Thermal monitoring of dams and levees

Krzysztof Radzicki – Cracow University of Technology (Poland)
Bonelli Stephane - IRSTEA (France)

Barcelona, 2016

Statistics of damming structures collapses due to internal erosion processes

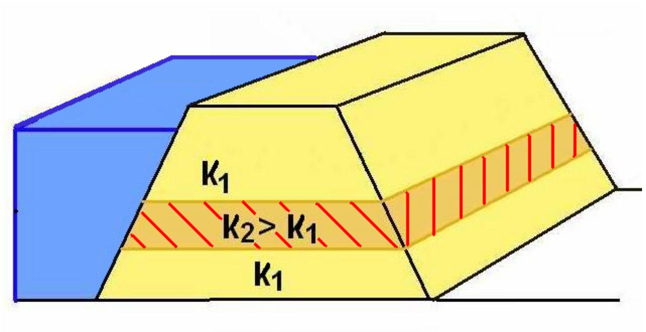
Earth dams (World, several years) Foster, 2000	46%
Flood protection dikes / levees (Poland, flood 2010r) Kledyński et all. 2012	30%

Collapse of dike in Cracow Bend of Vistula (2010)

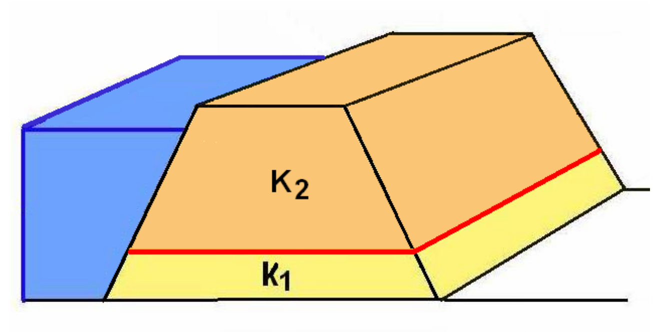
- The failure occurred at night
- No recent signs of danger

Internal erosion

SUFFUSION

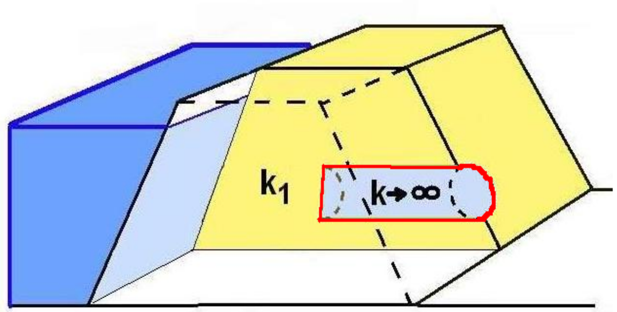


CONTACT EROSION

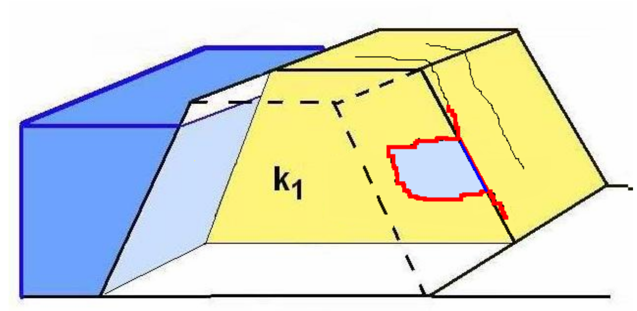


Risk of piping

BACKWARD EROSION

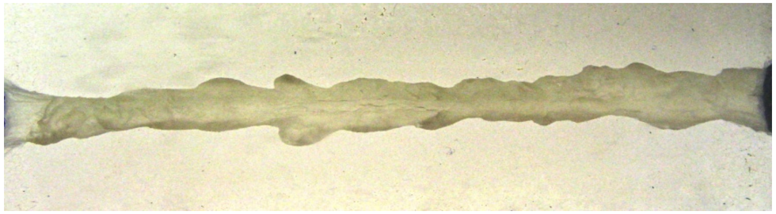


CONCENTRATED LEAKS



High risk of piping

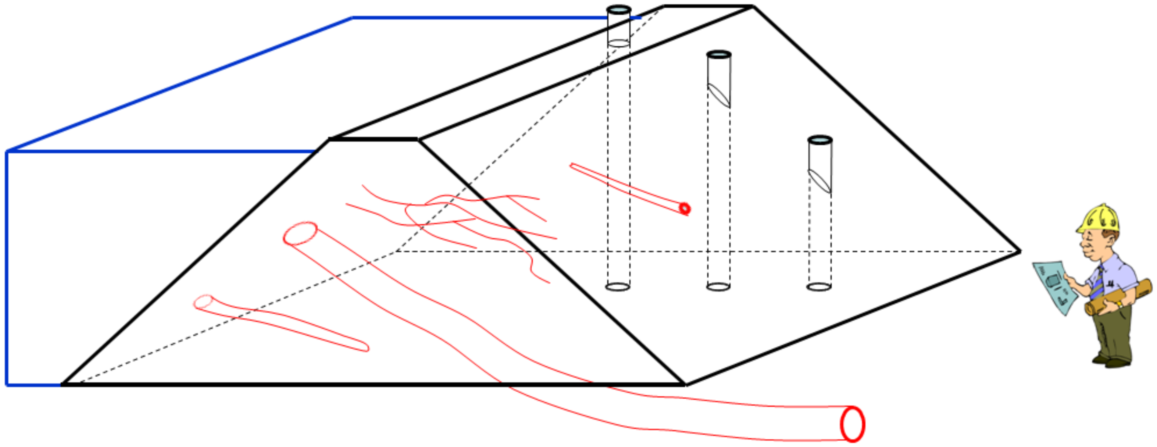
PIPING



The problem of piping detection and monitoring

Visual inspections, spot geotechnical studies, geophysical surveys, spot sensor monitoring (if it exists),

- ✓ are not sufficient to reliably detect and assess the development of erosion processes
- ✓ especially in the early stages of their development,
- ✓ and especially during the floods to keep levees safe!



„The frequency of piping failures is significantly higher on first filling and early in the life of the dam.”

FOSTER et al.. (2000 - The statistics of embankment dam failures and accidents.)

„In the majority of failures, breaching of the dam occurred within 12 h from initial visual indication of piping developing, and in many cases this took less than 6 h”.

FOSTER et al.. (2000 - A method for assessing the relative likelihood of failure of embankment dams by piping.)

The problem of reliable condition assessments and monitoring of EARTH DAMS

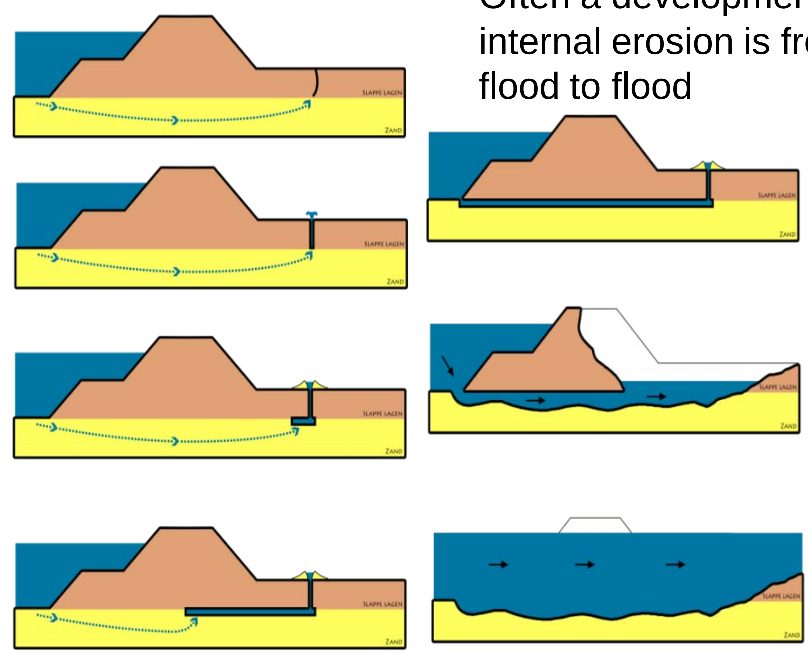
- The necessity to minimize the probability of dam collapse
- Aging of dams
- Internal erosion is one of the main threats to the safety of dams
- Shortage of decision support tool for the identification of sections requiring renovation
- Assessment of dams state based on spot measurements

100m high Teton dam (1976) – collapse in 3 hours due to piping

The problem of reliable condition assessments and monitoring of LEVEES

- The necessity to minimize the probability of disaster of dikes protecting valuable areas particularly urban and industrial
- Often poor condition of existing levees
- Shortage of methods for identification of vulnerable sections, especially in the early stages of development of erosion processes, especially the piping
- Shortage of diagnostic tools enabling automatic detection of internal erosion threats during flood defense
- Shortage of methods to assess the most vulnerable sections of levees among all the sections where leakages were detected
- Shortage of decision support tools for identification of critical sections of levee after the flood that require immediate repair
- Condition assessment of the levee based on spot, usually geotechnical measurements

Often a development of internal erosion is from flood to flood



ICOLD bulettin B164 (2013)

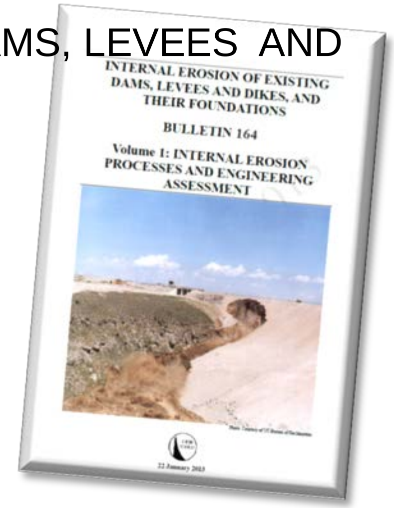
EWG ICOLD recommendations

European Working Group on Internal Erosion of ICOLD

ICOLD’s Bulletin no 164 (2013): „INTERNAL EROSION OF EXISTING DAMS, LEVEES AND DIKES, AND THEIR FOUNDATIONS”

VOL.1 INTERNAL EROSION PROCESSES AND ENGINEERING ASSESSMENT

<Many less direct means of detecting seepage are now available. The most promising is temperature measurement which can be used to infer localized flow. Fiber optic cables facilitate data collection and make it possible to cover large parts of the dam. Remote sensing options also offer great potential in detecting whether the seepage has caused erosion. These will be discussed in detail in Volume 2 of the Bulletin.>



Jean-Jacques FRY (2012), the chairman of ICOLD European Working Group on Internal Erosion - 80th ICOLD annual meeting in Kioto

PAPER : „HOW TO PREVENT EMBANKMENTS FROM INTERNAL EROSION FAILURE?”

<In our opinion, Distributed Fibre Optic Temperature measurement is the best method …. Remote control monitoring of temperature by fibre optic is the only method available for practical application, which has been used successfully during the last 10 years during the last 10 years in Germany, Sweden and France>

<The IJkdijk-piping tests clearly demonstrate the reliability and the capabilities of the fiber optic system to detect the early stage of a piping process.>

Coupled heat and water transport

DIFFUSION-ADVECTION EQUATION

$$C_\Theta \frac{\partial T}{\partial t} + C_f \vec{q} \frac{\partial T}{\partial x} - \lambda_\Theta \frac{\partial T}{\partial x^2} = 0$$

SYSTEM NONDIMENTIONAL

$$\vec{q} = const.$$

$$\overline{x} = \frac{x}{L} \qquad \overline{t} = t\frac{L^2}{D_\Theta} \qquad D_\Theta = \frac{\lambda_\Theta}{C_\Theta}$$

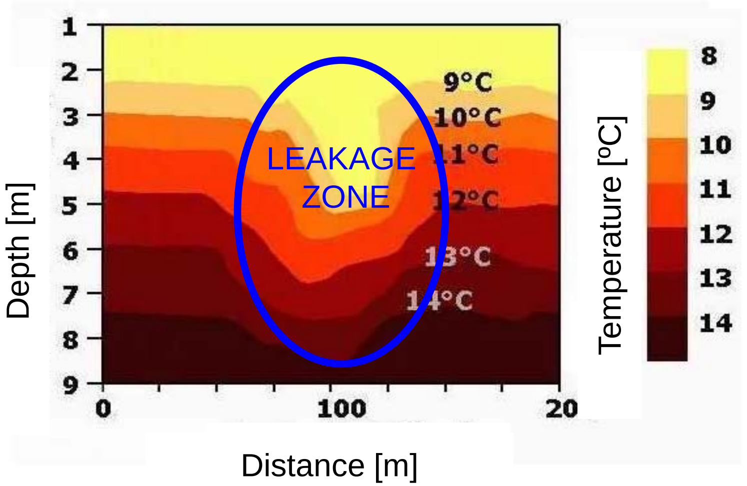
$$\frac{\partial T}{\partial \overline{t}} + Pe\frac{\partial T}{\partial \overline{x}} - \frac{\partial T}{\partial \overline{x}^2} = 0$$

