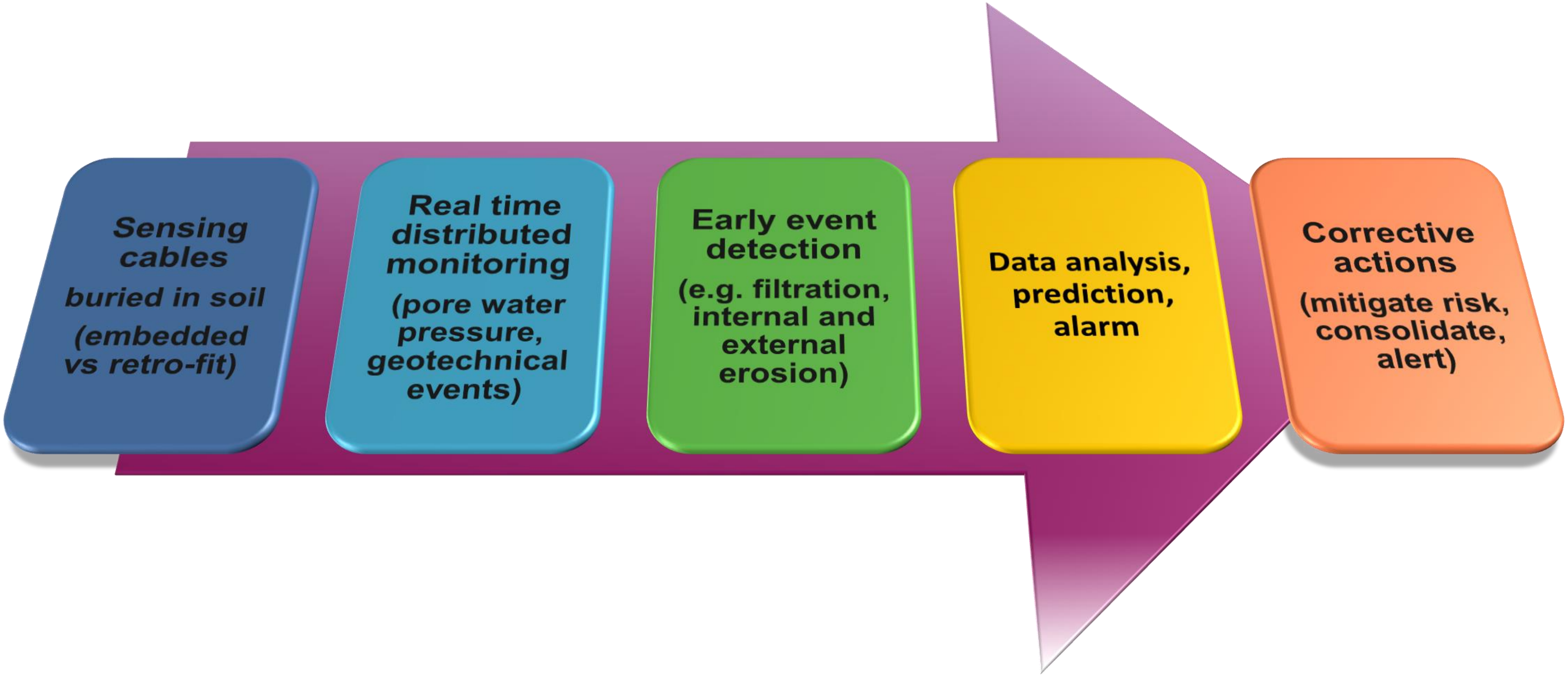
Distributed pore water pressure transducer

- Spatially distributed and reliable fiber-optic sensor for measuring pore water pressure with high resolution and high accuracy.

- The measuring range of the pore water pressure sensor should cover the range of pressures
  - from 0.1 meters of water column or 1 kPa
  - to 100 meters of water column or 1 MPa

- The developed sensor could replace standard piezometers

Implementation of fiber optics sensing to levees monitoring



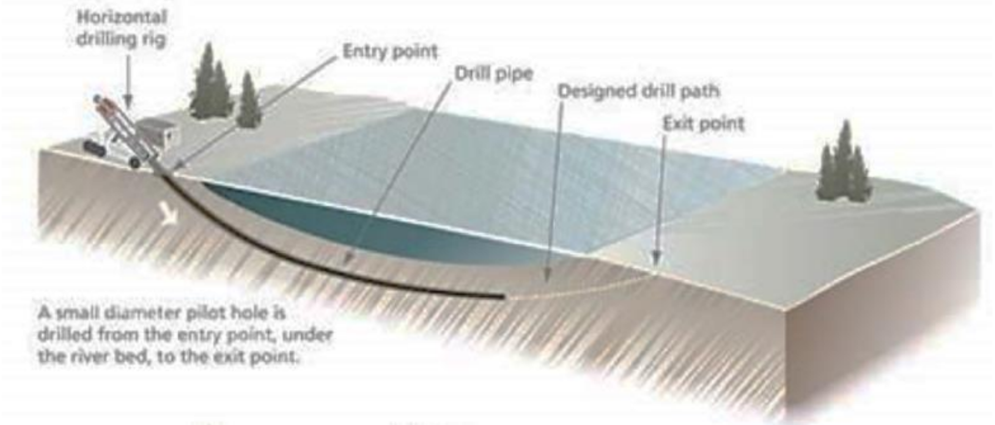
Installation procedure, multiparameter sensitivity

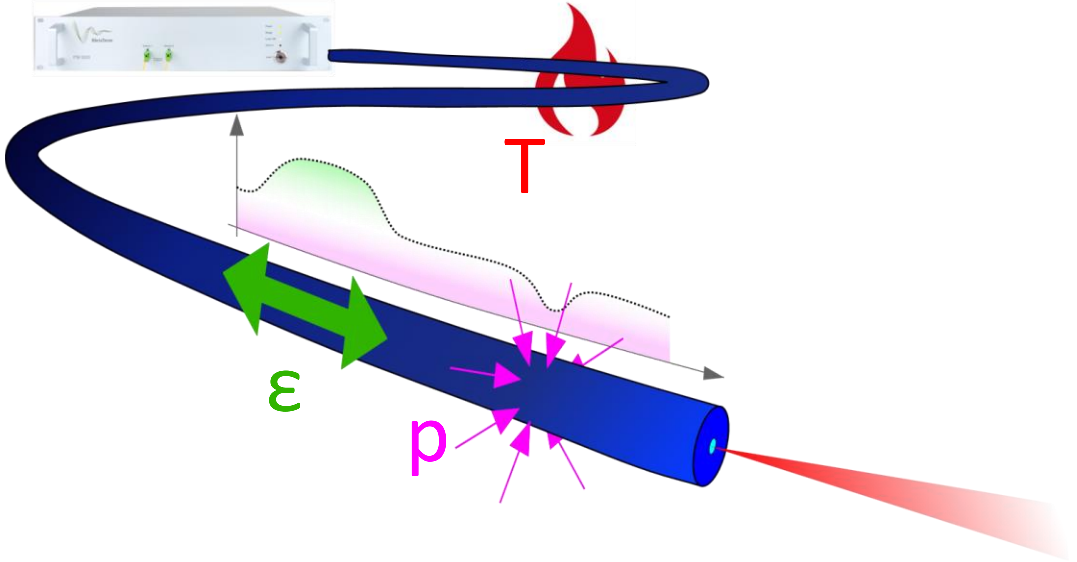
1. Compatibility with <u>field installation</u>
   - ✓ directional drilling

2. Suitable for continuously monitoring <u>long lengths</u> (x 10 km)

3. Compatibility with existing DFOS measurement techniques:
   - ✓ Rayleigh
   - ✓ Brillouin

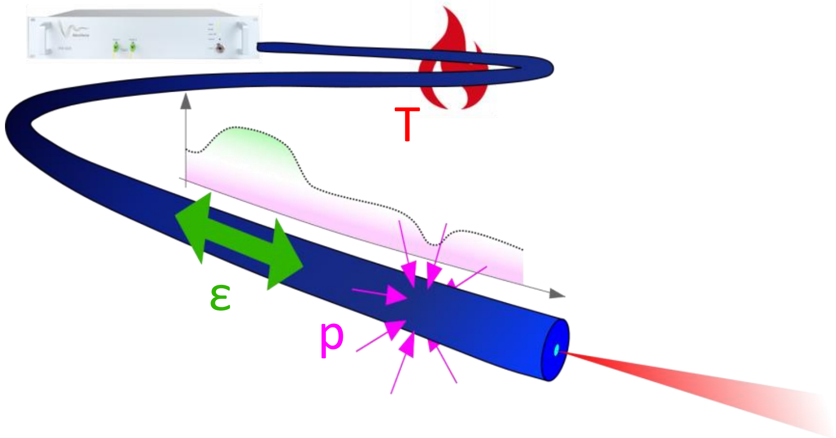
4. Multi-parameter sensitivity:
   - ✓ pore water pressure
     - ✓ total pressure
       - ✓ soil deformation
         - ✓ temperature
           - ✓ (*humidity*)





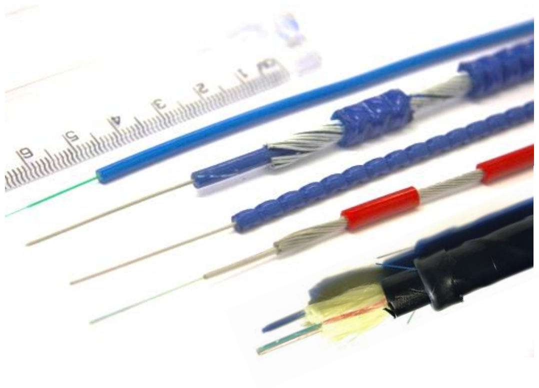
What is DFOS technology?

- By interrogating the natural backscattering of light within the optical fiber, strain and temperature can be derived
- The optical fiber itself acts as a measurement sensor → “distributed”



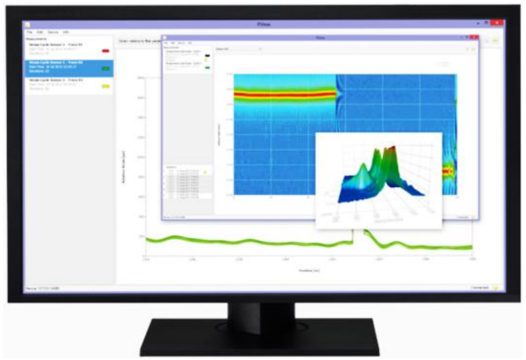
Components of the sensing system

❑ **Sensors (FOS)**



❑ **FO Interrogator**

❑ **Measurements & data analysis**

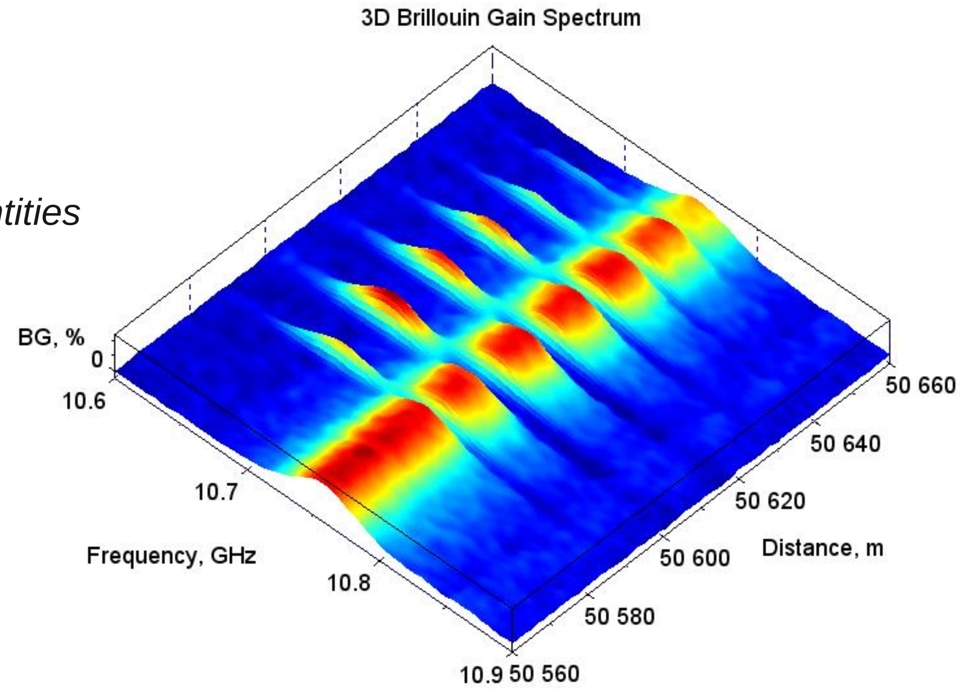


How does DFOS work?

- The evolution of the frequency shift continuously measured at each position along the sensor depends linearly on **strain** and **temperature**:

$$\Delta \nu_i = \underbrace{\boldsymbol{\nu_{t_1}} - \boldsymbol{\nu_{t_0}}}_{\text{Optical measurement}} = C_\varepsilon \cdot \boldsymbol{\Delta\varepsilon} + C_T \cdot \boldsymbol{\Delta T}$$

Optical measurement *Monitored physical quantities*



$\Delta\nu$: Frequency shift	$[Hz]$
$\mu\varepsilon$: Micro Strain	$[10^{-6}]$
C_ε: Mechanical strain coefficient of the sensor	$\left[\frac{Hz}{\mu\varepsilon}\right]$
C_T: Temperature coefficient of the cable	$\left[\frac{Hz}{\mu\varepsilon}\right]$

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$\mu\varepsilon$: Micro Strain $[10^{-6}]$

C_ε: Mechanical strain coefficient of the sensor $\left[\frac{Hz}{\mu\varepsilon}\right]$

C_T: Temperature coefficient of the cable $\left[\frac{Hz}{\mu\varepsilon}\right]$

DFO Sensing technology	Strain Coefficient*	Temperature Coefficient*
Rayleigh OFDR	-0.1499 MHz/με	-1.5674 MHz/°C
Brillouin BOTDA/BOFDA	0.0507 MHz/με	1.0018 MHz/°C

* for bare standard single mode optical fiber

Advantages and characteristics of DFOS systems

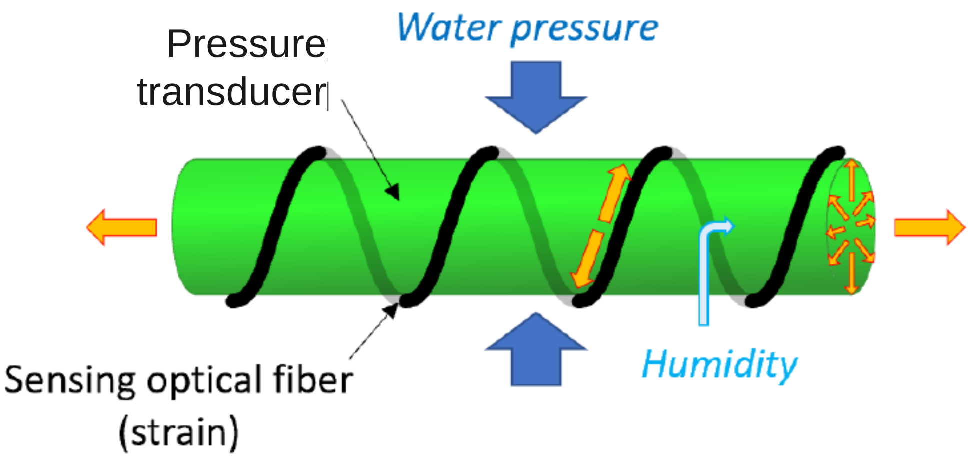
- High spatial resolution and range of several kilometers
- High sensitivity to mechanical strain and temperature
- Sensors resilient to harsh environment (no corrosion in water, ruggedizes designs available)