Peclet number

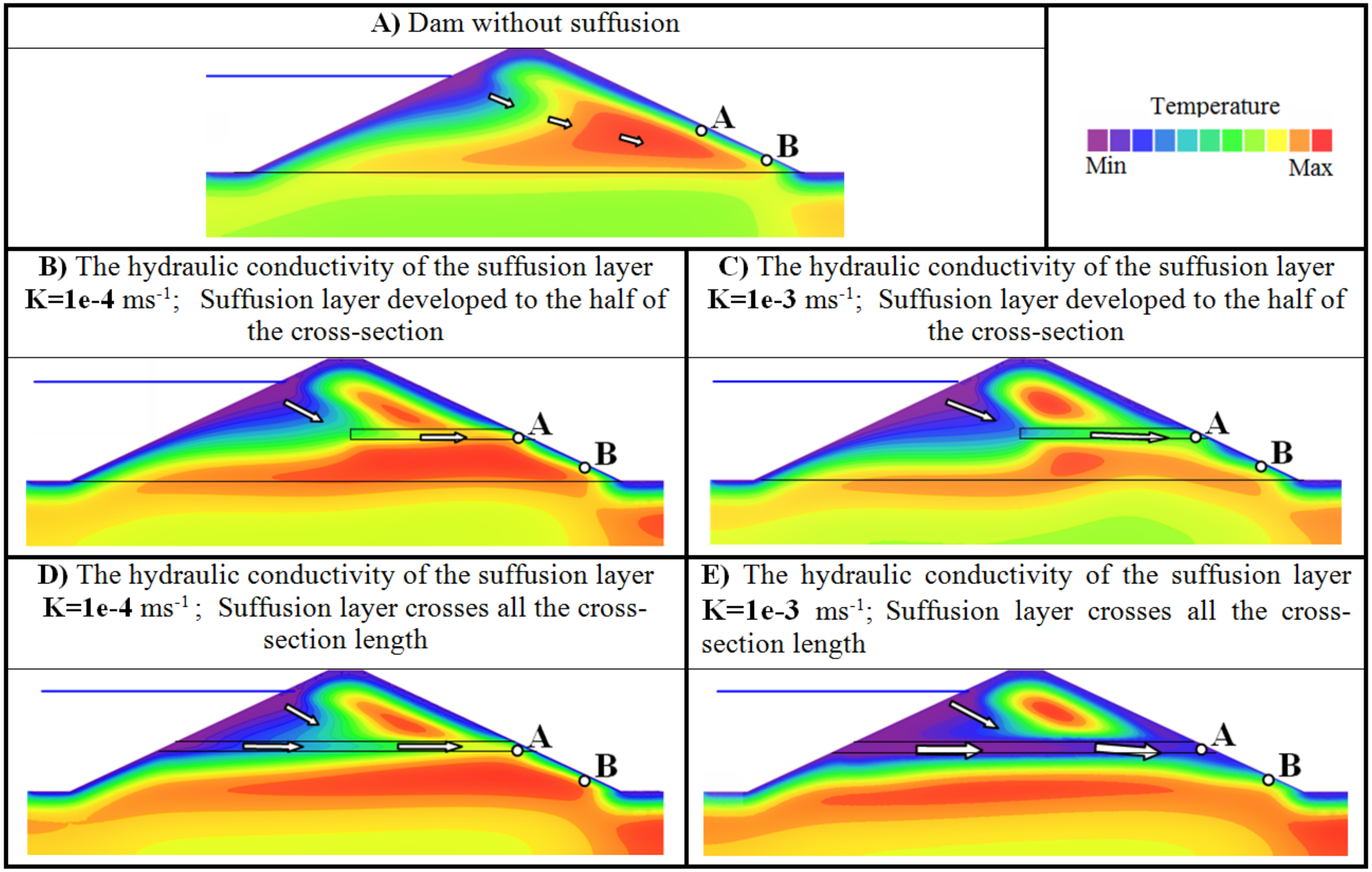
$$Pe = \frac{advection}{conduction} = \frac{C_\Theta \vec{q} L}{\lambda_\Theta}$$

Conduction domination $Pe < 1$

Advection domination $Pe > 1$



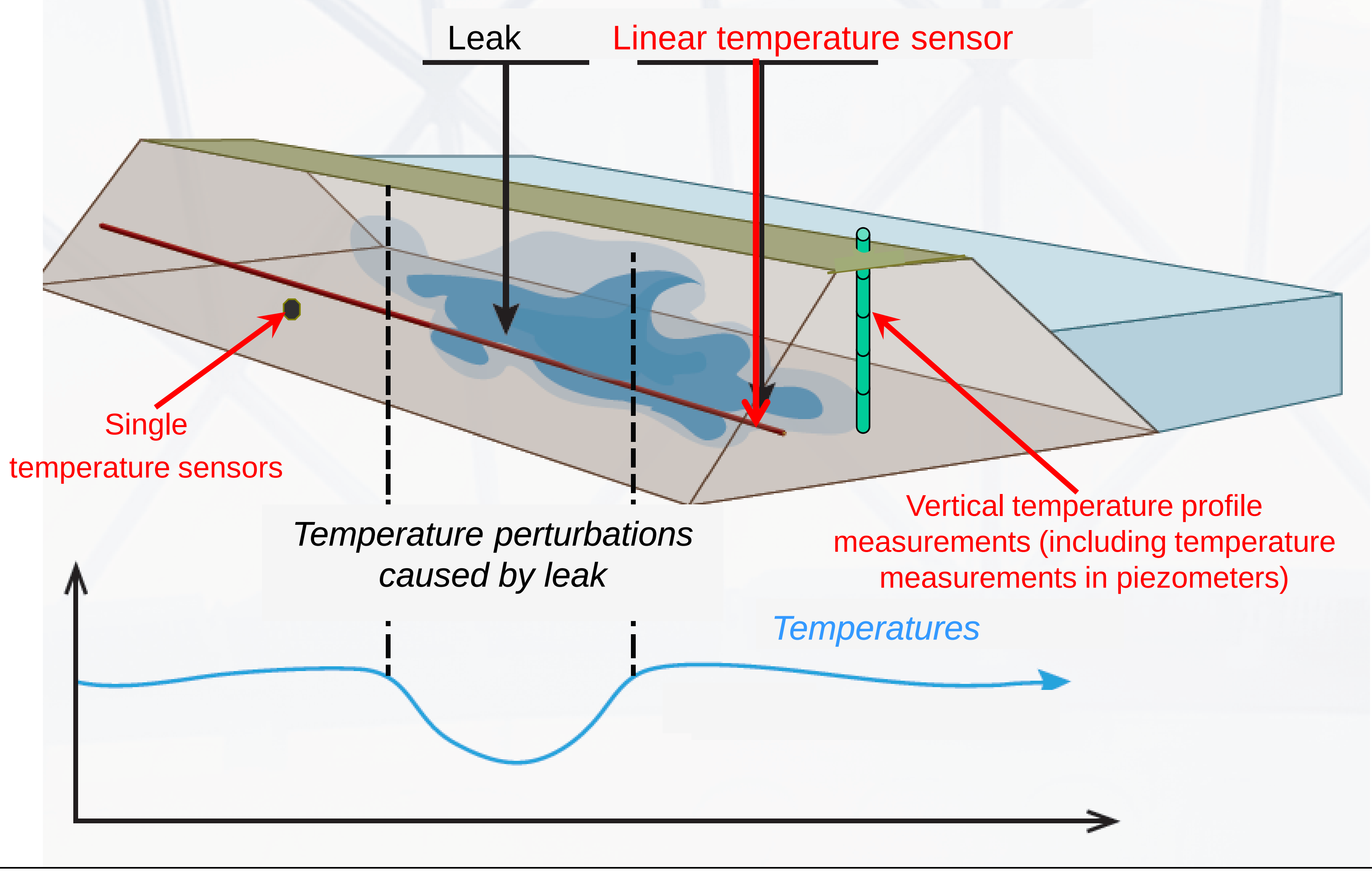
Example of the impact of internal erosion development on the temperature field in the damming structure



Temperature fields of a dam cross-section registered at the same time instant for different lengths of suffusion layer and for different values of suffusion layer hydraulic conductivity.

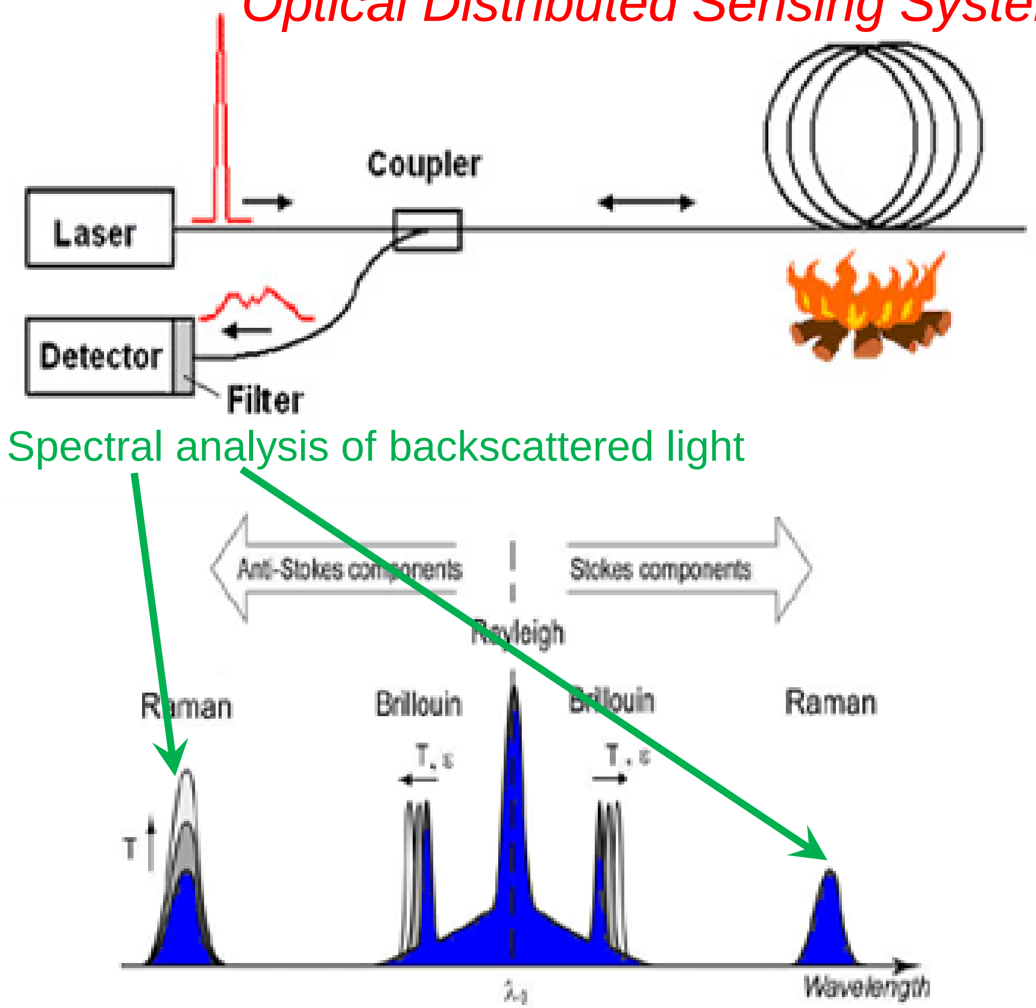
Radzicki and Bonelli (2012)

Methods of temperature measurements



Linear temperature sensors

Optical Distributed Sensing Systems



Fiber optic temperature sensing:

- Spatial resolution 1m
- Resolution ± 0,1°C
- Measurement distance
  - up to 30km with one fiber optic cable

Optimal for installation on new damming constructions (dams, levees,….), during renovations and assuming the decades-long application

Problems with DFOTS application at existing structures

COST OF APPLICATION

- Costly earthworks of cable installation
- Costly technology for short distances of measurements and/or particularly for temporally leakage or erosion problem monitoring (costly sensing head - DTS unit)

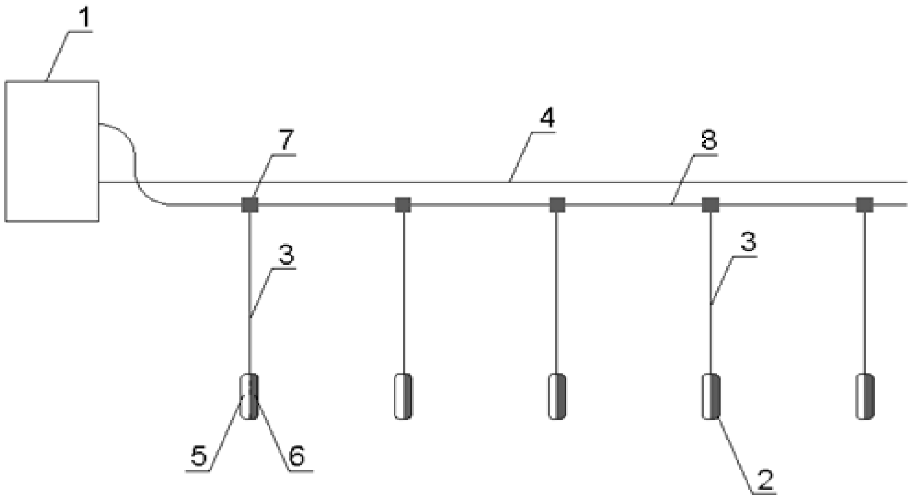
SAFETY PROBLEMS OF THE STRUCTURE

- Earthworks affect the body or the foundation of the structure. Foundation structure must be rebuilt very carefully.
- In the case of high water level in the body of damming structure the risk of fiber optic cable installation can be to high to accept this monitoring solution application

Linear temperature sensors

MPointS

Driving Multi Points Sensor to use for passive or/and active quasi continuous thermal monitoring



MPointS are mounted without an excavation by inserting successive sensors in a series, one after another without necessity of the earthworks.