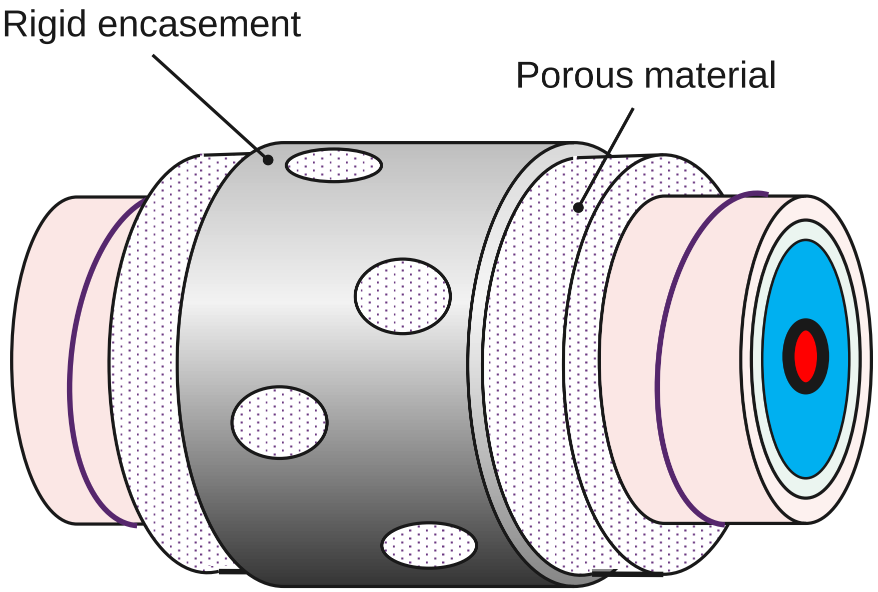
DFO Sensing technology	Spatial Resolution	Range	Acquisition	Strain Accuracy
Rayleigh OFDR	± 0.1 mm	70 m (< 2 km)	5-10 s (250Hz up to 50m)	± 1 με
Brillouin BOTDA/BOFDA	0.2 m to 10 m	> 50 km	1-15 min	2 με

From standard fiber optic cable to engineered DPS sensor

- **Measurement principle:**

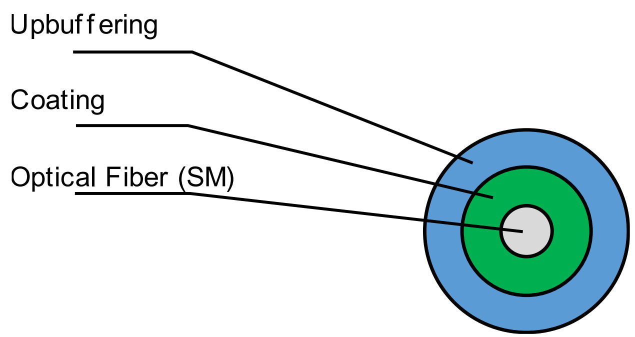
Hydrostatic pressure induces strain along the sensing fiber, which is detected by DFOS



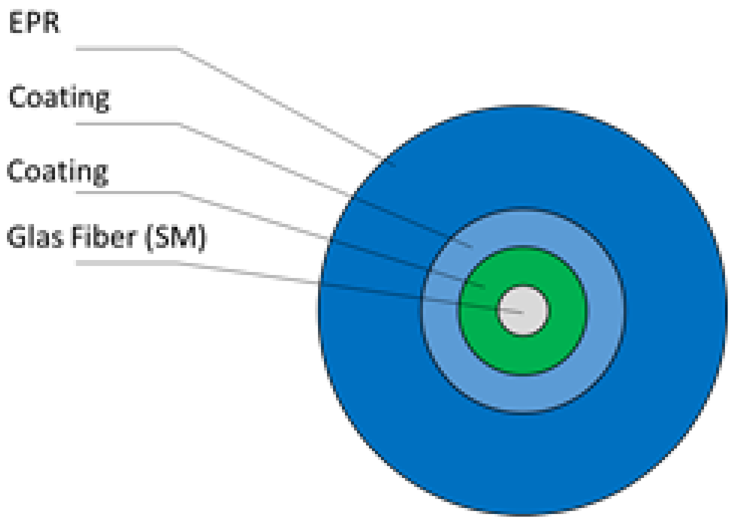


Evaluation of FOS with radial simmetry

- Tight buffered Single Mode Fiber
  - Outer diameter: 0.9 mm
  - Tensile strength: ~15 N/%



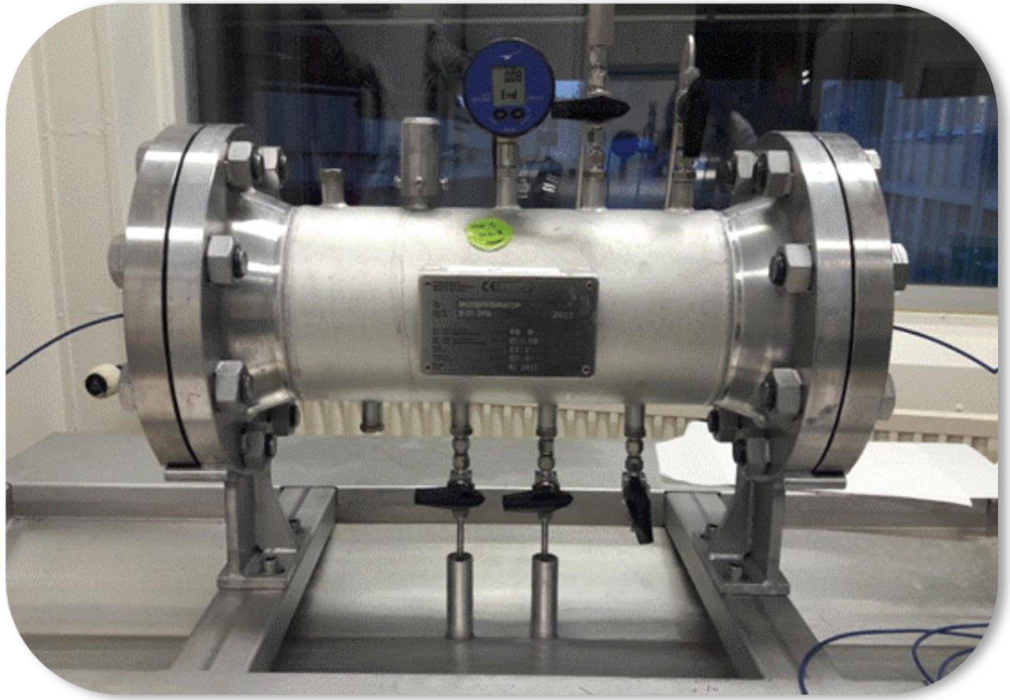
- Non metallic Distributed Strain Sensing cable
  - Outer diameter: 2.8 mm
  - Tensile strength: 26 N/%



Hydrostatic pressure sensitivity test

Hydrostatic pressure chambers

- 1 – 50 bar (~500 m water column)

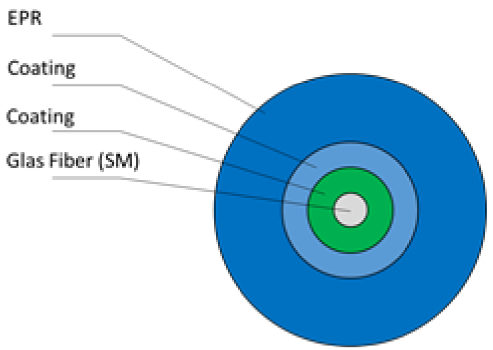


- 50 – 200 bar (~2000 m water column)

Hydrostatic pressure sensitivity test

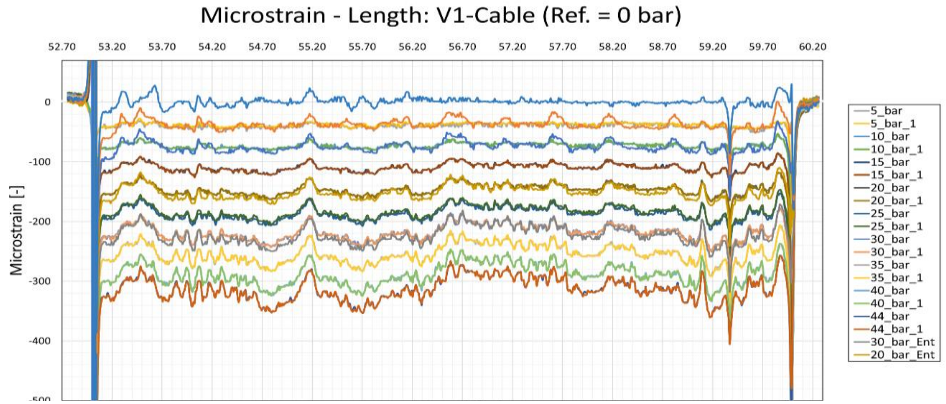
Spatially distributed strain Measurements performed with Luna OBR

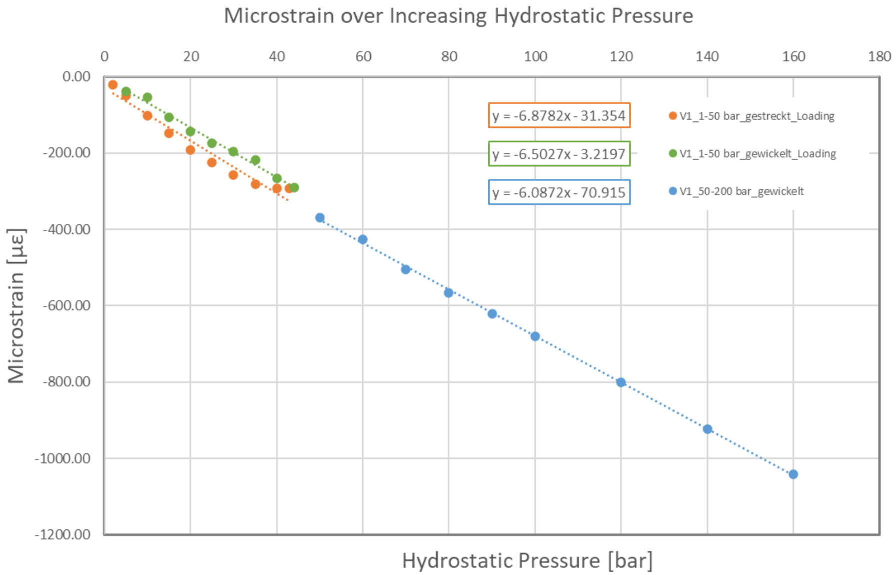
- Cable type:
  - **Non metallic DSS cable** OD:2.8 mm



DSS-V1 straight	DSS-V1 with geom. overlength	DSS-V1 with geom. overlength
1 – 50 bar	1 – 50 bar	50 - 160 bar
-6.88 µε/bar	-6.50 µε/bar	-6.09 µε/bar

- Pressure-strain coefficient:
  - Cp = ~ -6 µε / 10 m (water column)
- Hydrostatic pressure measurement accuracy:
  - 3 m (water column)





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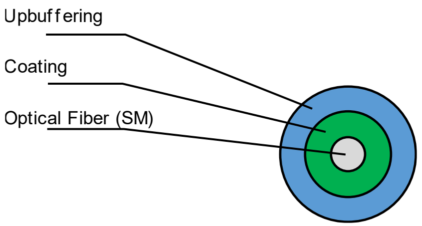
Hydrostatic pressure sensitivity test

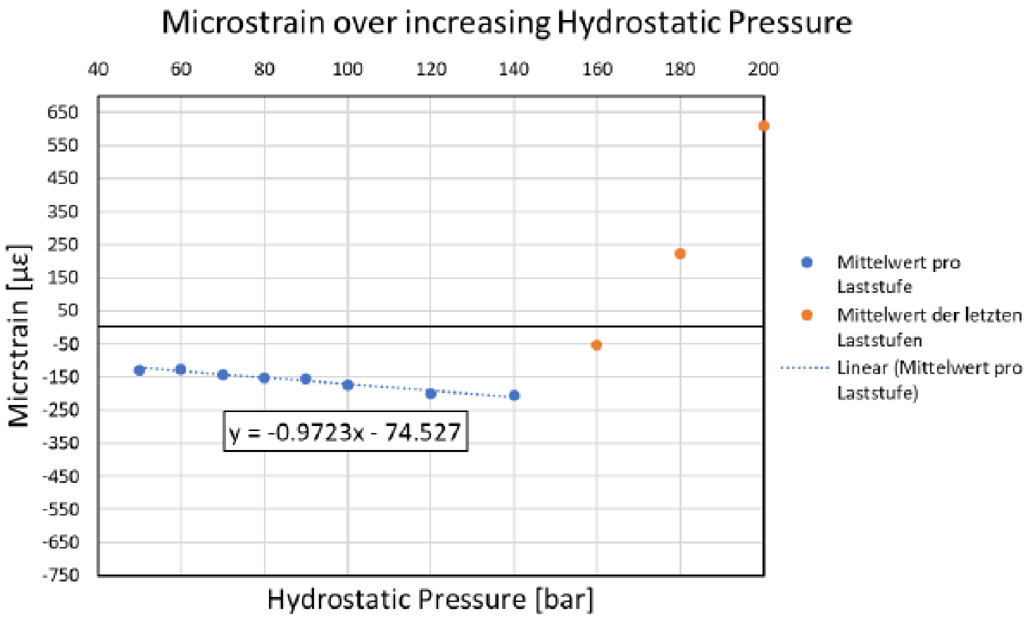
Spatially distributed strain Measurements performed with Luna OBR

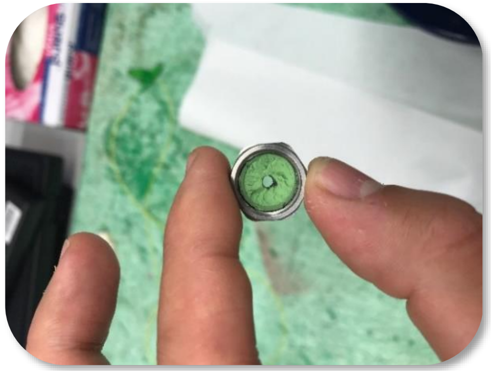
- Cable type:
  - **Tight buffered optical fiber**
    OD: 0.9 mm

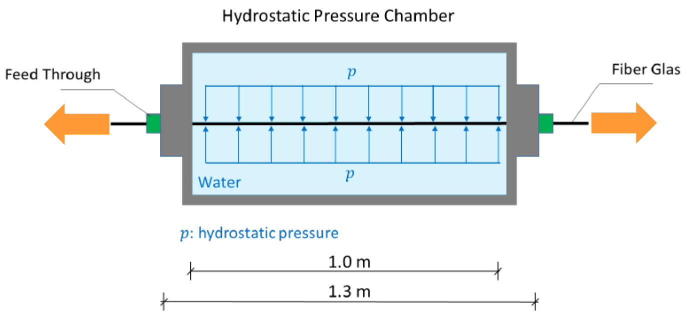


Tight-buffer with geom. overlength	Tight-buffer straight
50 - 140 bar	150 – 200 bar
-0.97 με/bar	slippage

- Pressure-strain coefficient:
  - Cp = ~ -0.97 με / 10 m (water column)
- Hydrostatic pressure measurement accuracy:
  - ~20 m (water column)

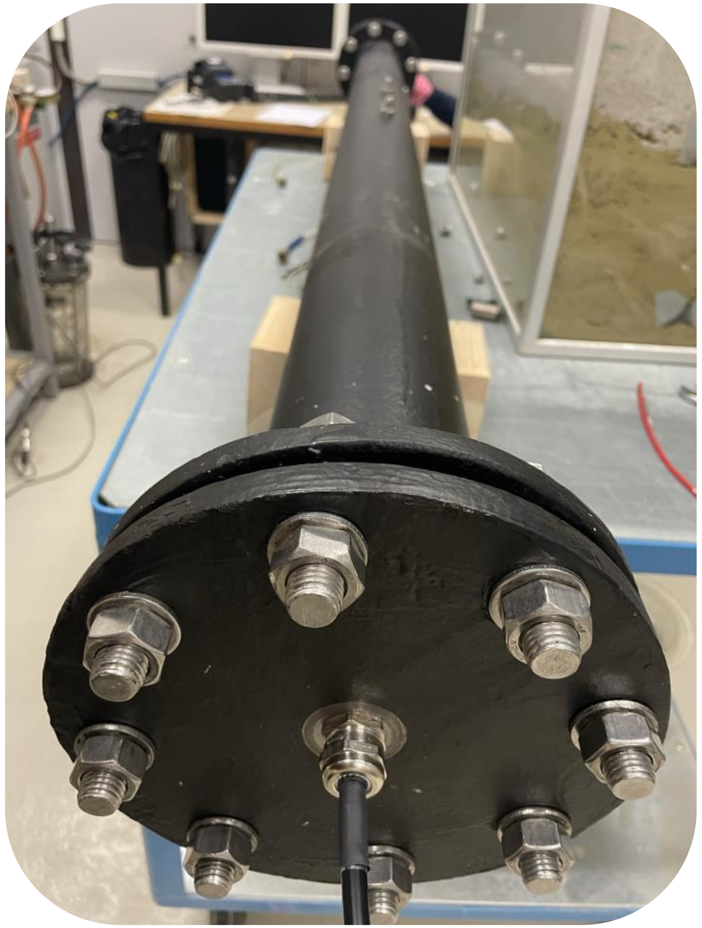






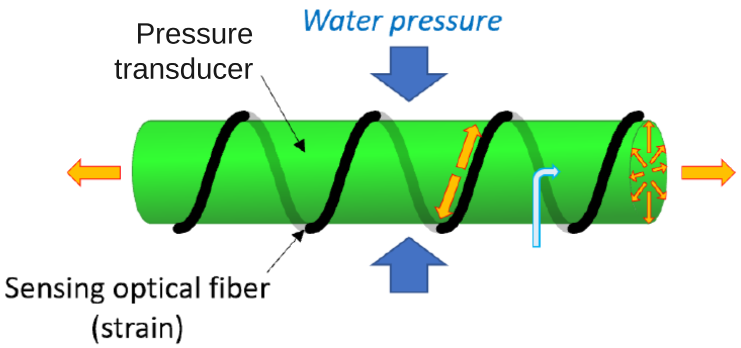
Hydrostatic pressure tests in laboratory - Instrumentation

- **Test setup**
- Measuring system:
  - Rayleigh → OBR 4600
  - Brillouin → BOTDA Omnisens
- Type of test
  - Pressure chamber 2 m length
  - Pressure controlled with GDS
  - Pressure range: 20 – 200 kPa (20 kPa Steps)



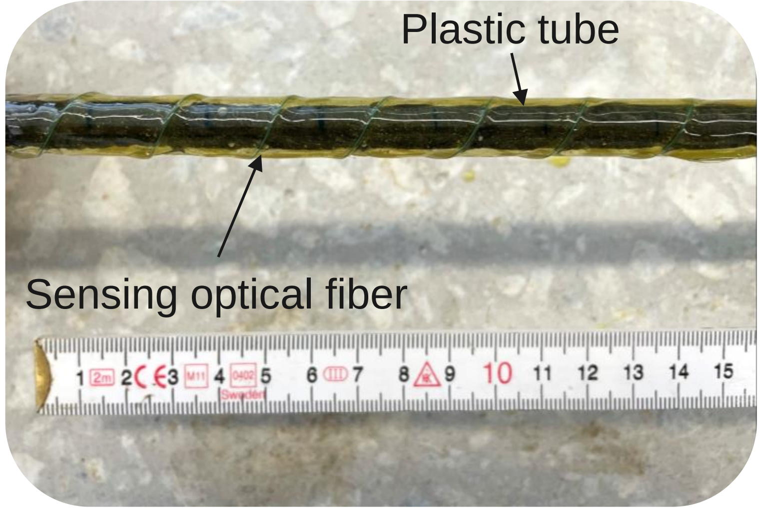
Evaluation of DPS prototypes with helically stranded fiber(s)

- **Concept**



- Hand-made **prototypes**:

- **Different designs** in terms of:
  - Tube material: Soft Polyurethan (PU)
  - Helix pitch: 2 - 5.5 cm
  - ø Tube: 6, 8, 10, 12 mm
  - Fiber type: Upbuffered SMF, bend-optimized
  - Outer sheath: Silicon, Shrinking tube

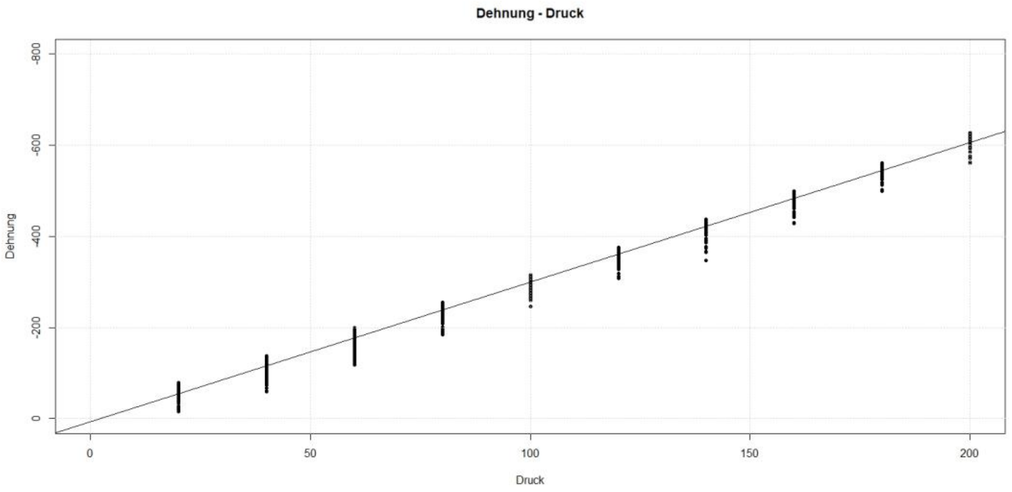


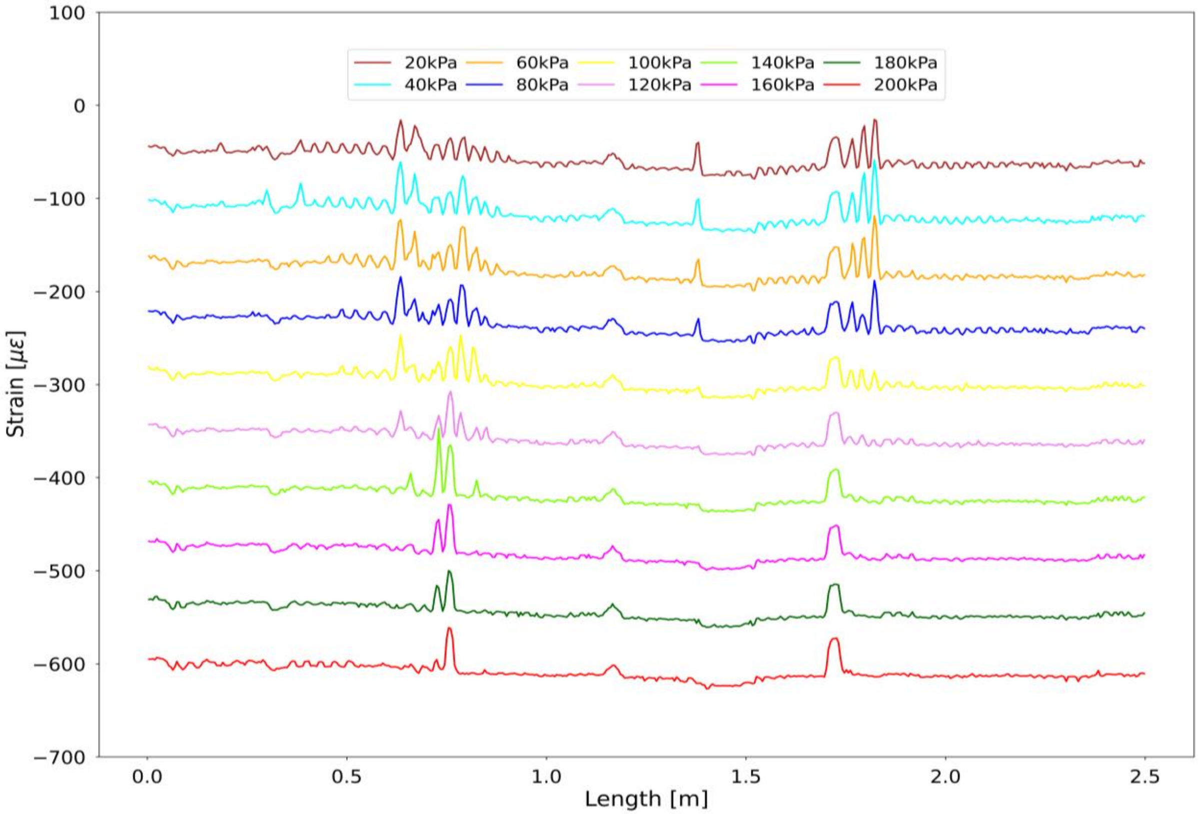
Evaluation of DPS prototypes with helically stranded fiber(s)

- **Results V 03 – OBR (Rayleigh)**
  - Spatial resolution : 1 mm
  - Strain – Pressure: με= −3.06*σ-6.93, $R2= 0.884$
  - Cp = **3.06** $\frac{\mu\varepsilon}{kPa}$

    → Pressure accuracy ~15 cm (water col.)

Id	Material	$\emptyset\ [mm]$	$t\ [mm]$	$I\ [mm^4]$	$O\ [-]$	$p\ [cm]$	FO
V03	Polyurethan	6.0	1.0	51.0	Tube	2.5	G.657



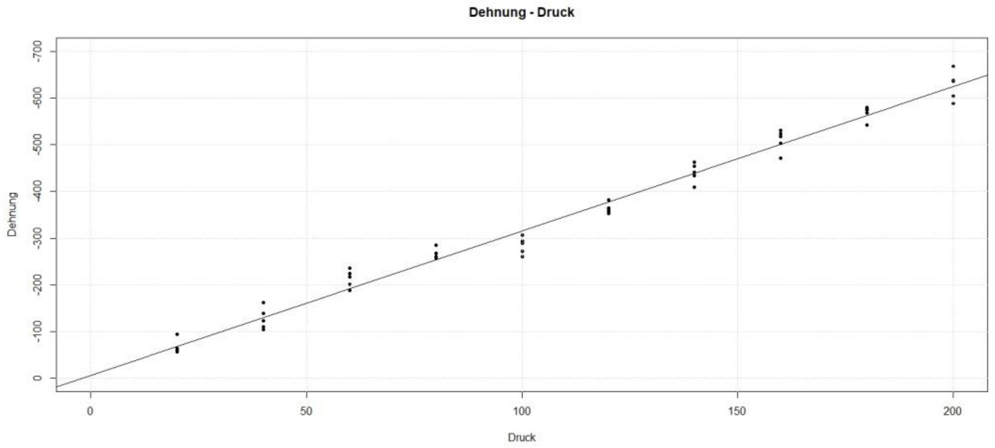


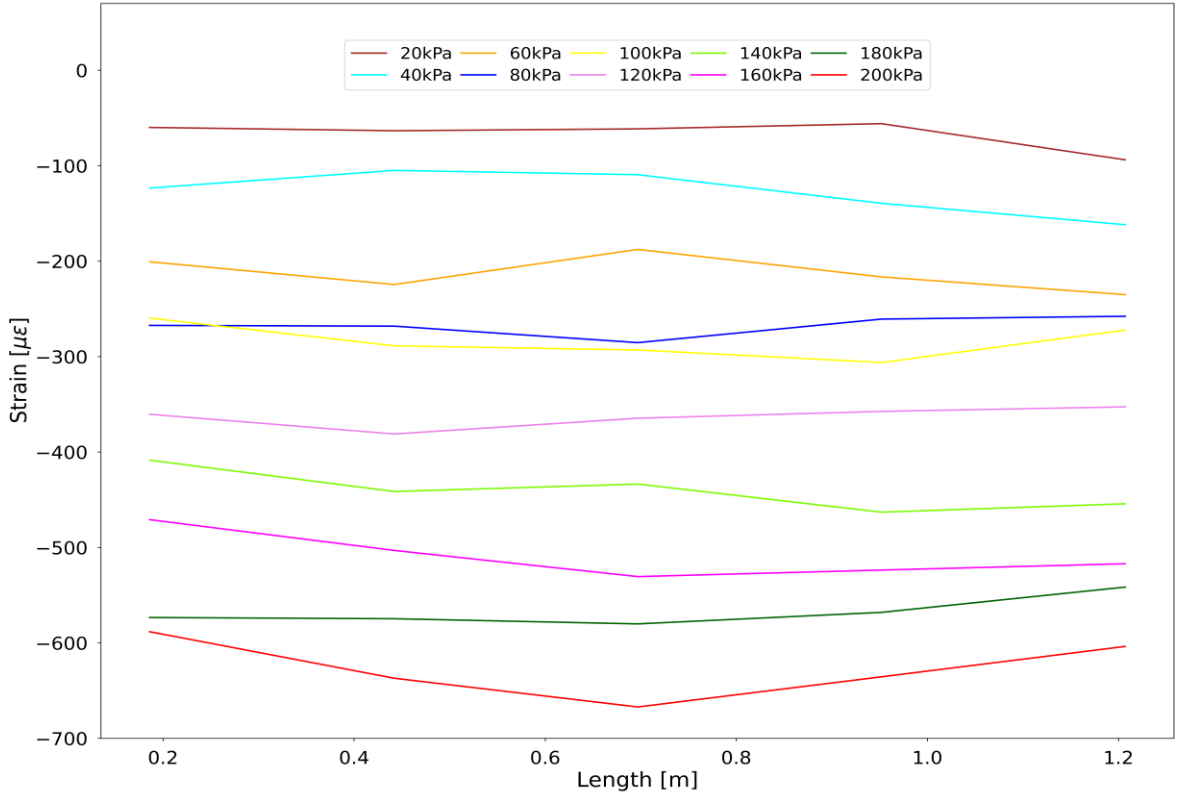
Evaluation of DPS prototypes with helically stranded fiber(s)

- **Results V 03 – BOTDA (Brillouin)**
  - Spatial resolution : 1 meter
  - Strain – Pressure: $\mu\varepsilon = -2.92 * \sigma - 12.28$, R2= 0.953
  - Cp = **2.92** $\mu\varepsilon / kPa$

    → Pressure accuracy ~15 cm (water col.)