MPointS can be installed along the damming structure particularly at its downstream toe instead of fiber optic cable.

Can be installed much deeper than fiber optis cabel

Particularly useful for monitoring of existing dams and embankments. Much cheaper and easier for installation than fiber optics.

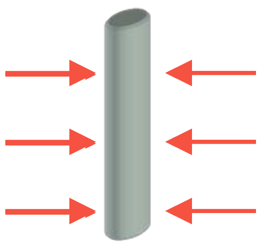
Optimal for use for temporary monitoring (up to several years) of leakages and internal erosion processes in order to optimize decisions abour necessity of renovation and/or about its range.

Linear temperature sensors

MPointS - installation

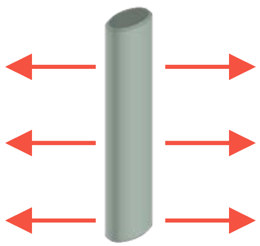
Passive and active thermal monitoring

PASSIVE METHOD



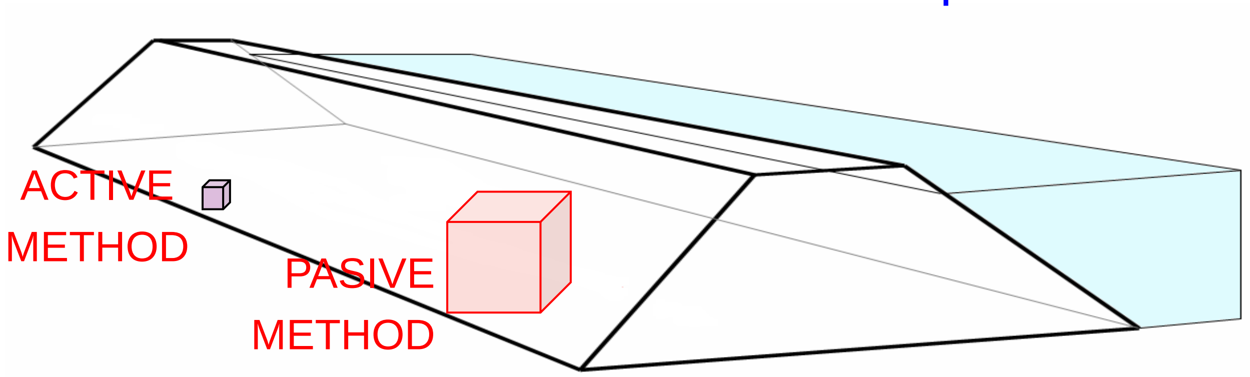
Natural temperatures
measurements

ACTIVE METHOD

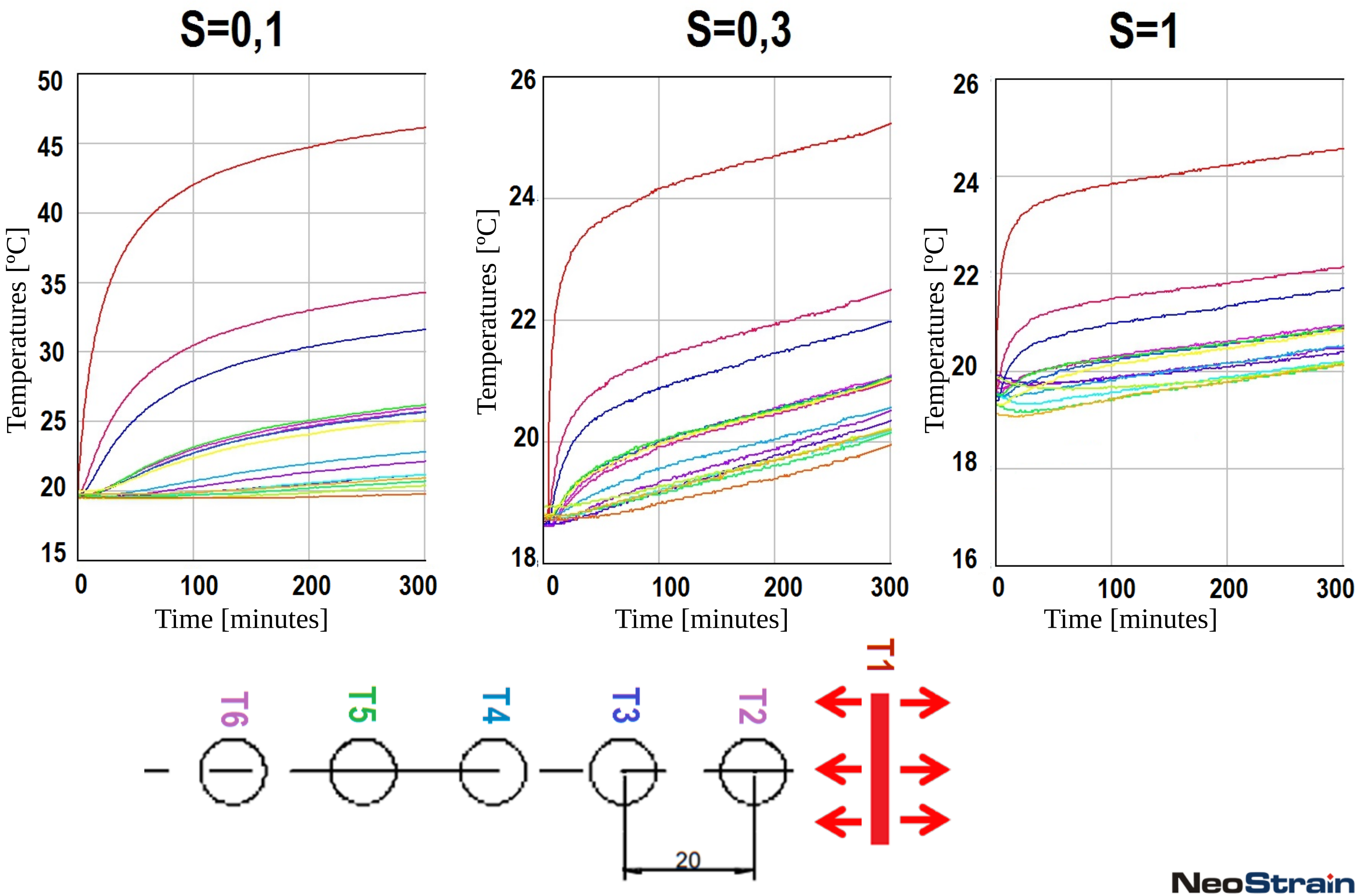


Heat emission
measurements

Schematic extent of the leak detection zone for spot measurements

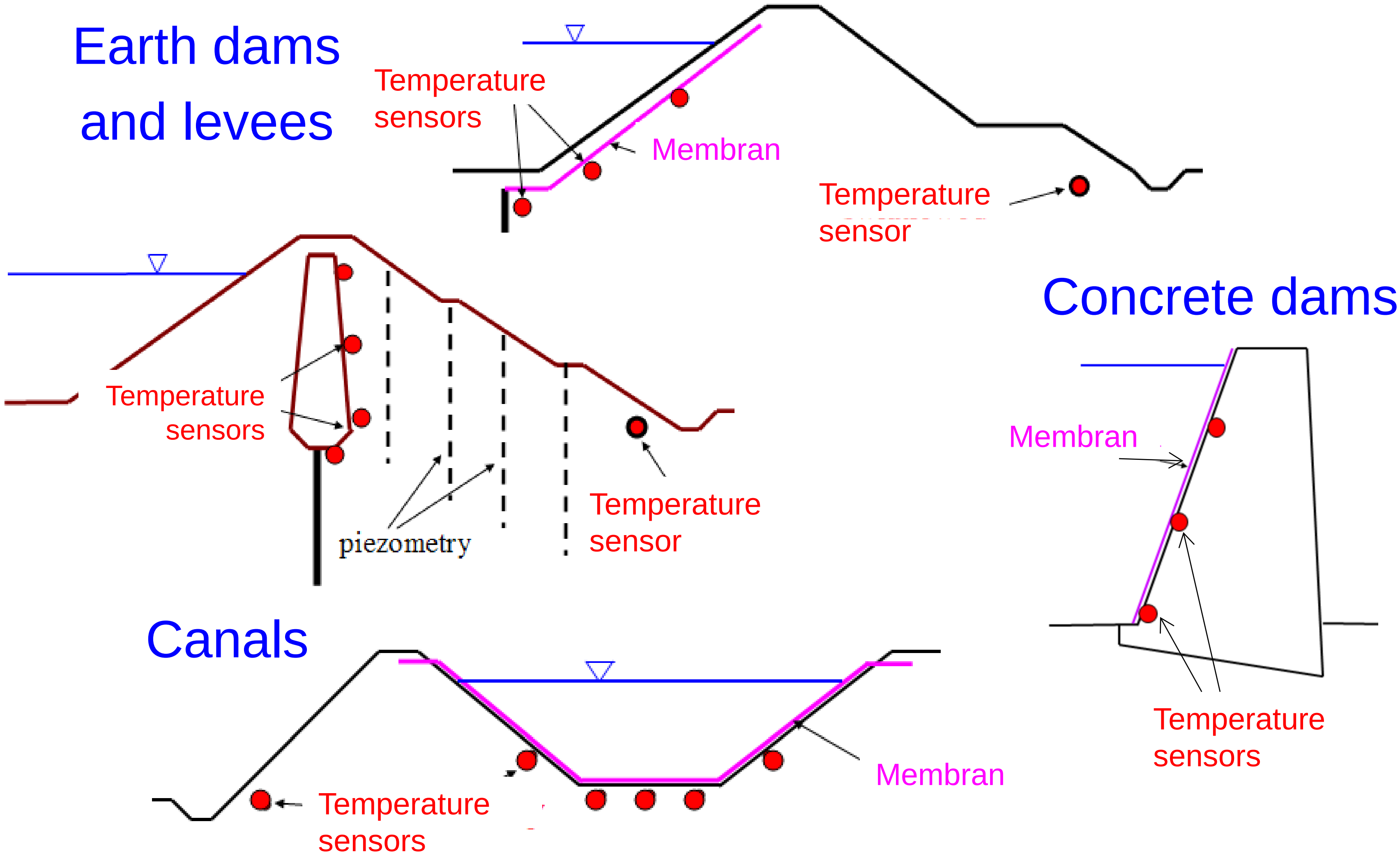


Active method – laboratory test of heat distribution for different moisture values



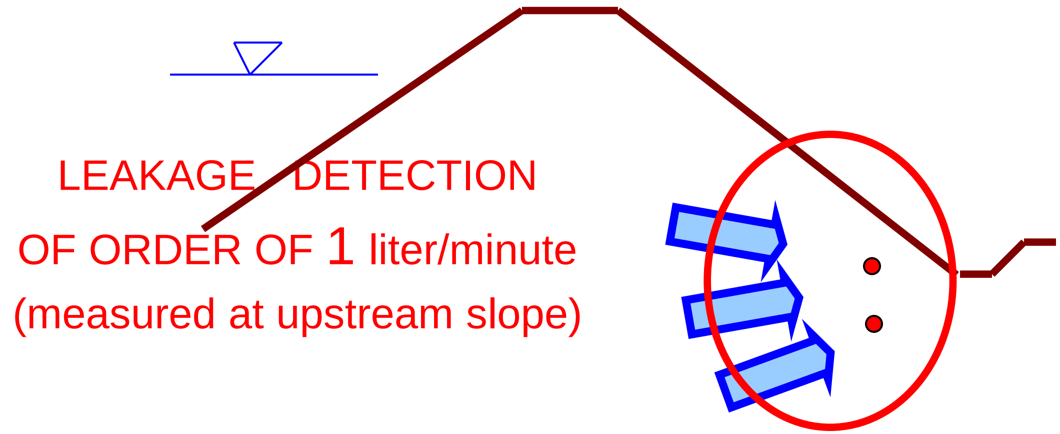
NeoStrain

Location of linear temperature sensors

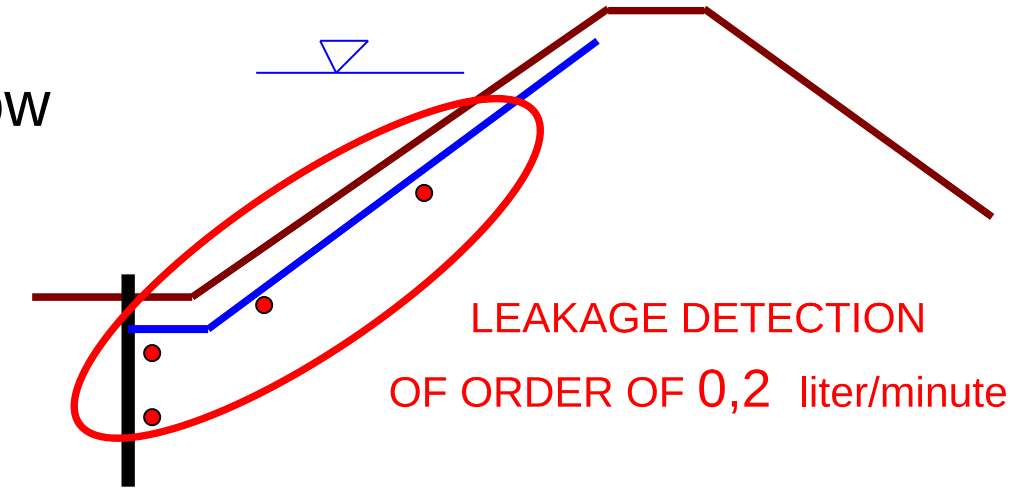


Research in real scale confirmed that thermal monitoring is reliable and precise tool and allows for early detection of leakages and internal erosion

Fiber optic located in downstream toe

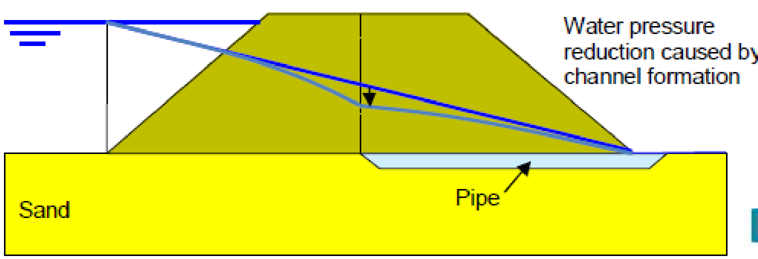


Fiber optic located below upstream membran



Radzickl (2009) , Beck et all. (2010, 2012),

2009 IjkDijk test

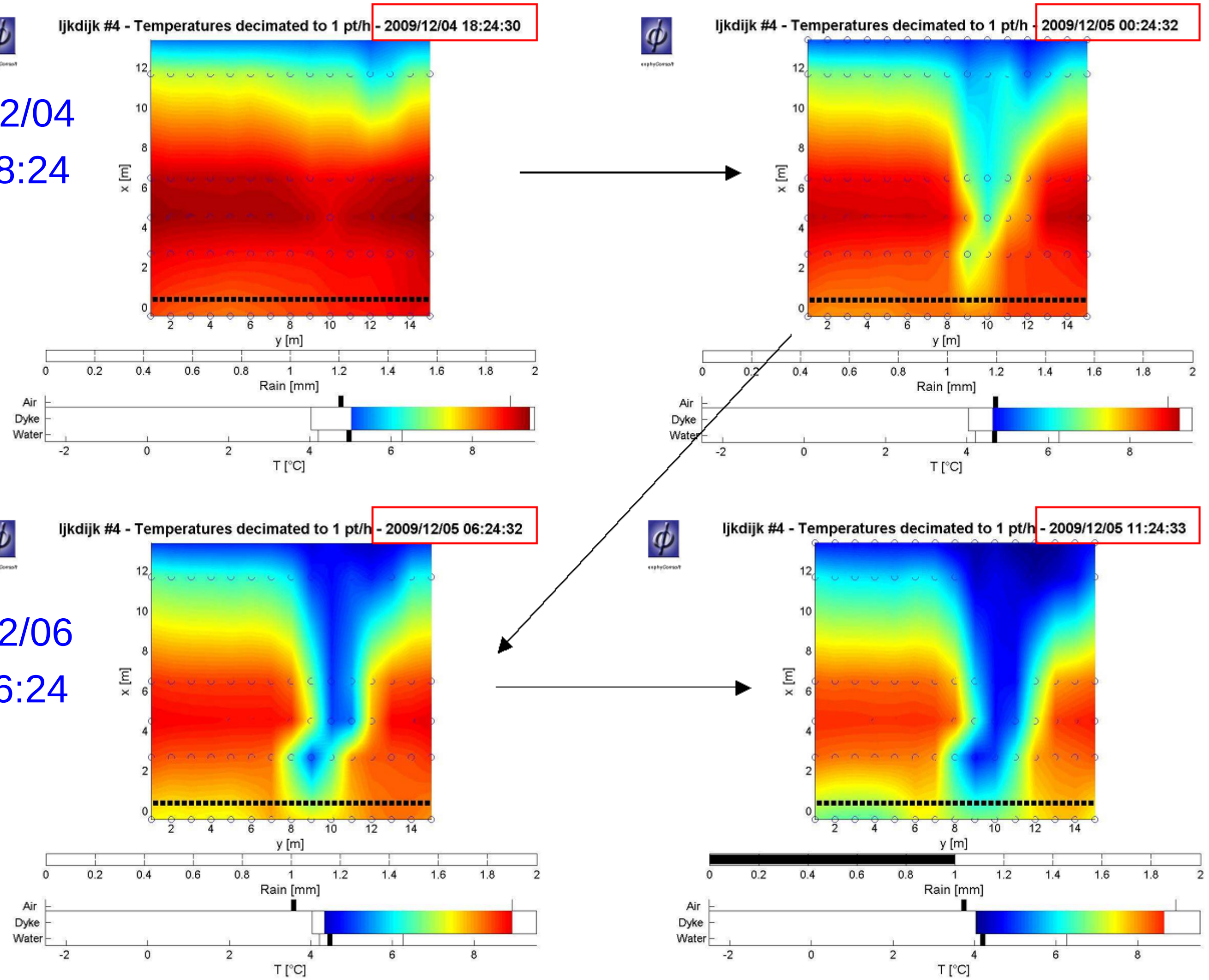


Deltares

2009 IjkDijk test

2009/12/04 18:24

2009/12/05 00:24



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Beck et all. (2010, 2012)

Models of passive thermal monitoring

General models division		*Signal processing models*		*Models with the physical meaning of the parameters*	
Model name		**Daily Analysis Model**	**Source Separation Model**	**Impulse Response Function Analysis Models (for example IRFTA model)**	**Amplitude Model**
Minimal period of the temperature data acquisition		**about 1 day**	**about 2-3 months**		**1 year**
Range of the application	**Type of the hydraulic structure**	Earth dams, dikes of the canals and flood protection levees	Earth dams and dikes of the canals		
	Hydraulic conditions	Saturated and unsaturated zone			Only saturated zone
	Thermal conditions	Analysis in relation to the reservoir temperature and air temperature as well to the other thermal sources.		Analysis in relation to the reservoir temperature and the air temperature.	Analysis only the dam's reservoir temperature influence; air temperature influence must be neglected
Method principle		Data daily analysis developed using signal analysis methodology	Source separation method	Modelling with an exponential approximation of the impulse response function of the system	Exact solution approximation of the relevant problem for the suffusion layer
Main advantages		The fastest leakage detection method. Possibility of the early warning, automatic leakage detection system installation	Leakage detection method	Parametrical evaluation of the coupled heat and water transport, including leakage detection possibility and its intensity assessment	Seepage velocity estimation in the suffusion layer
Described examples of the model application		Beck et al., 2010	Beck et al., 2010; Cunat , 2012	Radzicki, 2009; Radzicki and Bonelli, 2010; Artières et al., 2007 Cunat, 2012	Johansson, 1997

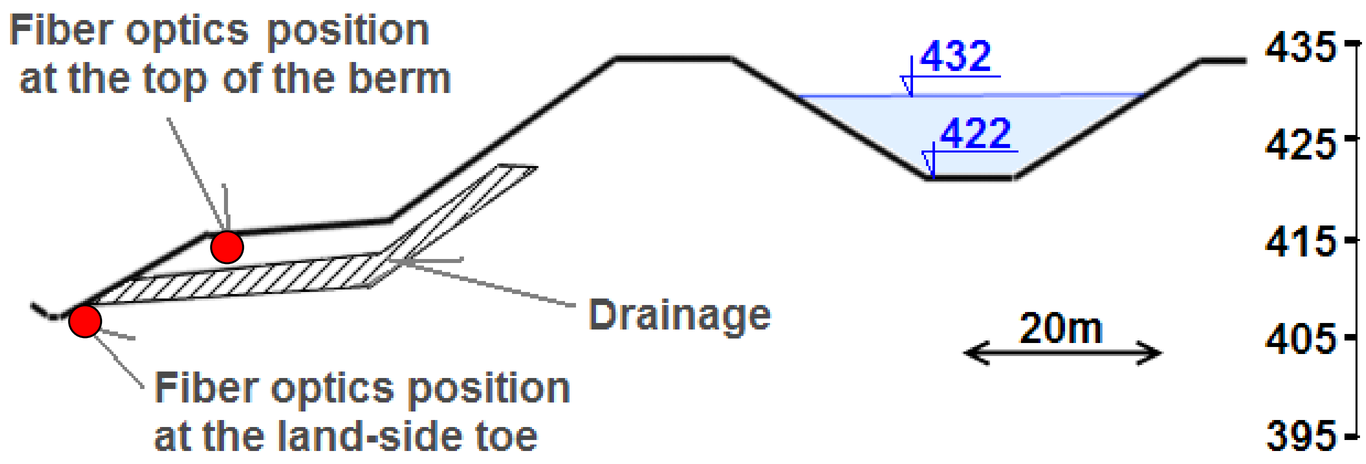
Radzicki (2012)