Id	Material	$\emptyset$ [mm]	t [mm]	I [mm^4]	O [−]	p [cm]	FO
V03	Polyurethan	6.0	1.0	51.0	Tube	2.5	G.657





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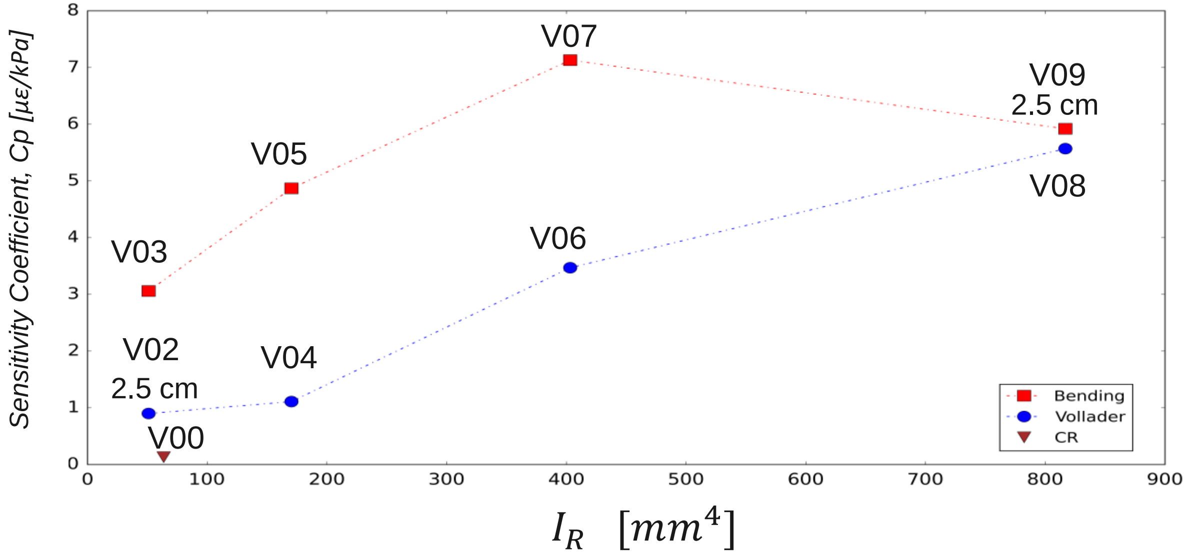
Evaluation of DPS prototypes with helically stranded fiber(s)

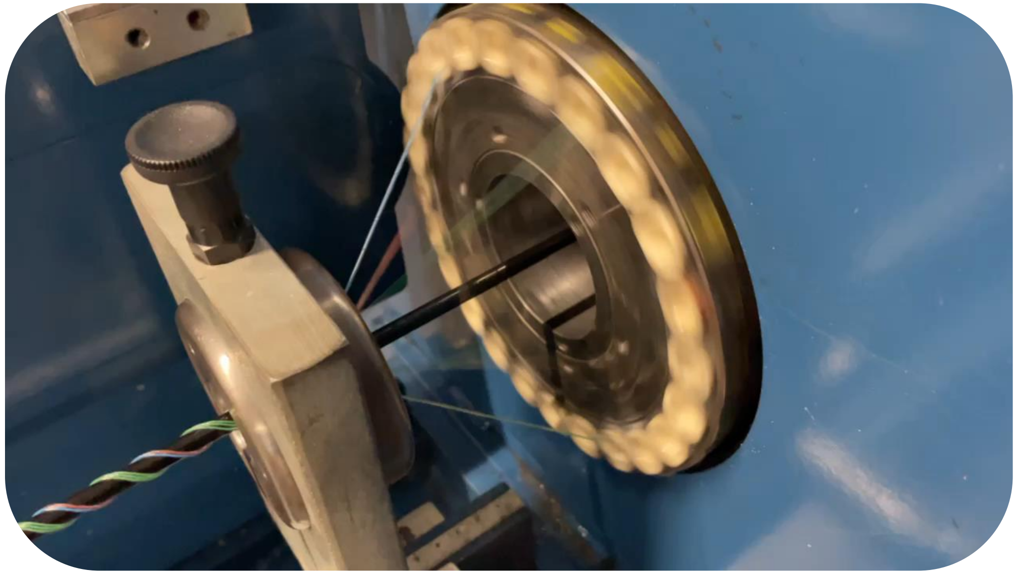
- ↑ Ø Tube/ I_R → ↑ pressure sensitivity
- ↓ Pitch length → ↑ pressure sensitivity
- Bend-optimized FO → ↓ optical attenuation

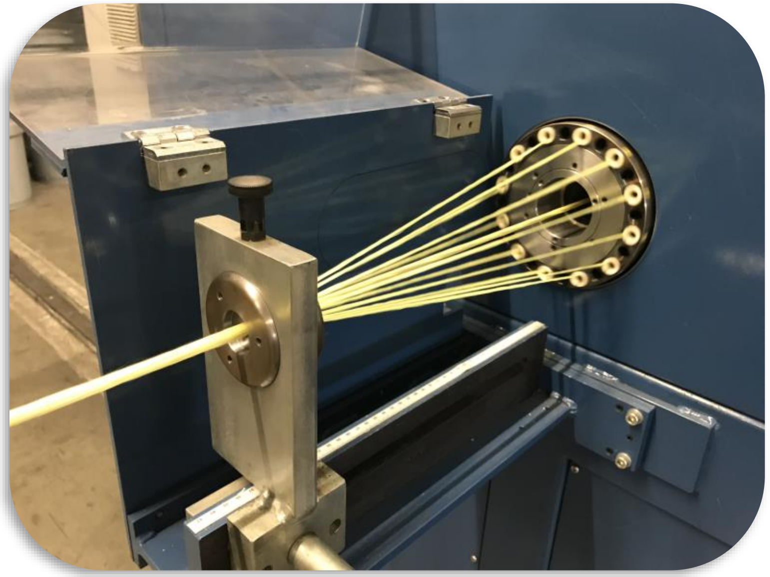


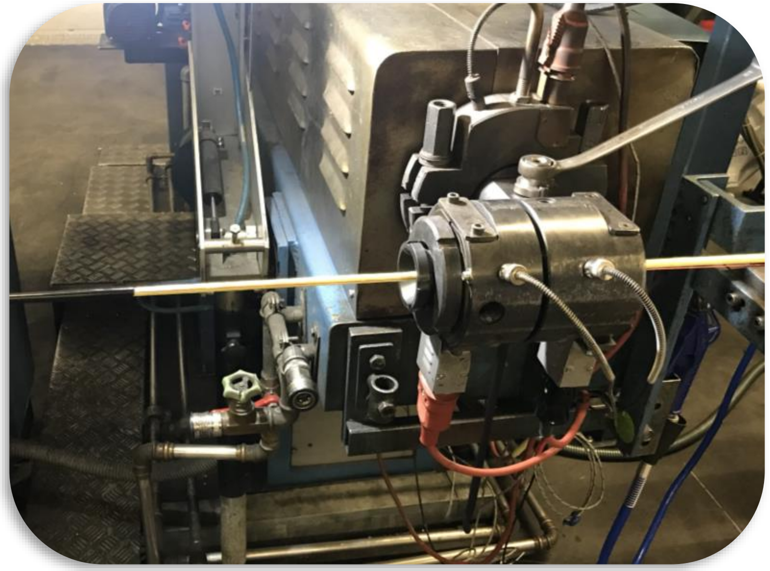
Name	Material	Diameter	Thickness	2° Moment	Outer	Pitch	Fiber
N [−]	M [−]	$\emptyset$ [mm]	t [mm]	I [mm^4]	O [−]	p [cm]	F [−]
V00	Neopren	6.0	6.0	63.6	Silicon	4.5	Vollader
V01	Polyurethan	6.0	1.0	51.0	Silicon	4.5	Vollader
V02	Polyurethan	6.0	1.0	51.0	Tube	2.5	Vollader
V03	Polyurethan	6.0	1.0	51.0	Tube	2.0	Bending
V04	Polyurethan	8.0	1.5	170.4	Tube	5.5	Vollader
V05	Polyurethan	8.0	1.5	170.4	Tube	2.0	Bending
V06	Polyurethan	10.0	1.75	403.3	Tube	5.5	Vollader
V07	Polyurethan	10.0	1.75	403.3	Tube	2.0	Bending
V08	Polyurethan	12.0	2.0	816.8	Tube	5.5	Vollader
V09	Polyurethan	12.0	2.0	816.8	Tube	2.5	Bending

DPS industrial prototypes

- **Industrial production:**
  - Central element:
    Empty tube, soft filled element
  - Central element material:
    Soft/Hard PU, aramid filling
  - Stranding pitch length:
    2.5 - 6.0 cm
  - Sensor outer diameter:
    OD = 9 mm
  - Fiber type:
    Bend-optimized
    Tight-buffer

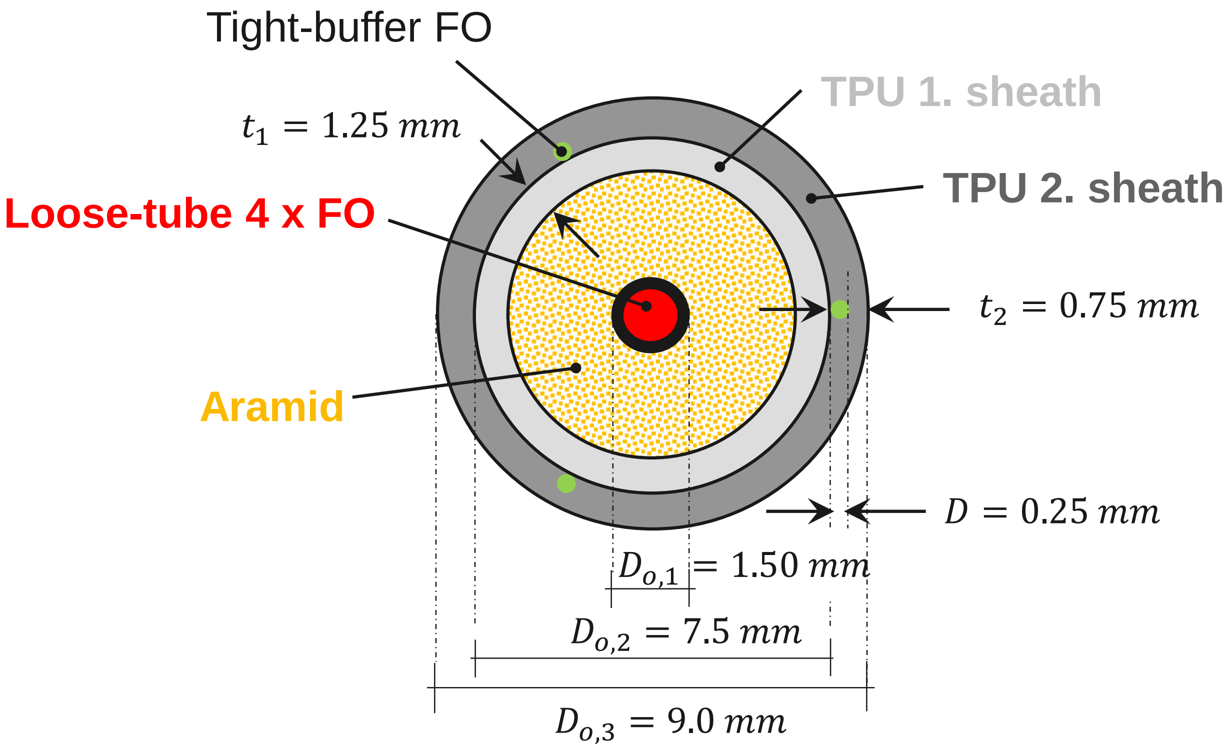


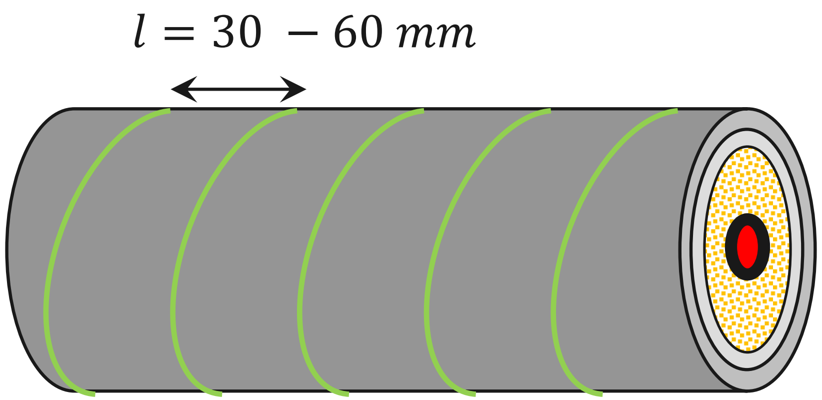




Design

- Center element:
  - Temperature compensation fibers
  - Longitudinal force bearing element
- Suitable stranding pitch:
  - sensitivity VS optical attenuation
- Bend-optimized fibers
  - SMF
- Multilayer sheathing for suitable sensitivity and mechanical protection





Product

- Center element:
  - Temperature compensation fibers (2 MMF + 2 SMF)
  - Longitudinal force bearing element
- Suitable stranding pitch:
  - sensitivity VS optical attenuation
- Bend-optimized fibers
  - SMF 125 or 80 µm
- Multilayer sheathing for suitable sensitivity and mechanical protection
- Sensor outer diameter: 9 mm

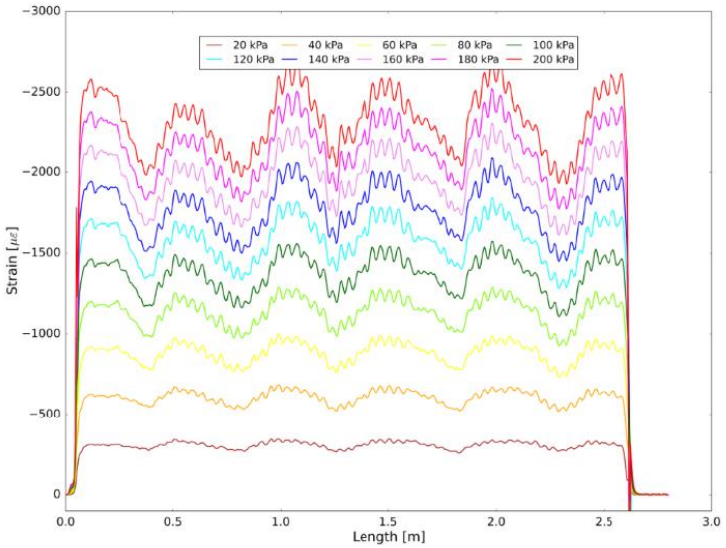
Evaluation of pressure sensitivity of DPS industrial sensor