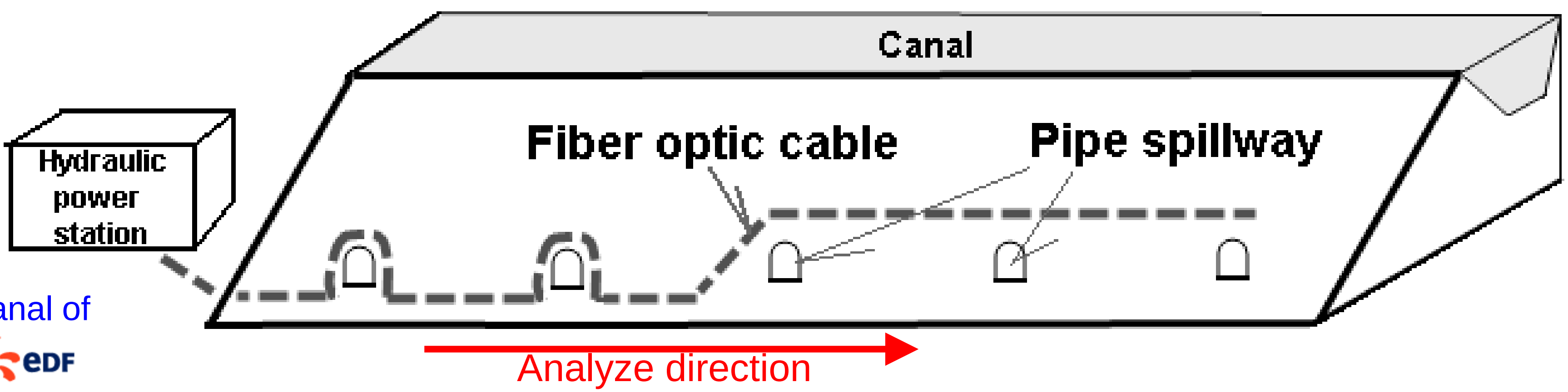
Examples of applications

DIKE OF THE ORAISON CANAL

Examples of applications

DIKE OF THE ORAISON CANAL

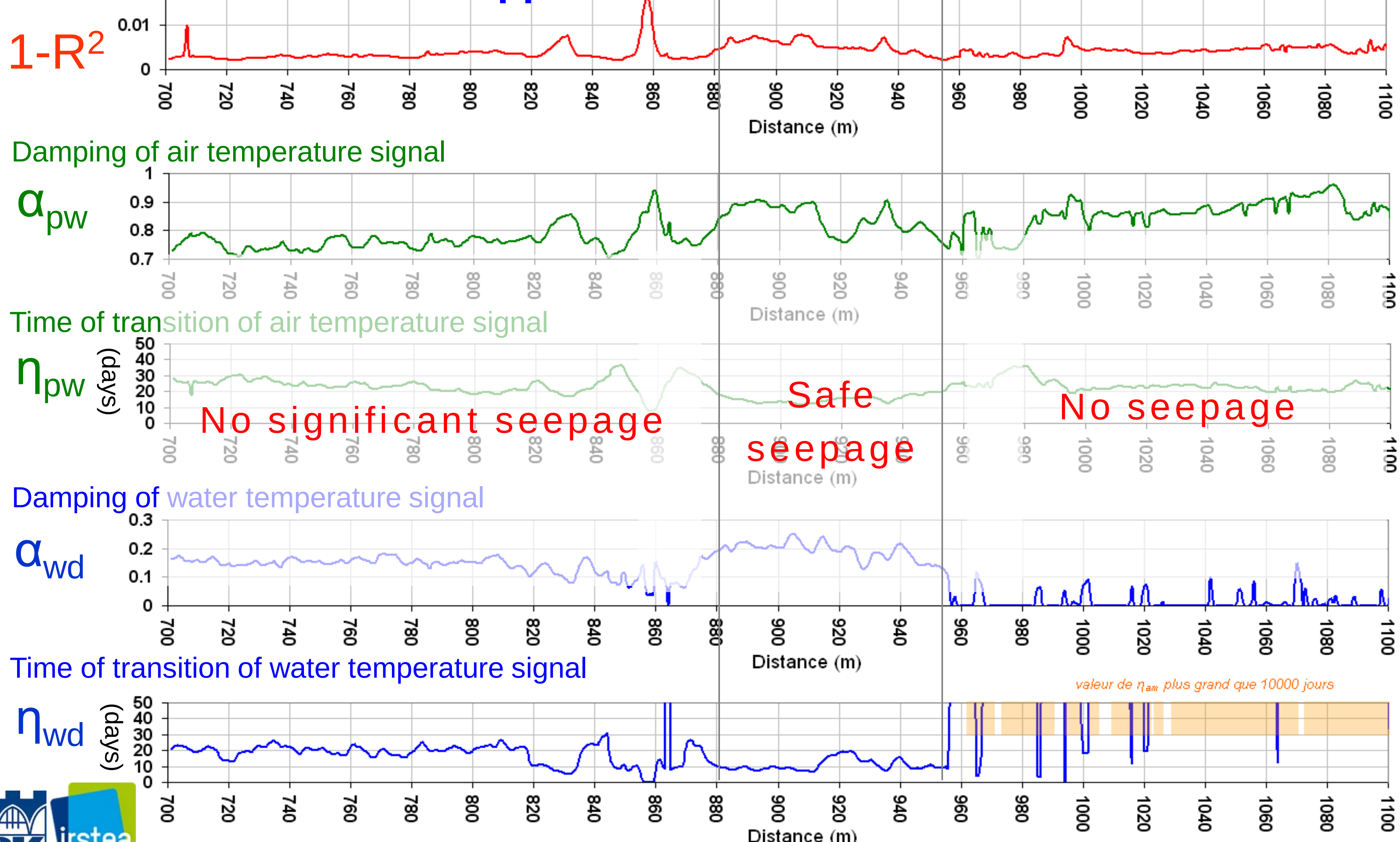




Canal of EDF

Examples of applications

IRFTA MODEL application results for dike of the Oraison canal



Radzicki and Bonelli (2009,2010)

Examples of applications

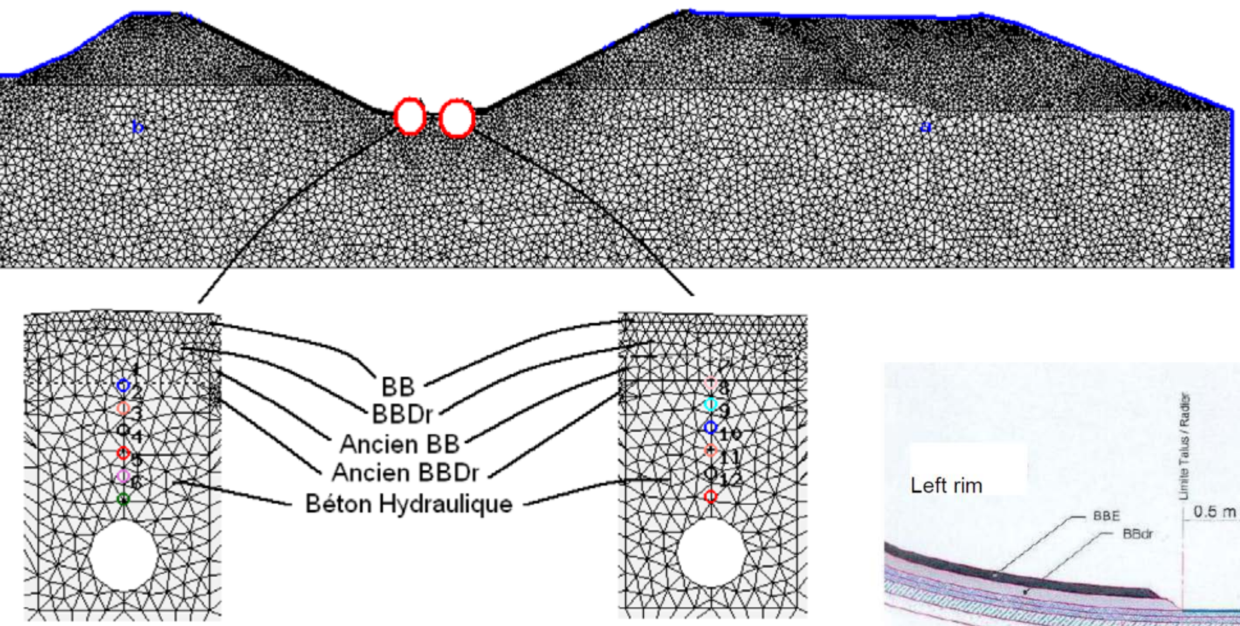
DIKE OF CURBAN CANAL OF DURANCE RIVER

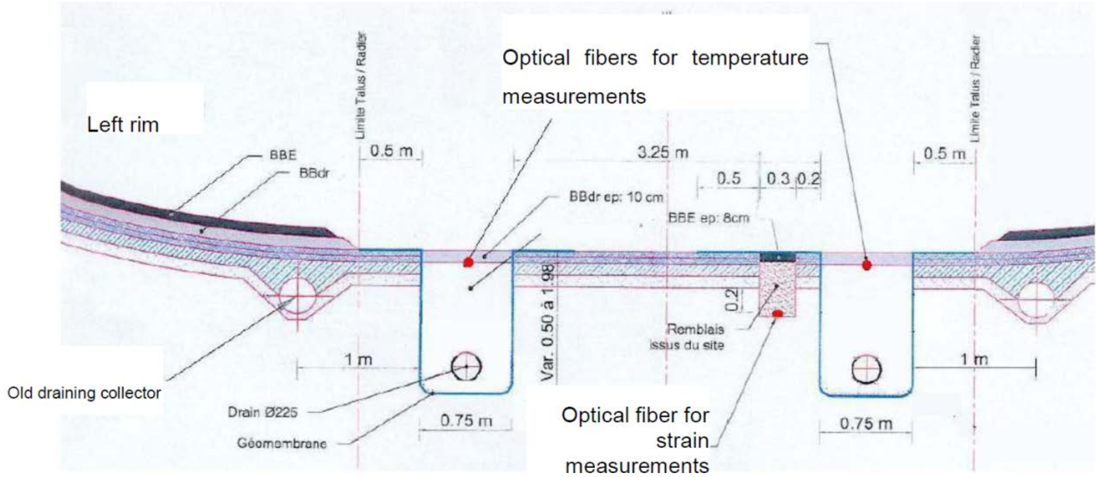
- 5 km of fiber optic

Canal of EDF

Examples of applications

DIKE OF CURBAN CANAL OF DURANCE RIVER

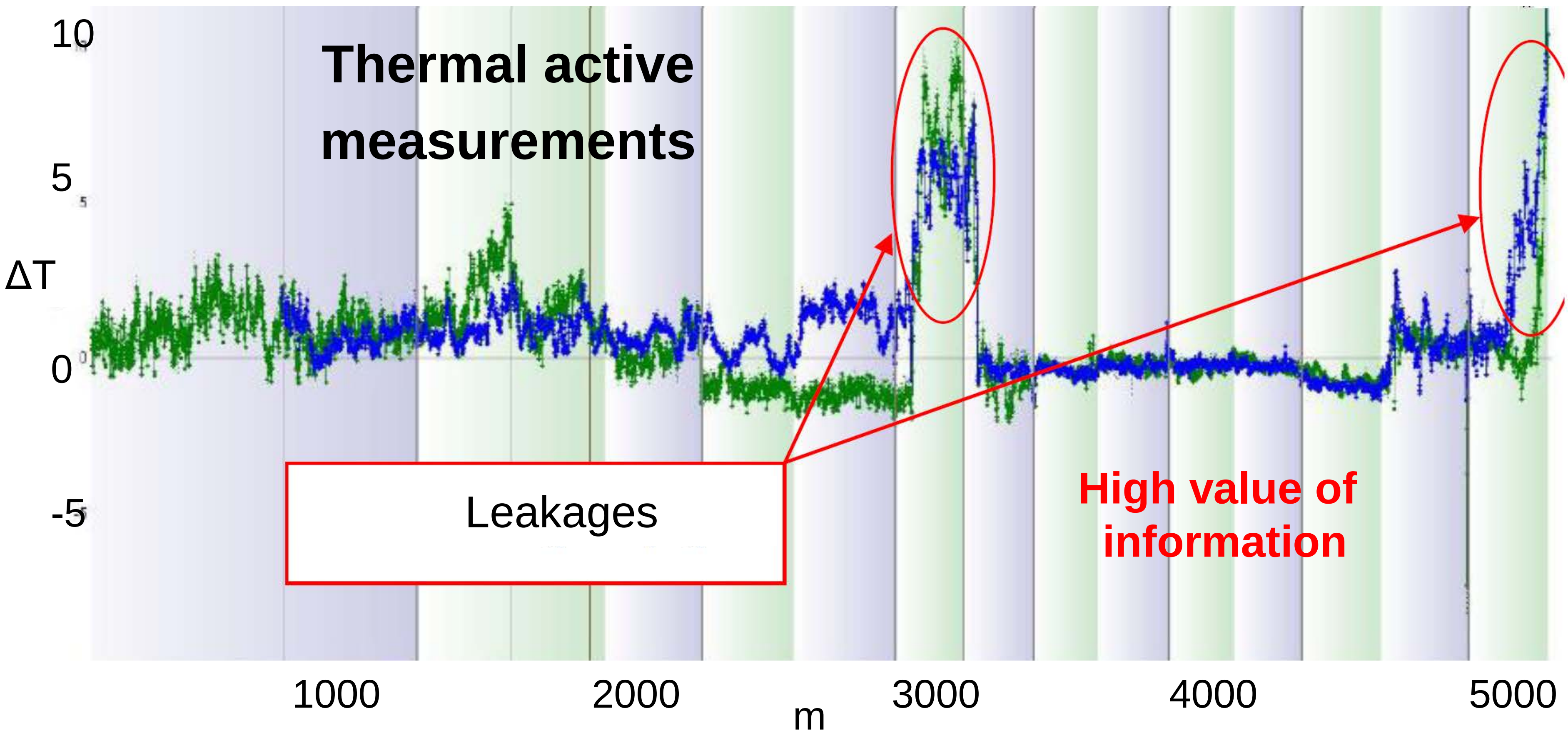




Courivaud et all. (2013)

Examples of applications

DIKE OF CURBAN CANAL OF DURANCE RIVER



Courivaud et all. (2013)