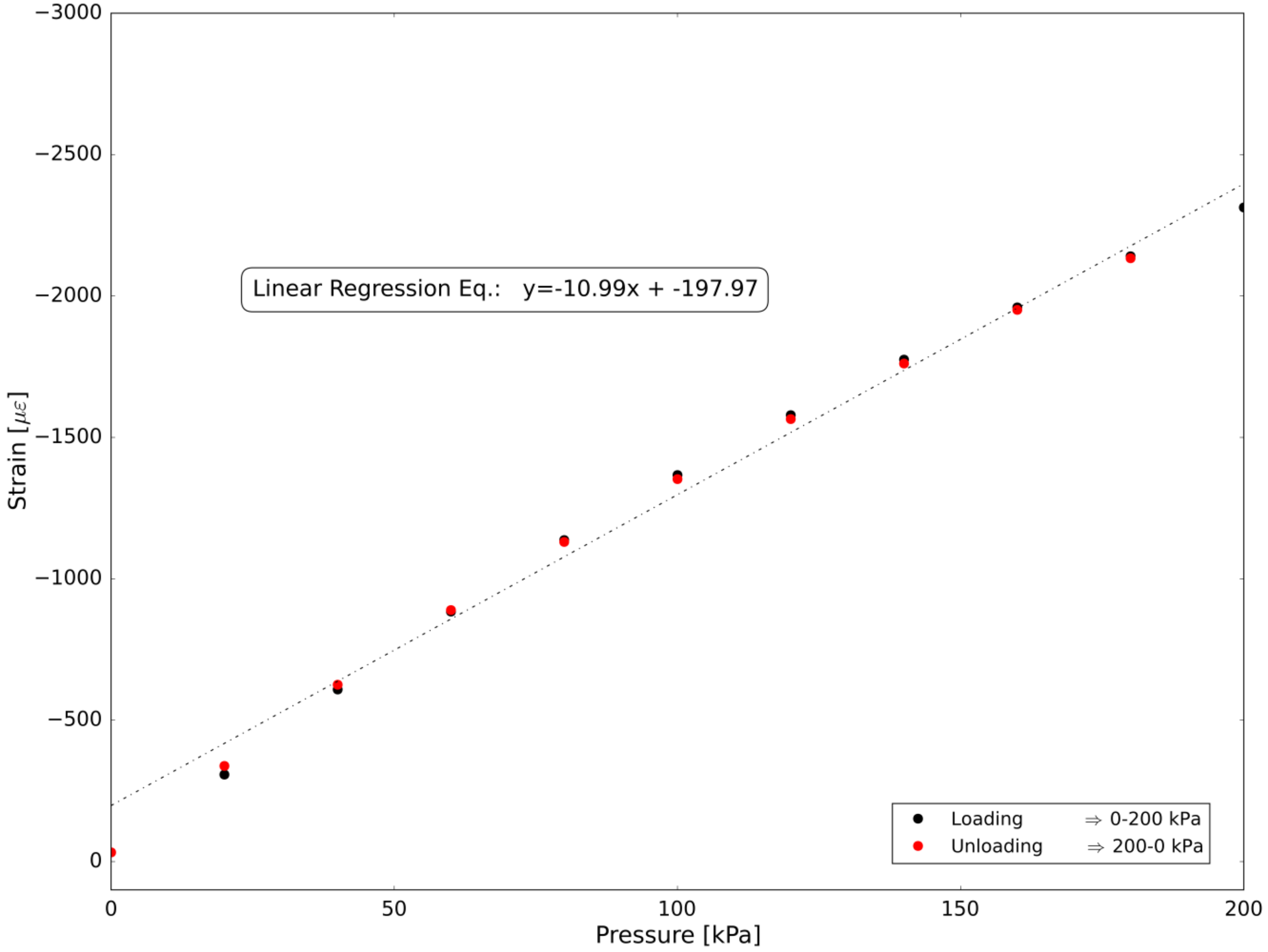
- Pressure-strain coefficient

  Cp = $-10.99 \left[\frac{\mu\varepsilon}{kPa}\right]$

- Equivalent to DPS sensitivity of

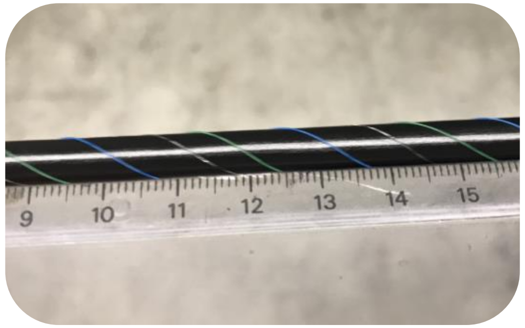
  ~2 cm of water column

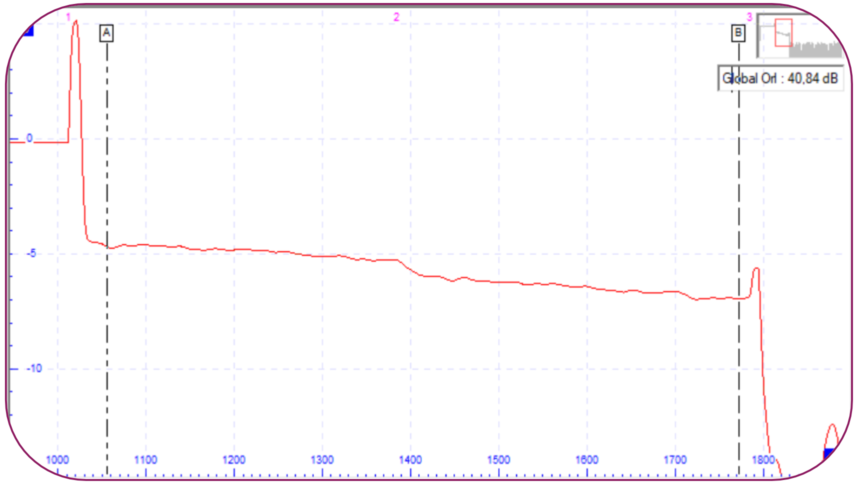


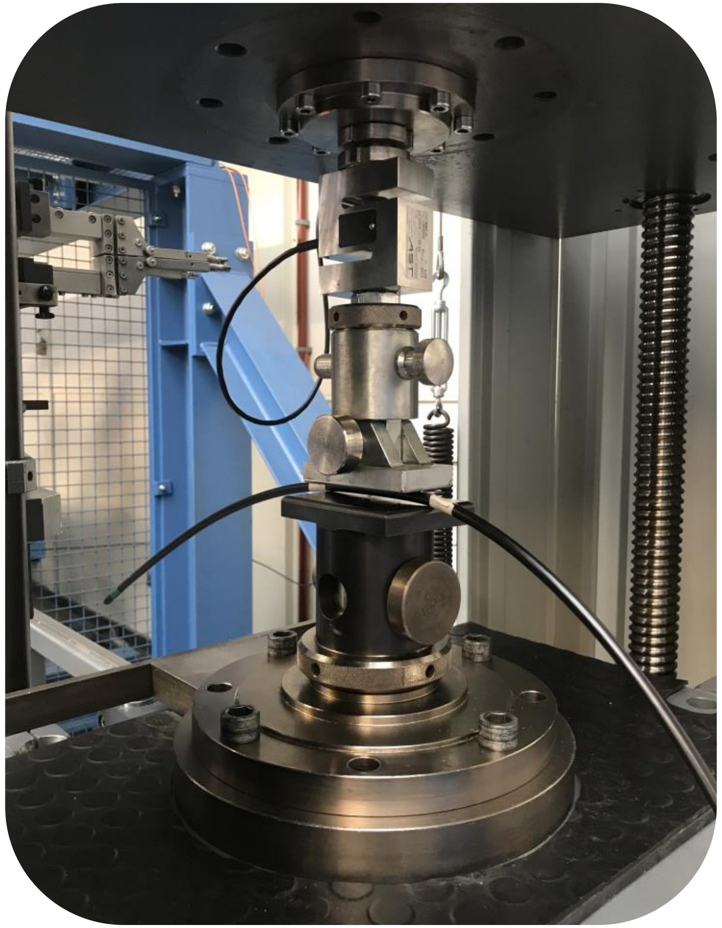


Design check, optical and mechanical tests

- Crush resistance for optimal sheathing definition
- In-line stranding pitch length
- Optical attenuation

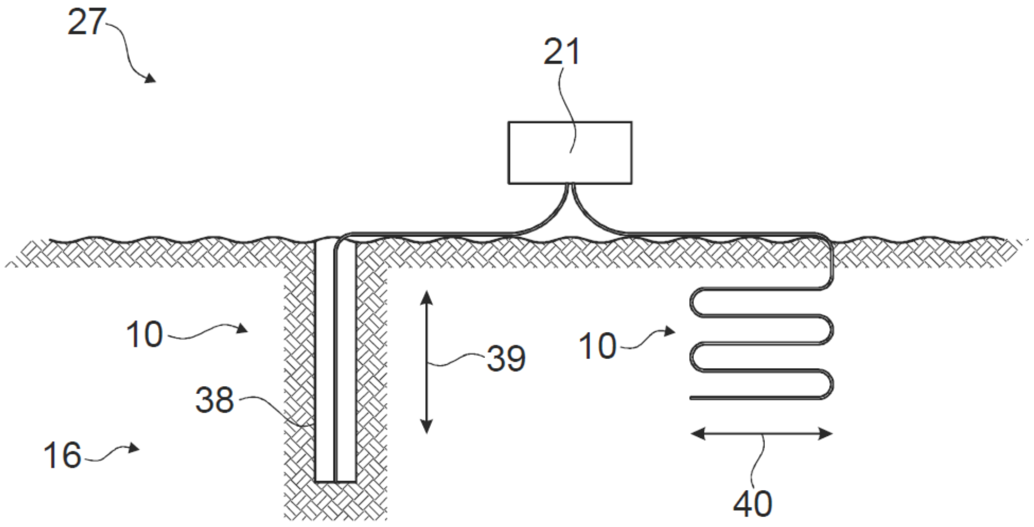


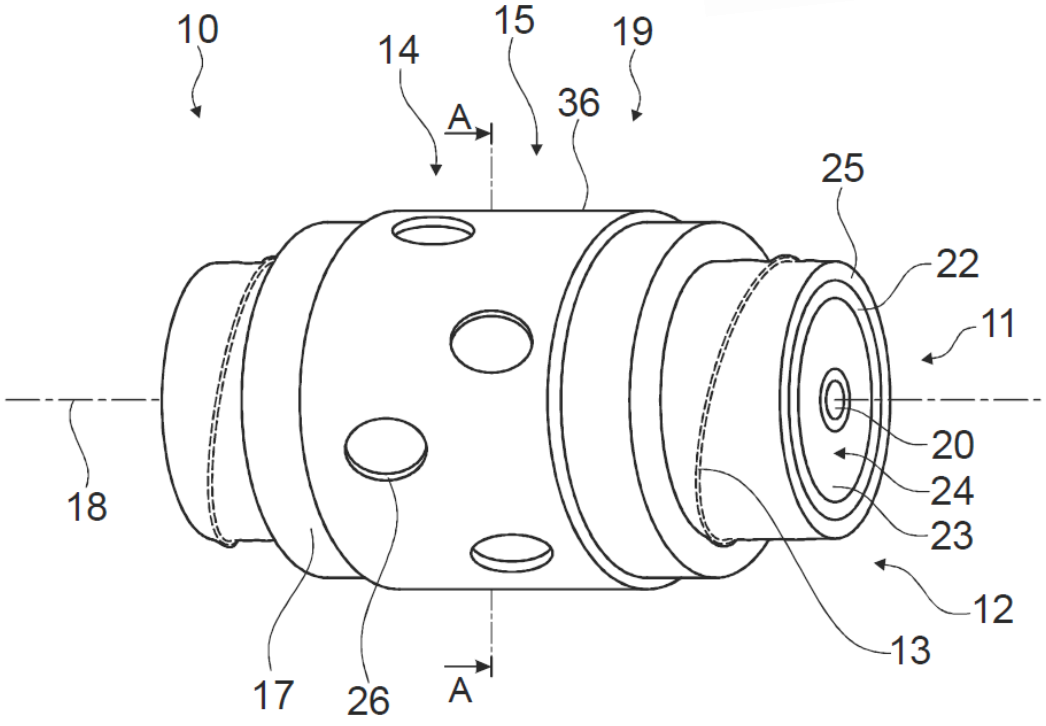




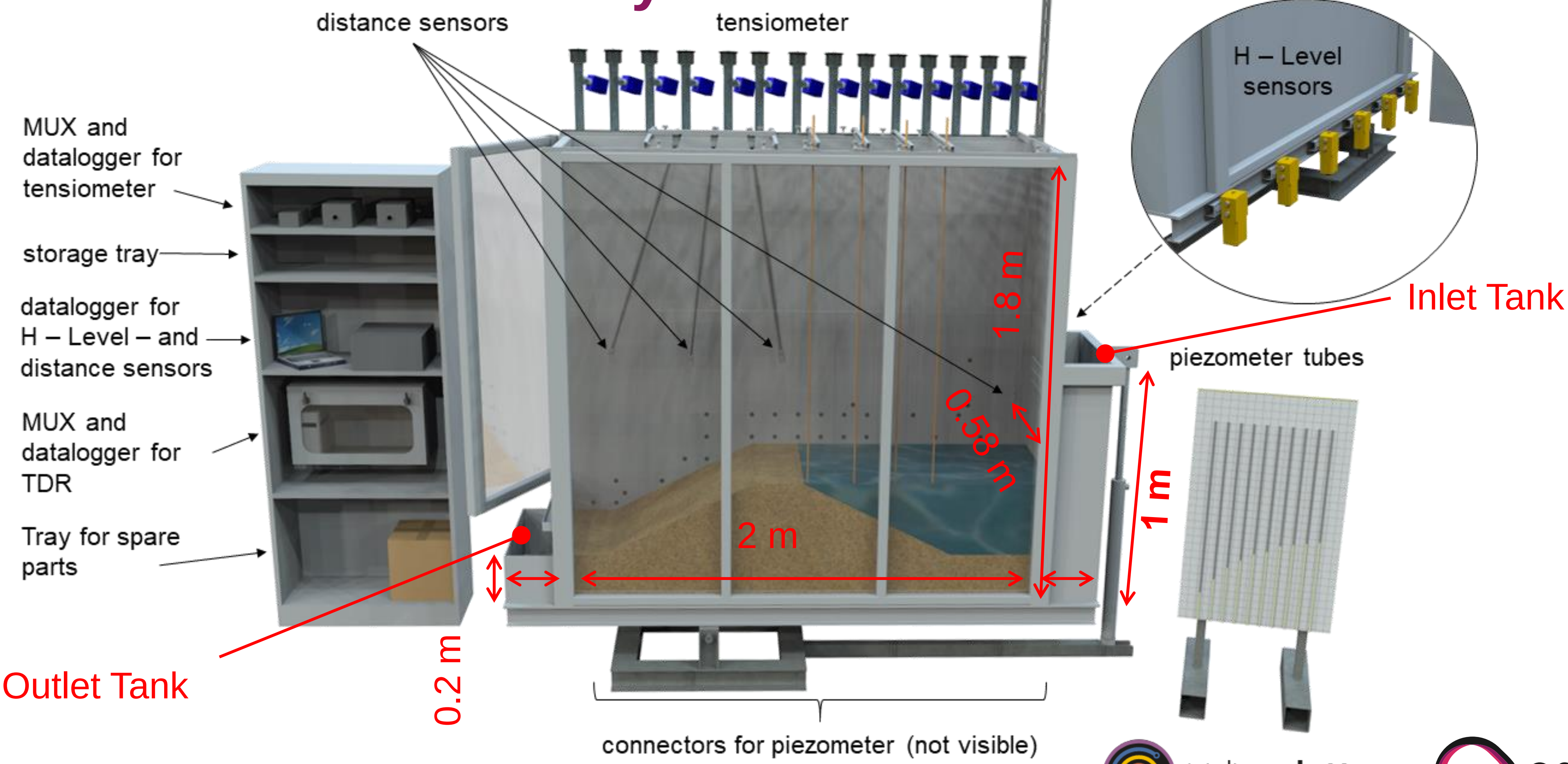
Patent application

- “Sensor system for measuring fluid pressure and method of manufacturing a sensor system”





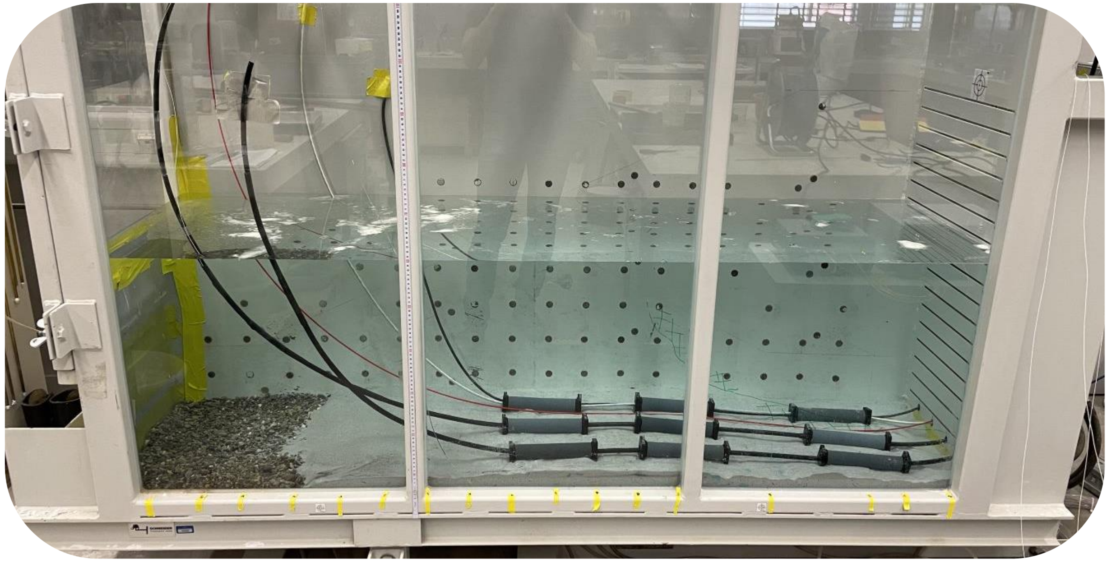
Calibration in laboratory scale - Sandbox

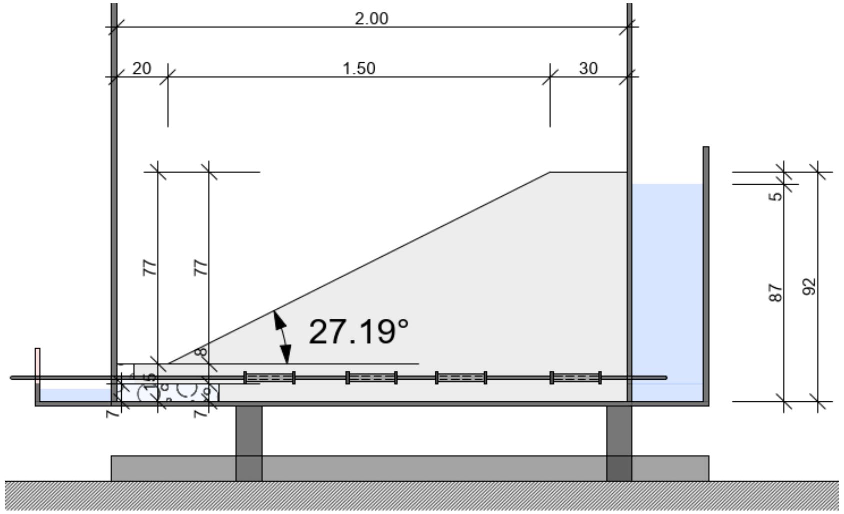


iridissolutions OST

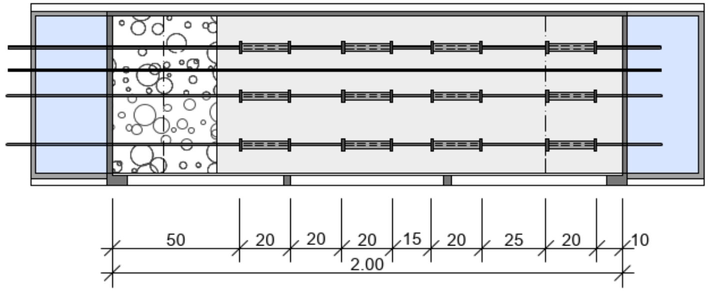
Sandbox test of prototypes with mounted piezometer filter

- With water (no sand)
  - Load steps: 1 – 6 kPa
- Topped with sand
  - Friction angle φ 44.2 Grad
  - Cohesion factor c = 3.09 kPa





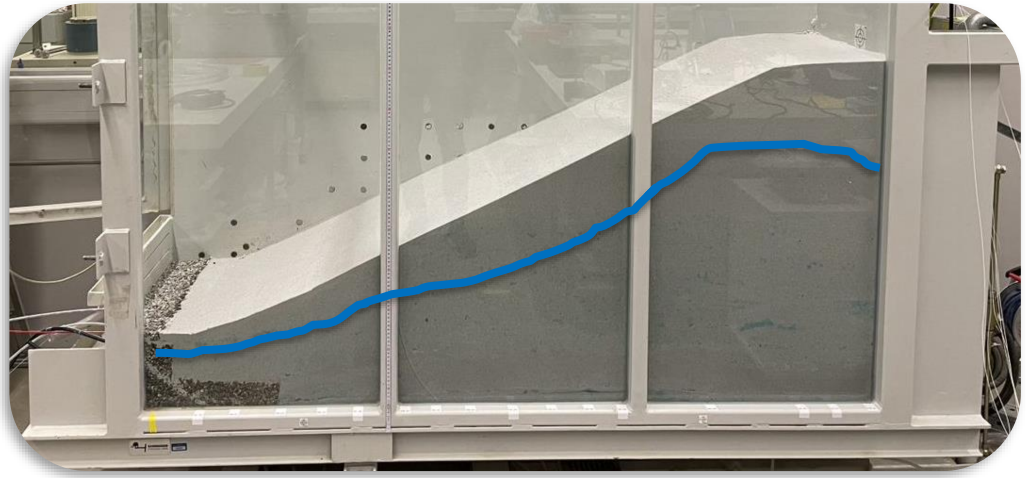
Schnitt_Damm 2

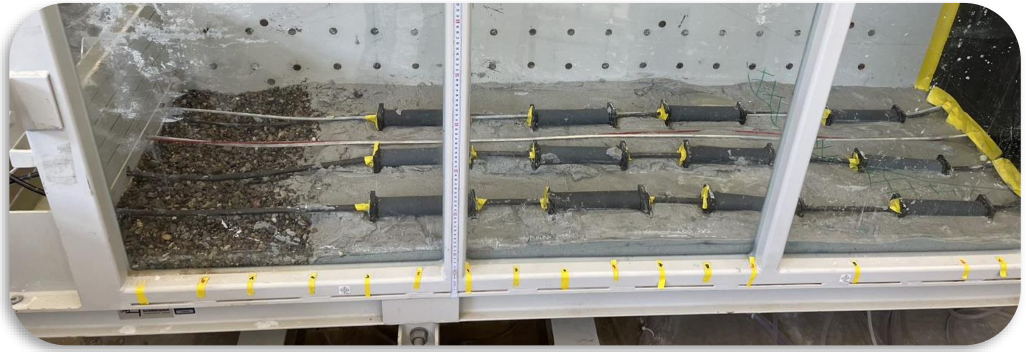


Grundriss_Damm 2

Sandbox test of prototypes with mounted piezometer filters

- Prototypes:
  - *V07.01_10mm*
  - *V07.01_10mm*
  - *V09.01_6mm industrial*
  - *V10.01_6mm handmade*
  - *Temperature sensor*
  - *V09.01_6mm industrial production*

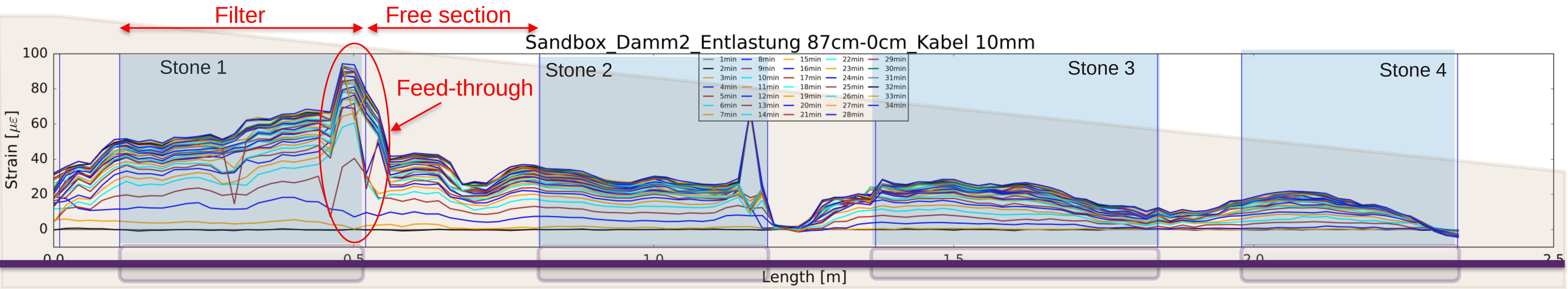




Sandbox test of prototypes with mounted piezometer filters

- **Results V 07.02 - OBR**

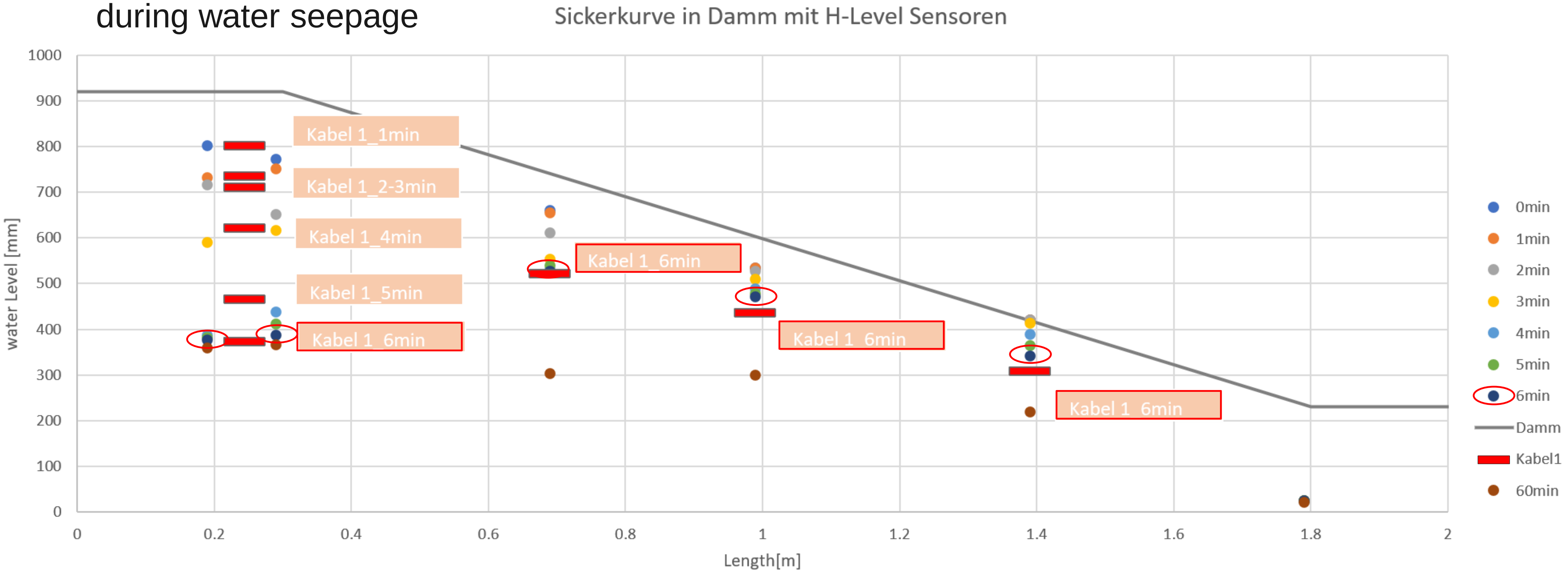
$N\,[-]$	$M\,[-]$	$\emptyset\,[mm]$	$t\,[mm]$	$I\,[mm^4]$	$O\,[-]$	$p\,[cm]$	$F\,[-]$	$Piezometer\,[-]$	$OBR\,[\mu\varepsilon/kPa]$ Pressure chamber	$OBR\,[\mu\varepsilon/kPa]$ Large Sandbox **Without sand**
V07.02	PU	10.0	1.75	403.3	Tube	2.0	Bending	4 Water Stone	7.13	12



Sandbox test of prototypes with mounted piezometer filters

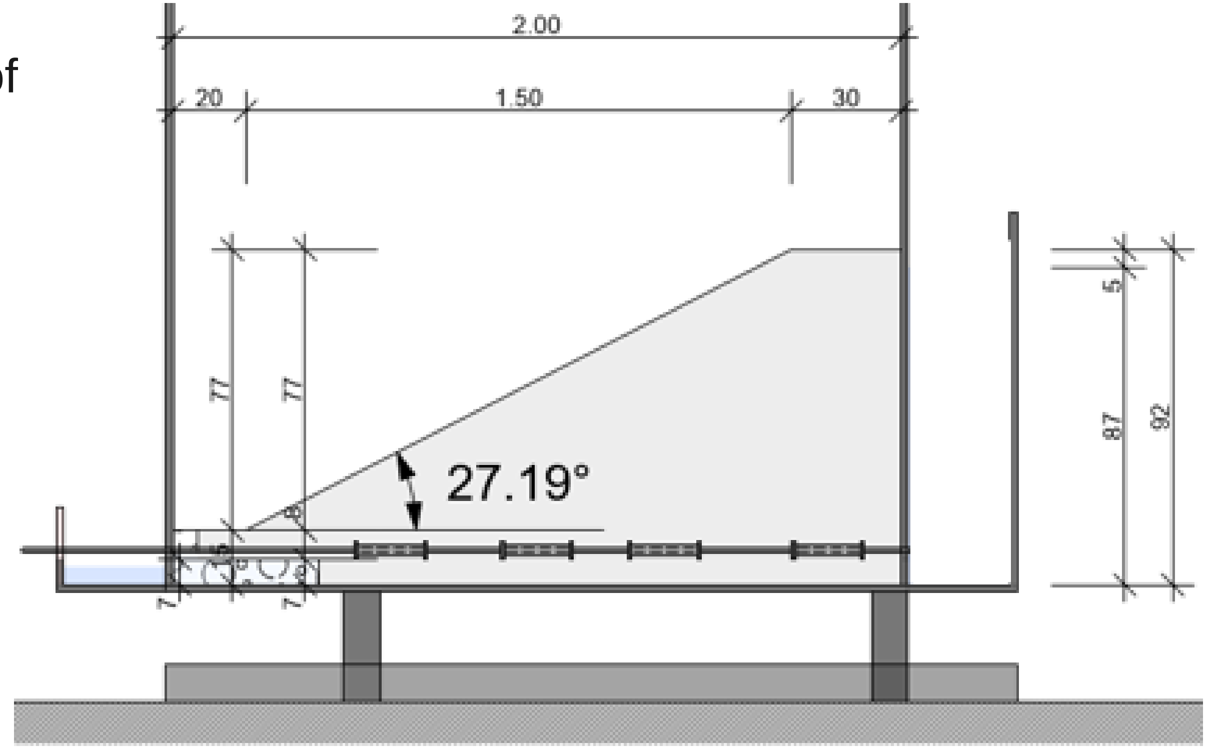
- **Results V 07.02 – OBR**
  - Time-spatial evolution during water seepage