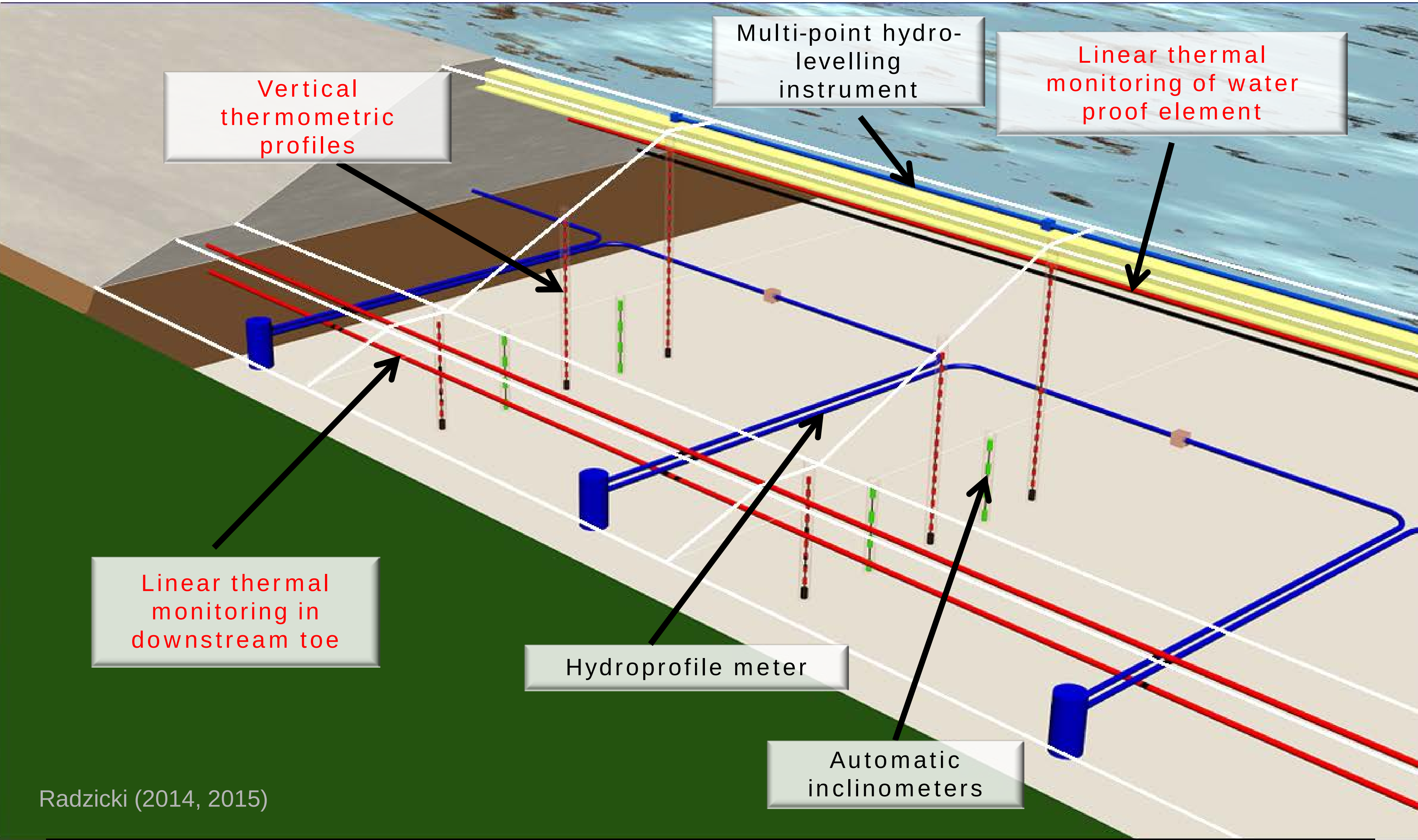
Examples of applications

RIGHT LEVEE OF RHINE RIVER

- 38 km of fiber optic

Courivaud et all. (2014)

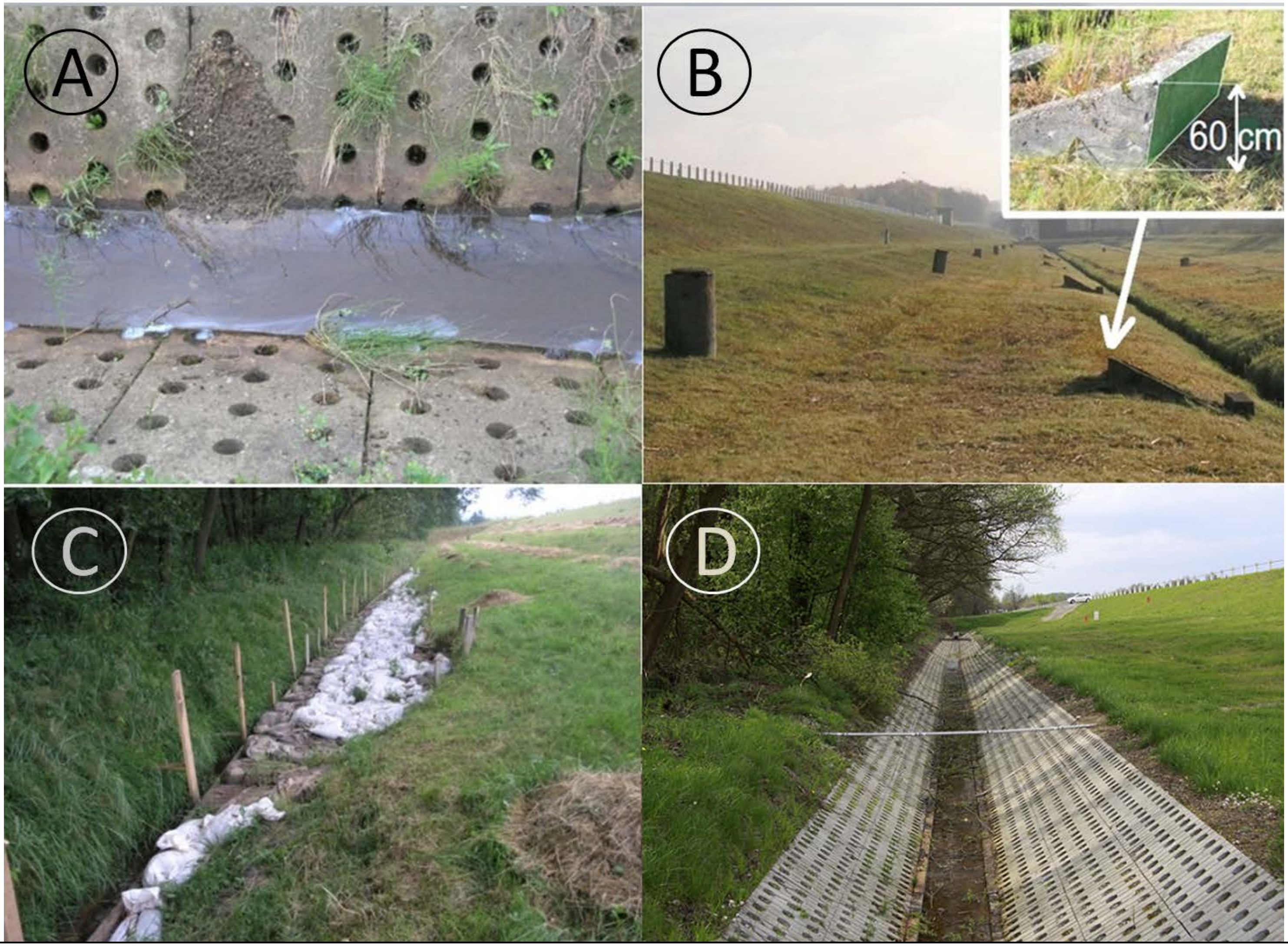
Quasi 3D thermal monitoring and displacements monitoring



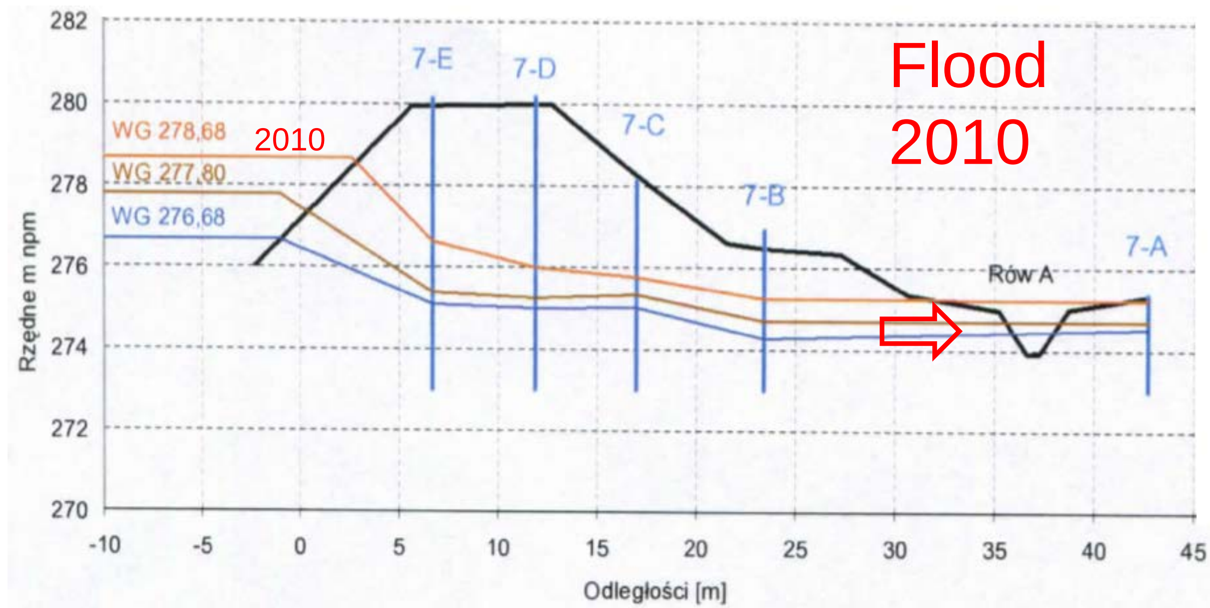
Radzicki (2014, 2015)