$N\,[-]$	$M\,[-]$	$\emptyset\,[mm]$	$t\,[mm]$	$I\,[mm^4]$	$O\,[-]$	$p\,[cm]$	$F\,[-]$	$Piezometer\,[-]$	$OBR\,[\mu\varepsilon/kPa]$ Pressure chamber	$OBR\,[\mu\varepsilon/kPa]$ Large Sandbox **Without sand**
V07.02	PU	10.0	1.75	403.3	Tube	2.0	Bending	4 Water Stone	7.13	12



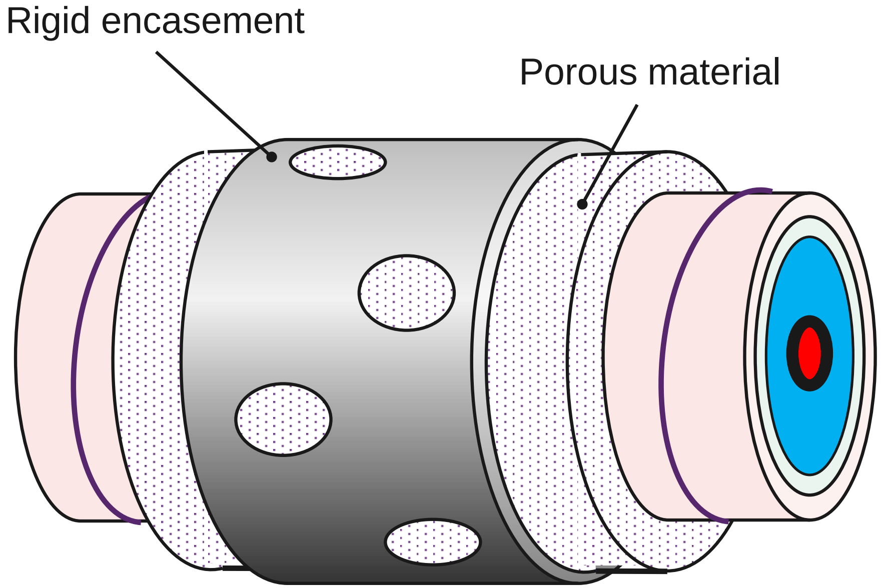
Sandbox test of prototypes with mounted piezometer filter

- Ongoing evaluations:
  - Temperature effects
  - Sensitivity to total earth pressure (segments of cable not covered by rigid porous filters)
- Hydrogeological events:
  - Piping
  - Other
- Test further versions of sensor:
  - Industrial DPS cable
  - Industrial piezometric filter

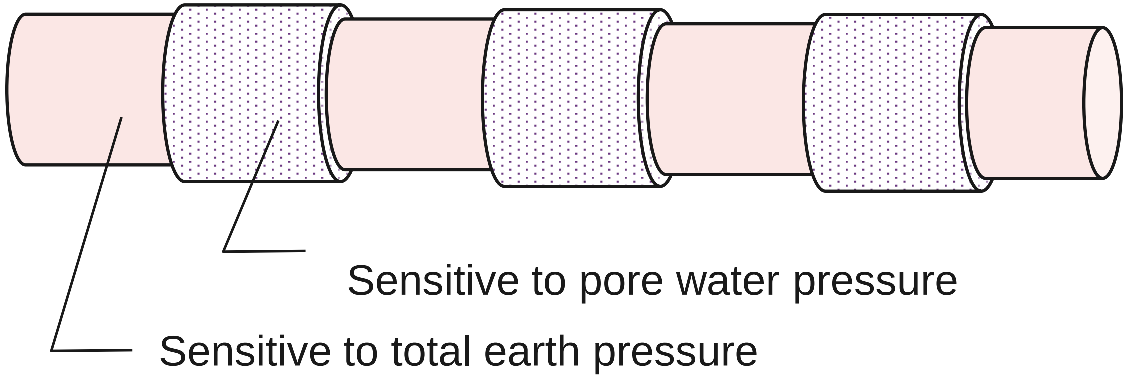


Piezometric filter

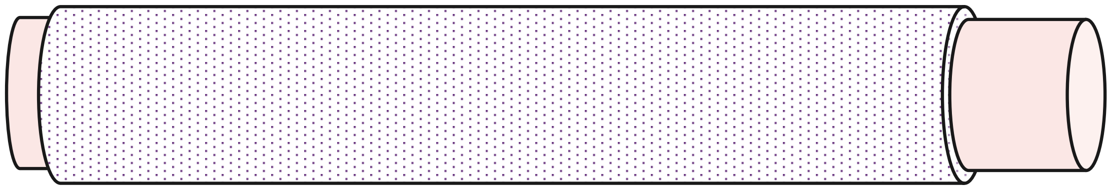
- Joint development with geotechnical instrumentation company



- **Segmented piezometric filter configuration**

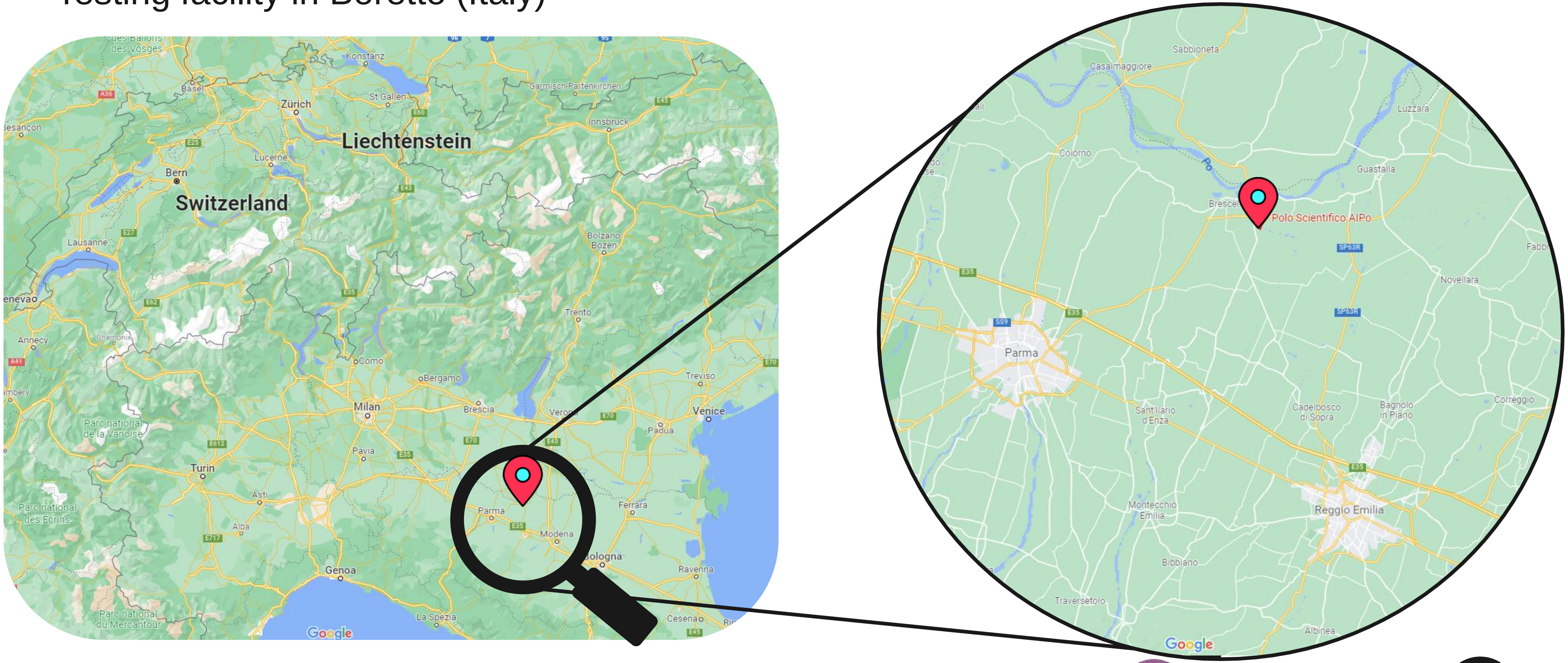


- **Continuous piezometric filter configuration**



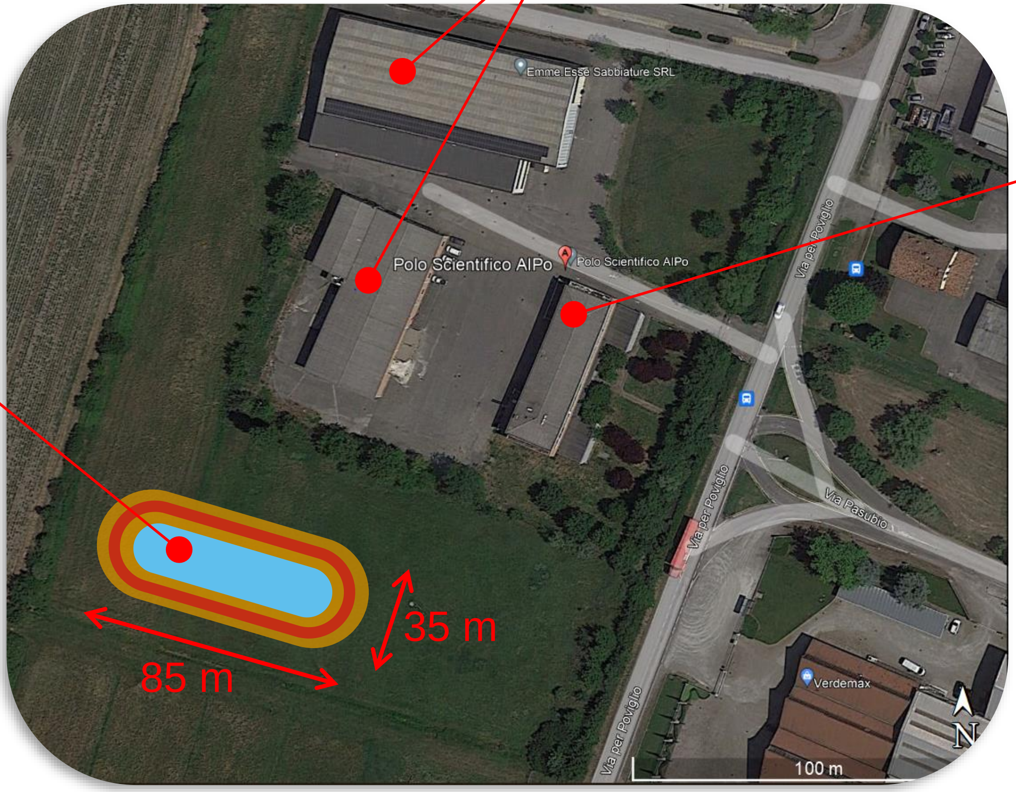
Validation in a full scale test

- Testing facility in Boretto (Italy)

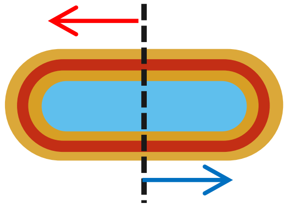


Validation in a full scale test

- Experimental embankment:
  - Length 85 [m]
  - Width 35 [m]
  - Height 3.5 [m]
  - Slope 1:2 [-]

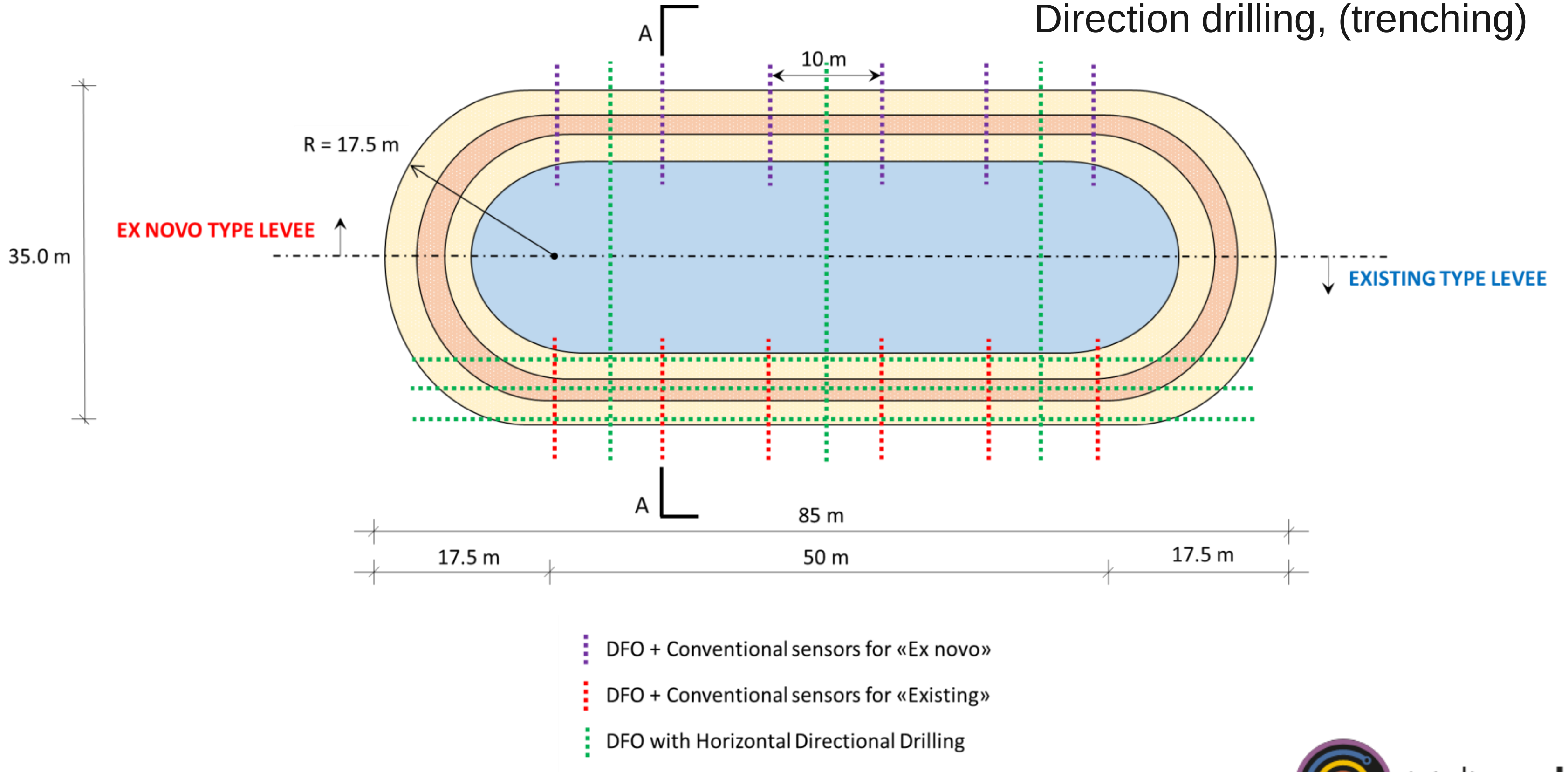


- Divided in two types constructed with two different materials:



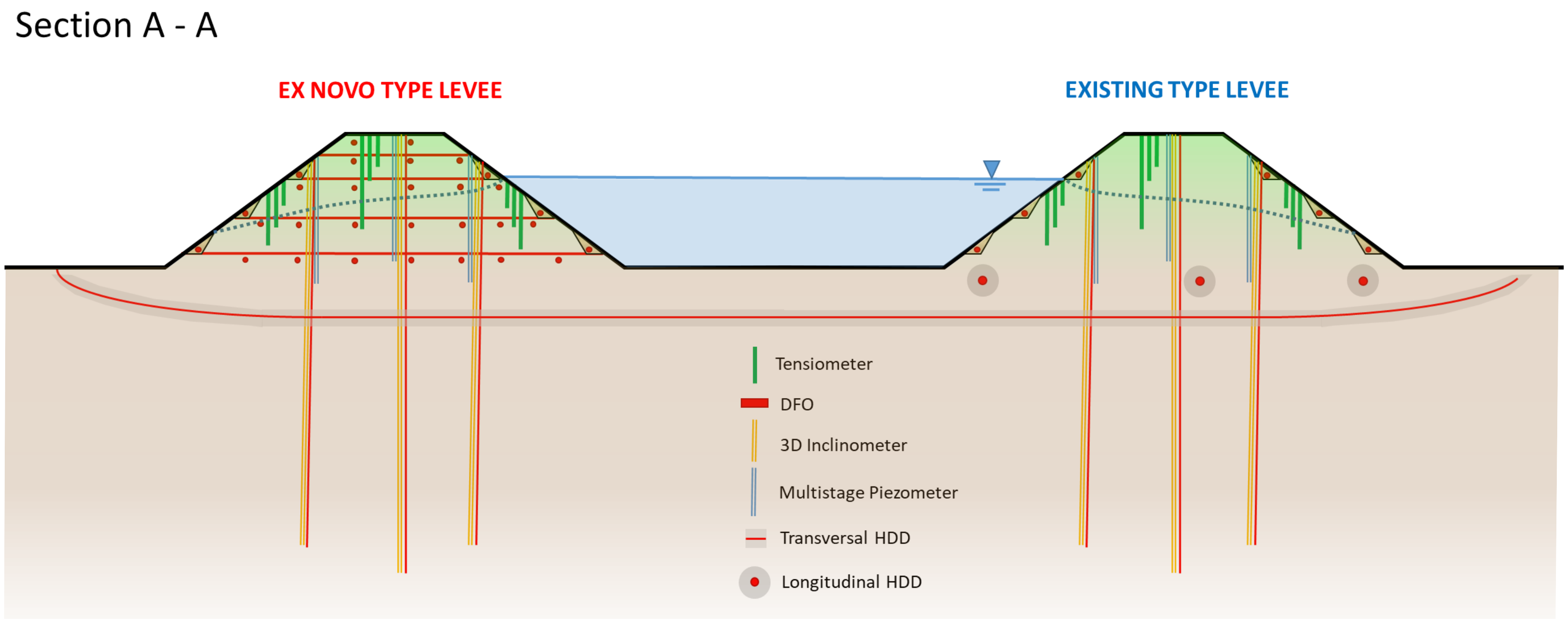
Validation in a full scale test

- Instrumentation divided in 2 types:
  - Ex Novo Levee
    - Sensors placed during the construction
  - Existing Levee (retrofit)
    - Sensors placed after the construction Direction drilling, (trenching)



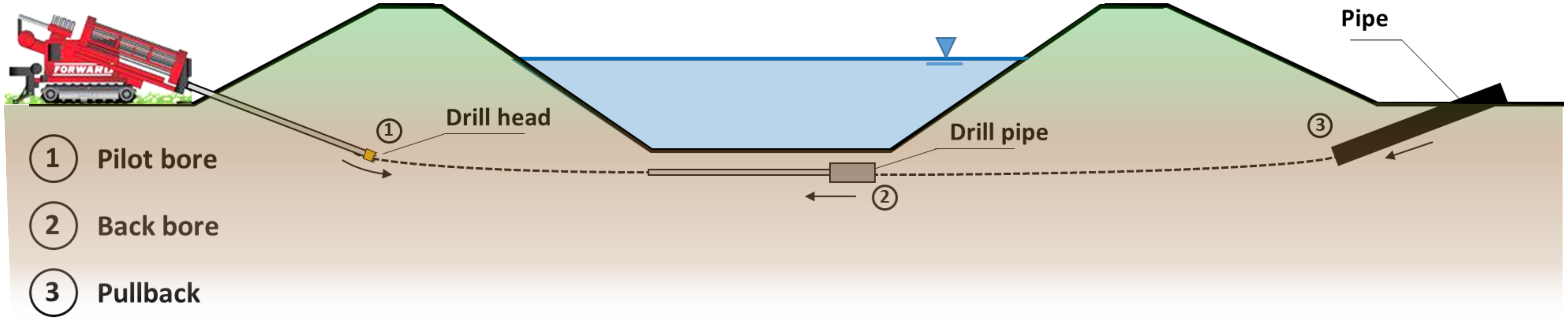
Validation in a full scale test

- Instrumentation divided in 2 types:
  - DFO sensors:
    - Strain
    - Temperature
    - Water Head
  - Conventional:
    - Inclinometer
    - Piezometer
    - Tensiometer



Validation in a full scale test – Installation procedure

- Instrumentation methodology for the existing type levee (retrofit):
  - Horizontal Directional Drilling (HDD)
    - Transversally
    - Longitudinally

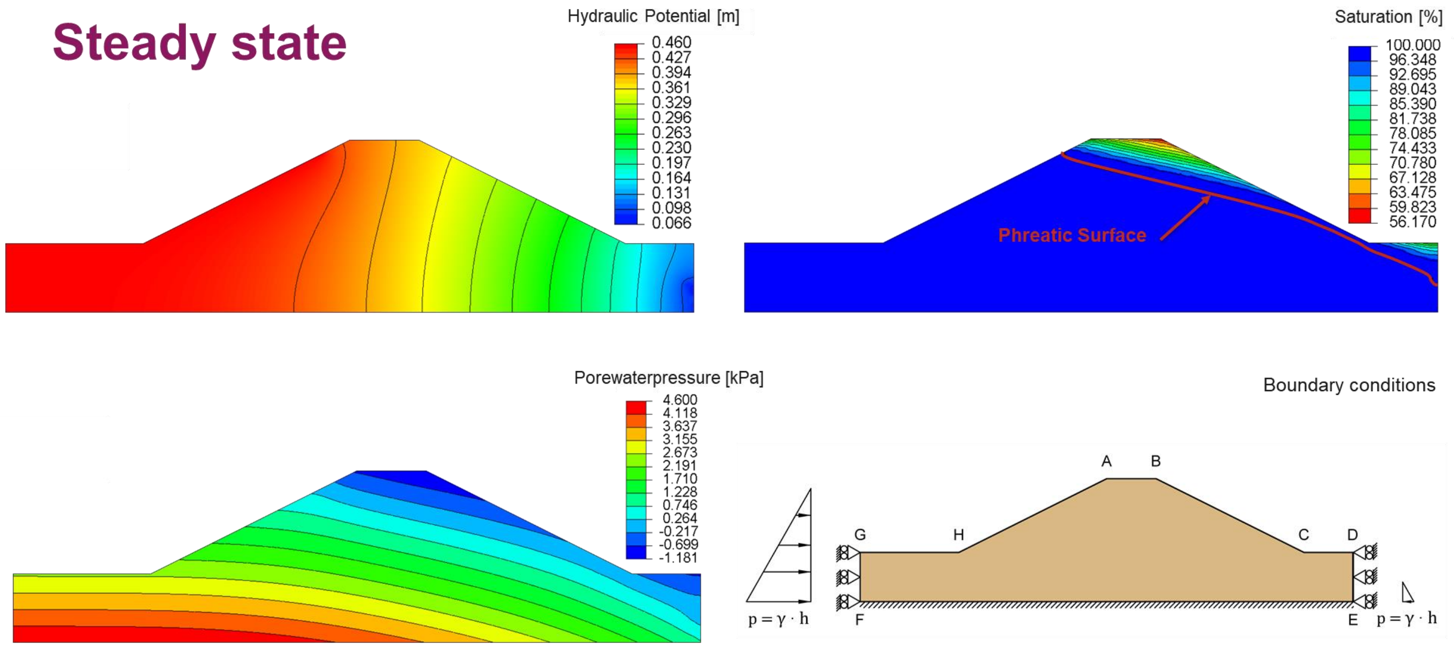


Interpretation

- Interpretation of the data with numerical and analytical models:
  - Dam filtration and seepages response
  - Erosion
  - Dam stability

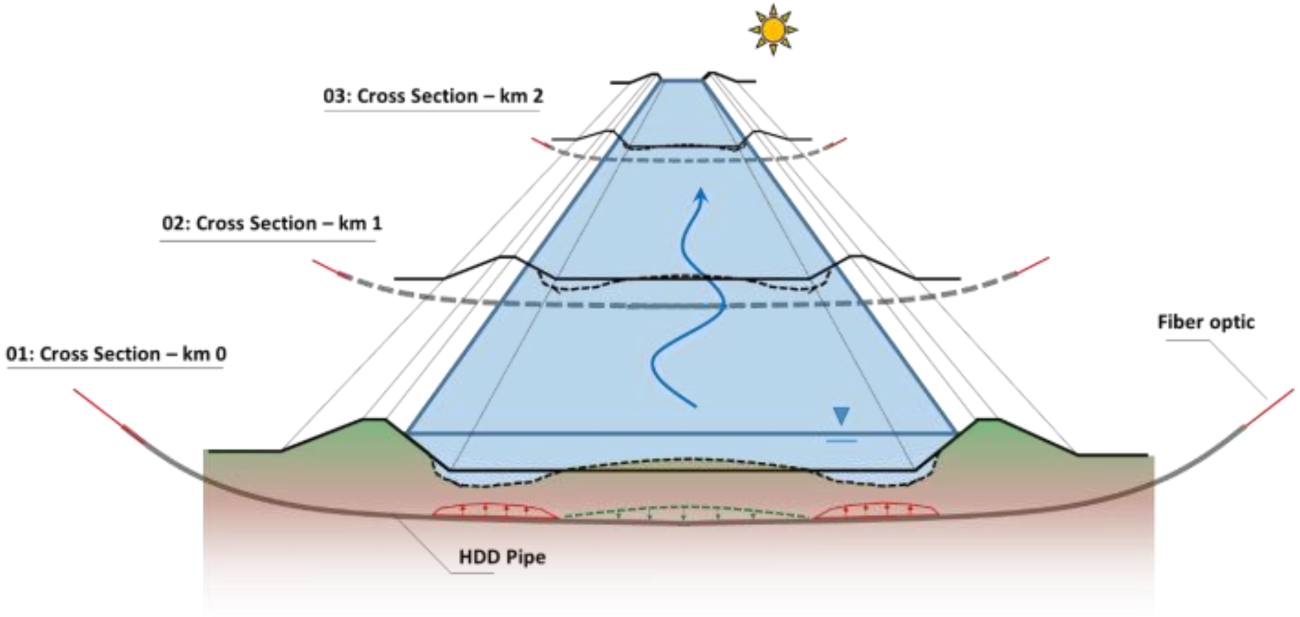
- Software
  - Comsol
  - Plaxis
  - Material Point Method software

Steady state



Project continuation

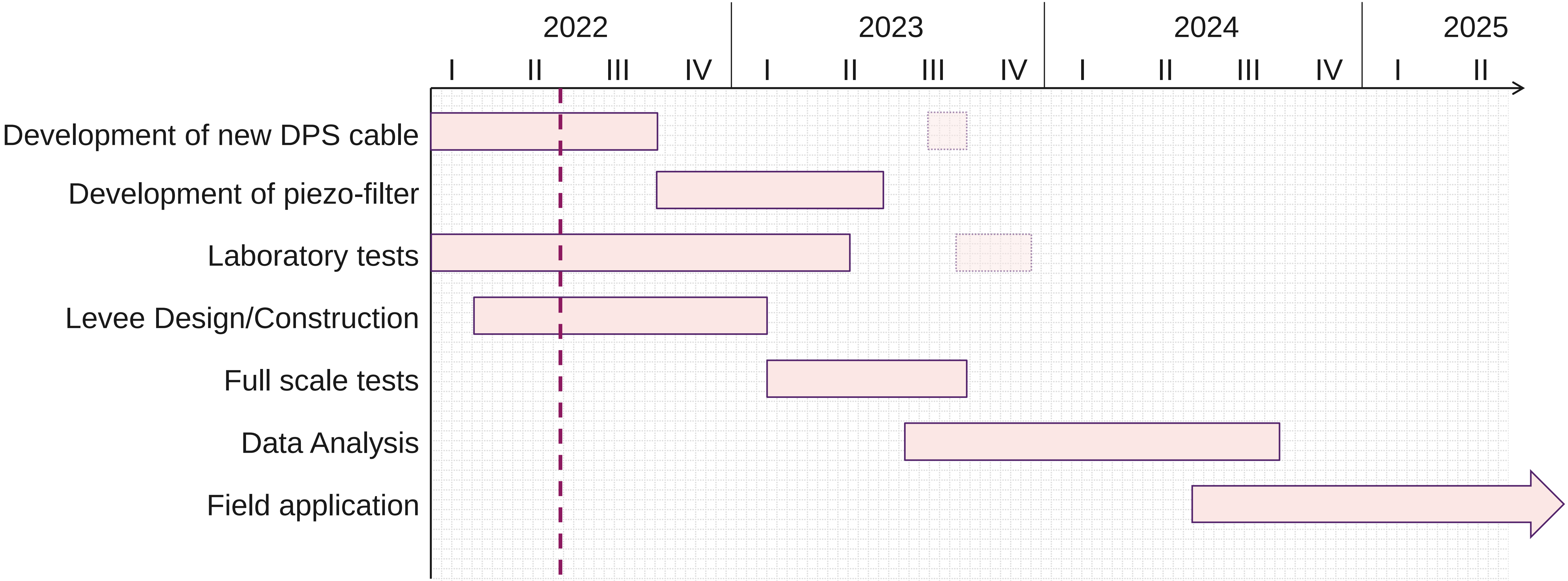
- The new DPS monitoring system will be implemented in a real levee on the Rhône river



Le Rhône élargi, à Viège (VS), © Kanton Wallis

Upcoming activities

Project Timeline



Who does the real work…

- Alessio Höttges, IBU - OST
- Prof. Carlo Rabaiotti, IBU – OST
- Isabel Sara Bohren, IBU - OST
- Eliane Geller, stud – OST
- R. Züger, stud - OST
- Fabian Kobler, stud – OST
- Hänni Lars, stud – OST
- Silvan Walker, IWK – OST
- Prof. Daniel Schwendemann, IWK - OST
- Alessandro Rosso, AIPO
- Agnese Bassi, AIPO
- Dr. Massimo Facchini, Iridis Solutions

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