Kozłowa Góra dam

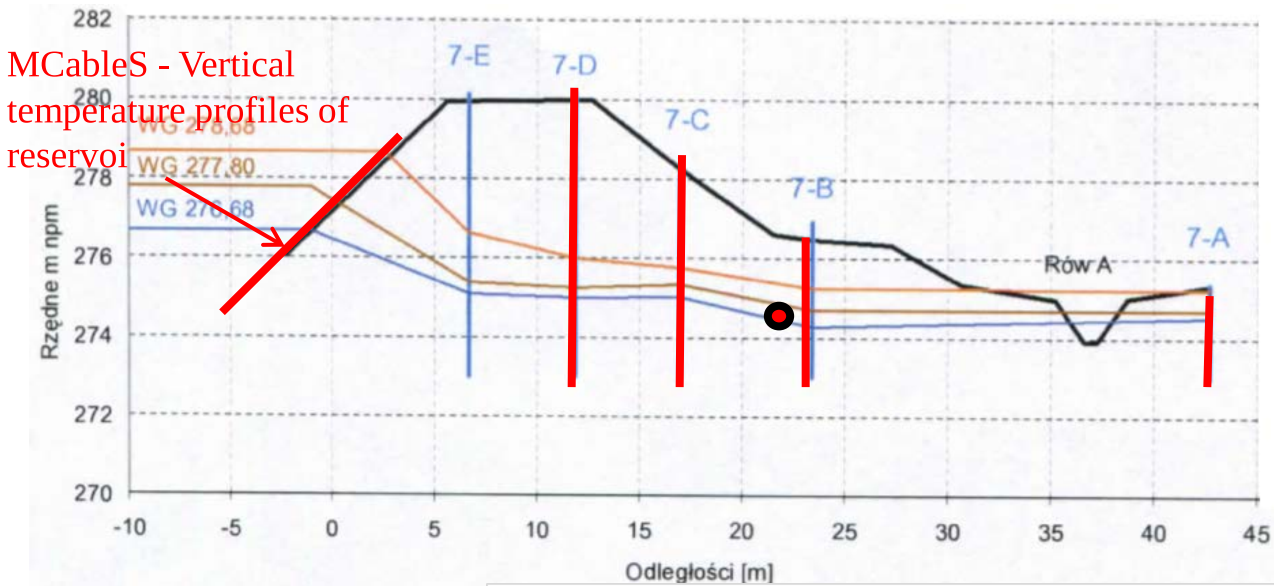
Kozłowa Góra dam



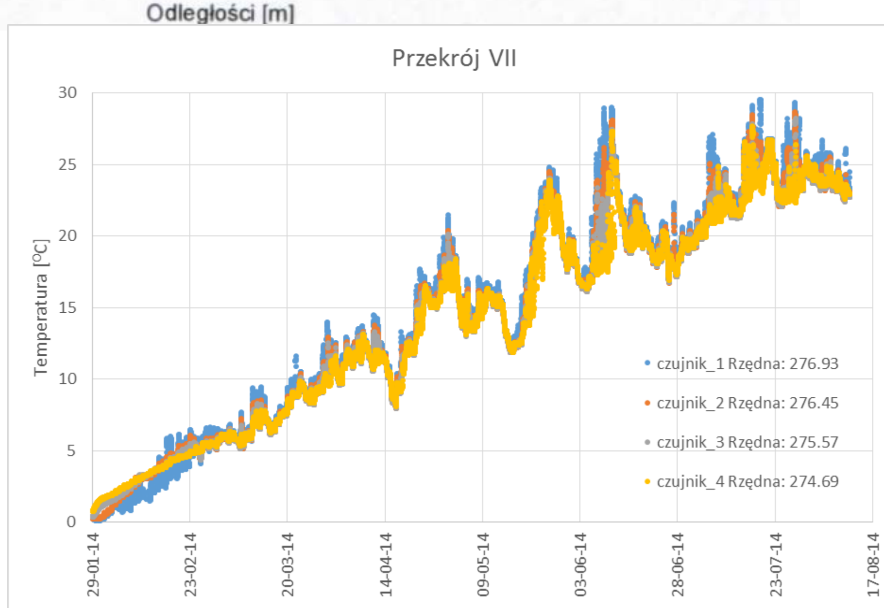
Kozłowa Góra dam – flood 2010



Kozłowa Góra dam



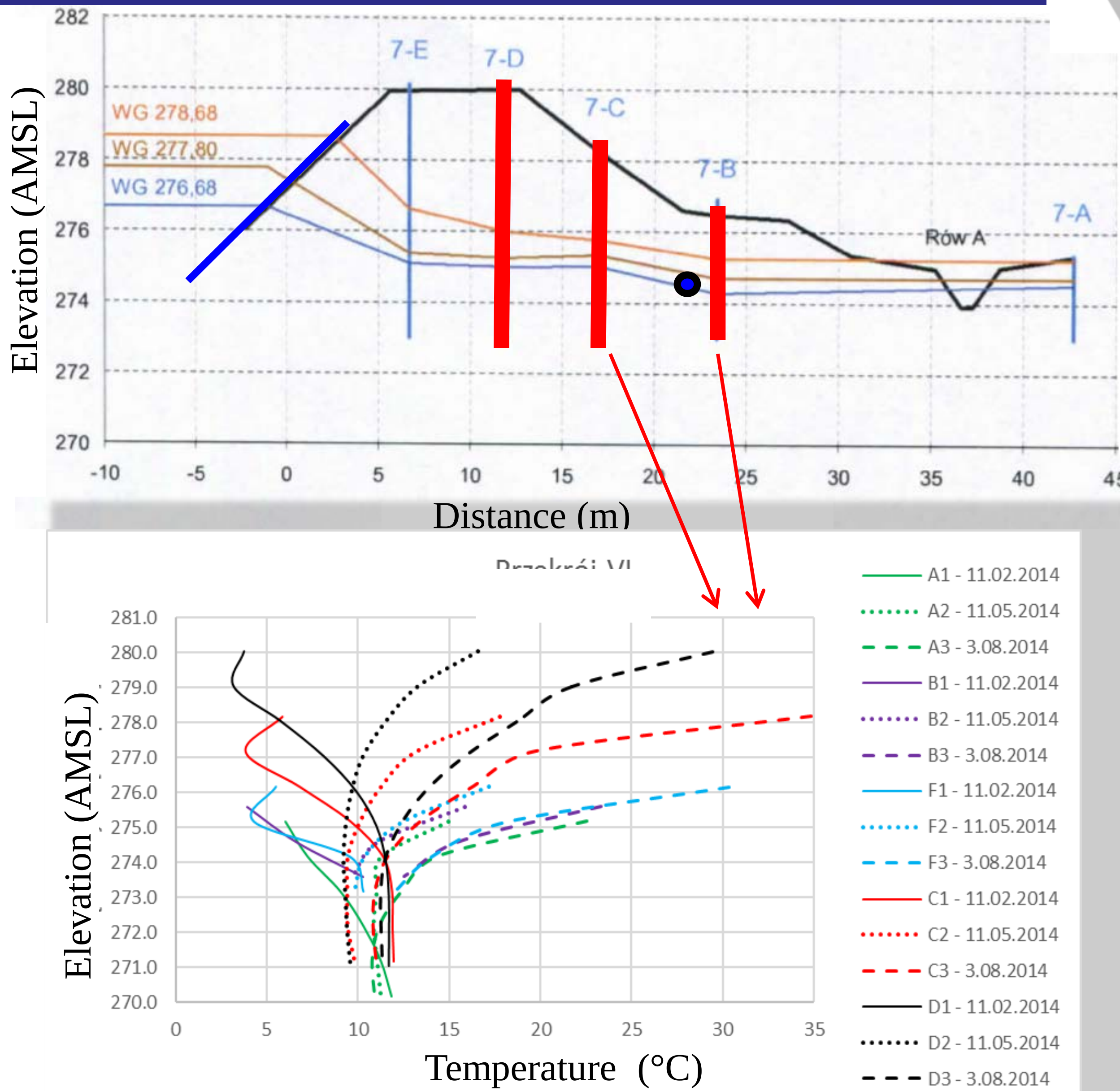
Cracow University of Technology & Irstea



Kozłowa Góra dam

MCableS

Measurements of vertical temperature profiles in the dam body in existing piezometres

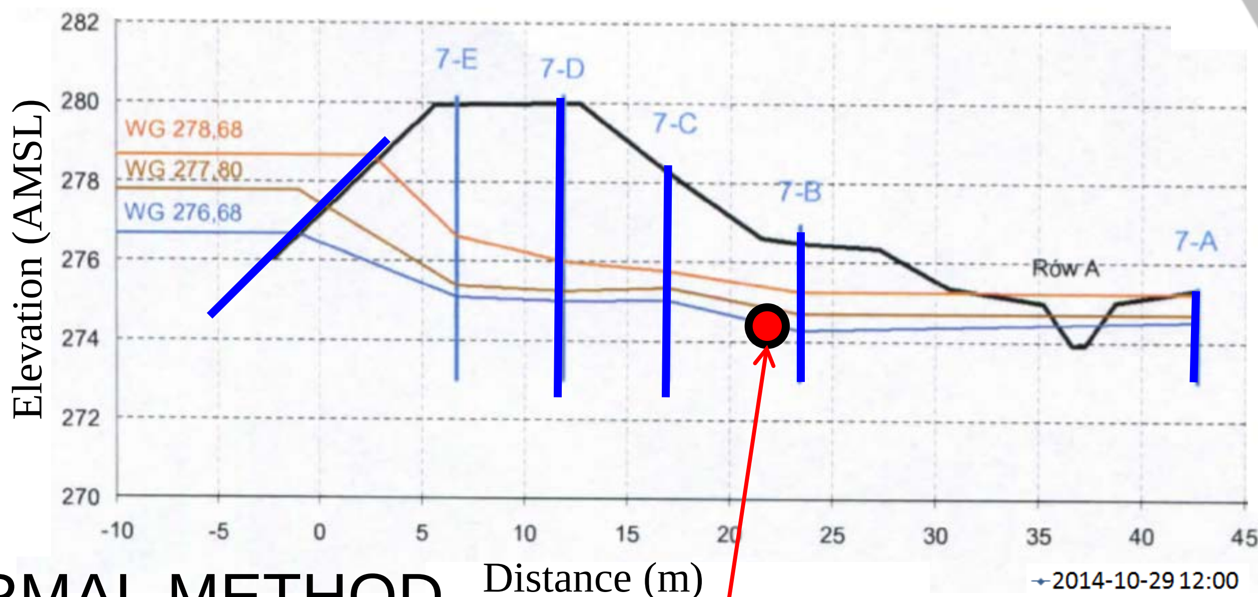


PASSIVE THERMAL METHOD

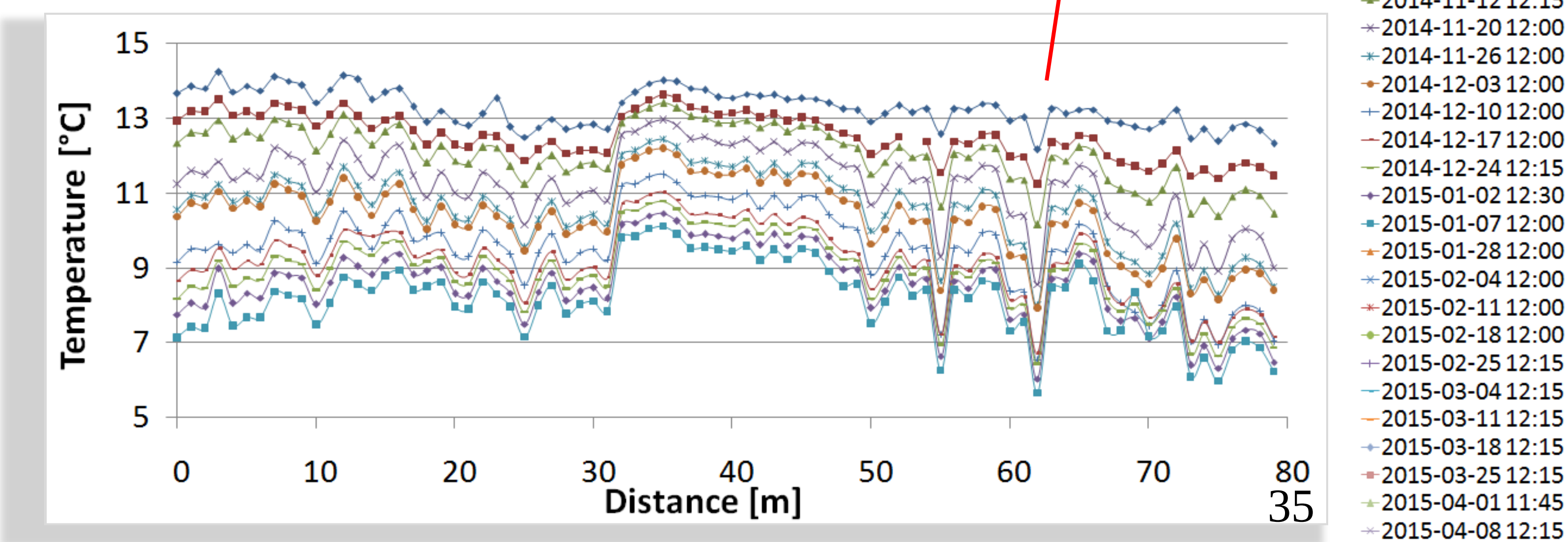
Kozłowa Góra dam

MPointS

QUASI LINEAR PASSIVE temperature measurements along the dam in the downstream toe

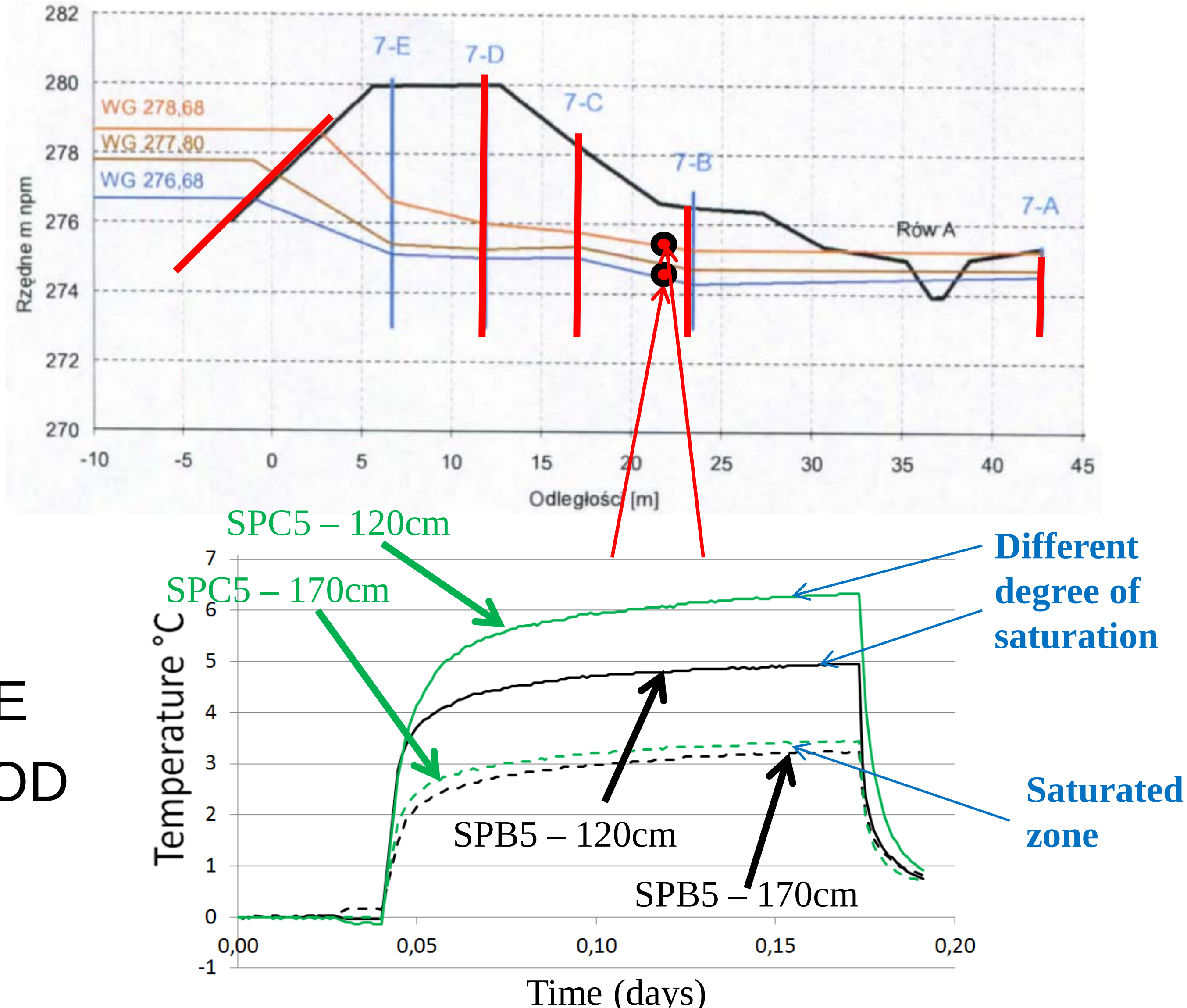


PASSIVE THERMAL METHOD

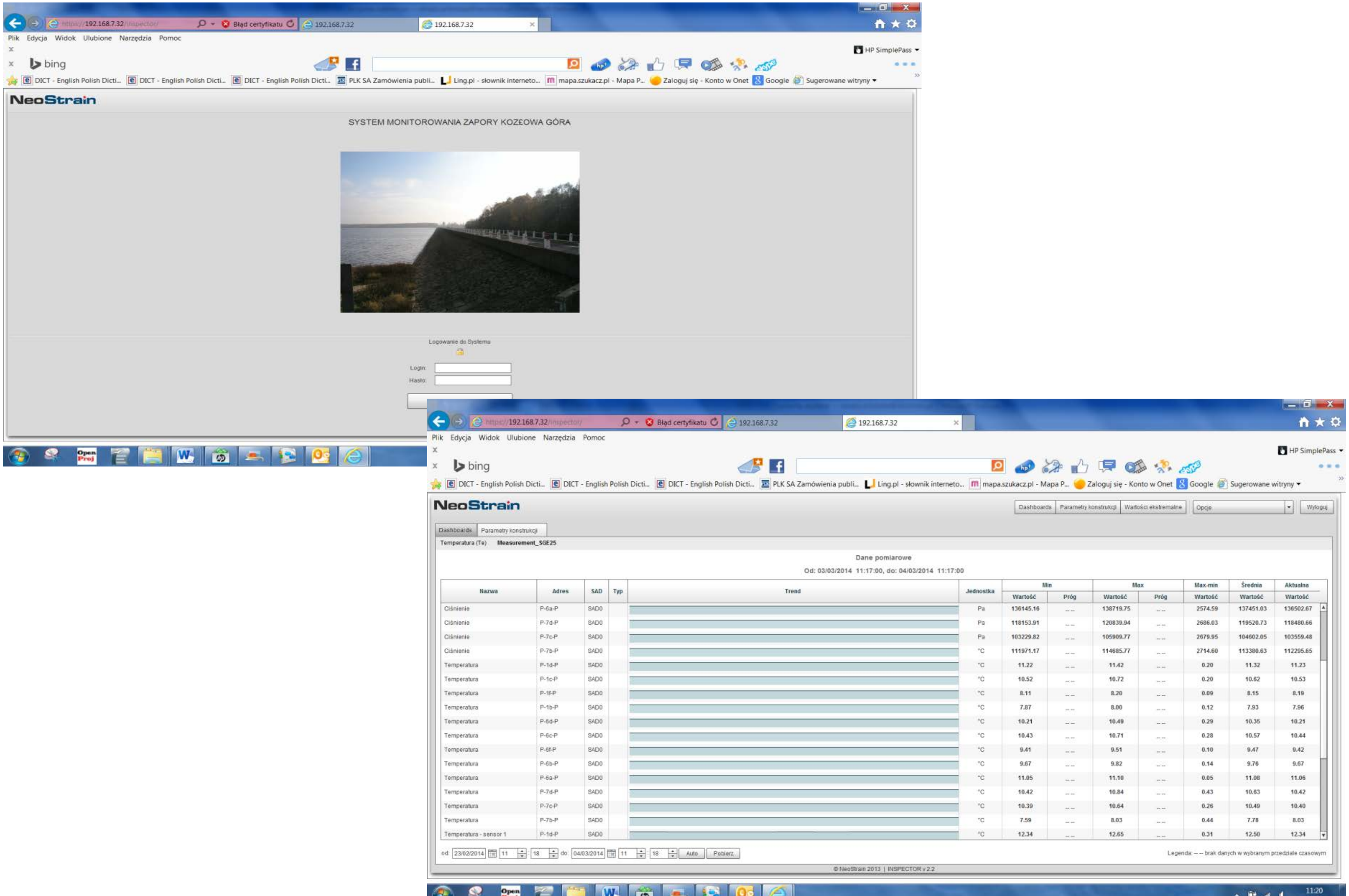


Kozłowa Góra dam

ACTIVE METHOD



Kozłowa Góra dam



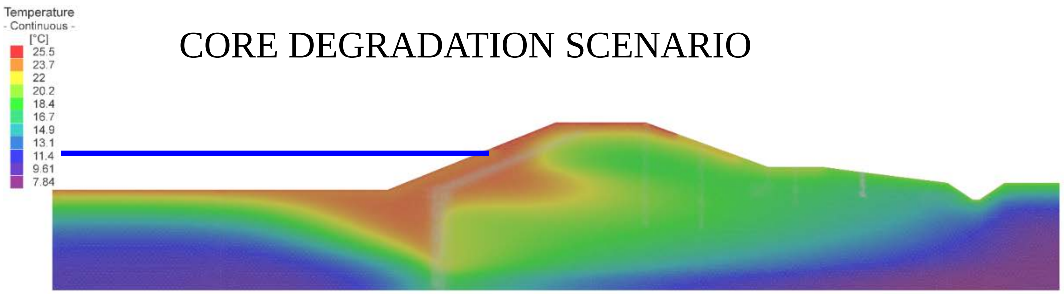
GÓRNOŚLĄSKIE PRZEDSIĘBIORSTWO WODOCIĄGÓW SPÓŁKA AKCYJNA

NeoStrain Therm3Detect®

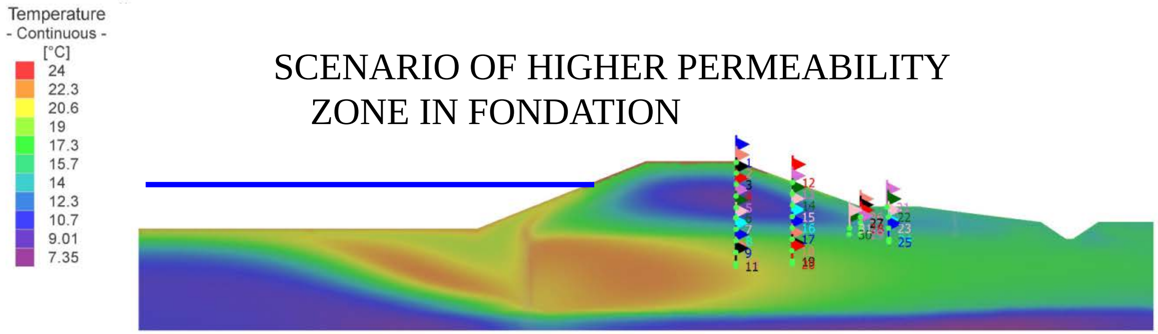
Kozłowa Góra dam – NUMERICAL MODELLING

Intermediate results of research carried out by:
K.Radzicki
P.Opaliński
S.Bonelli

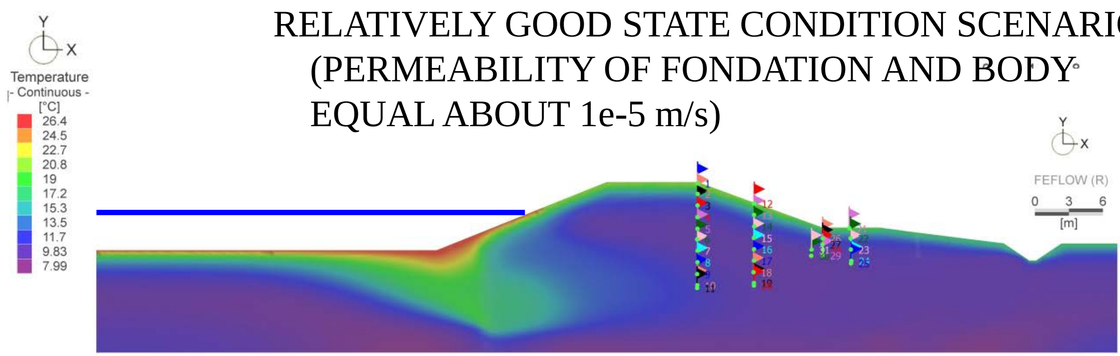
CORE DEGRADATION SCENARIO



SCENARIO OF HIGHER PERMEABILITY ZONE IN FONDATION



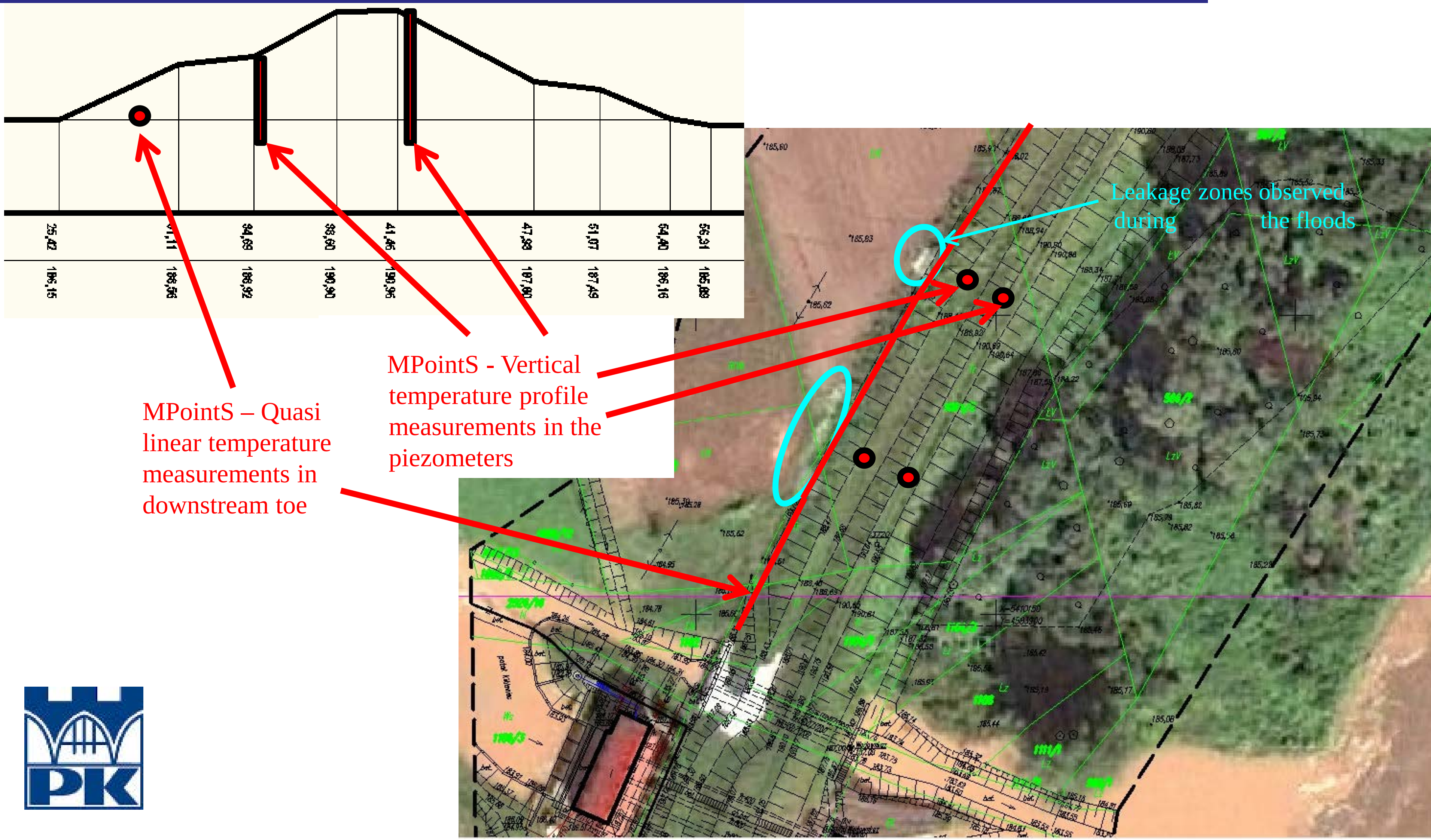
RELATIVELY GOOD STATE CONDITION SCENARIO (PERMEABILITY OF FONDATION AND BODY EQUAL ABOUT 1e-5 m/s)



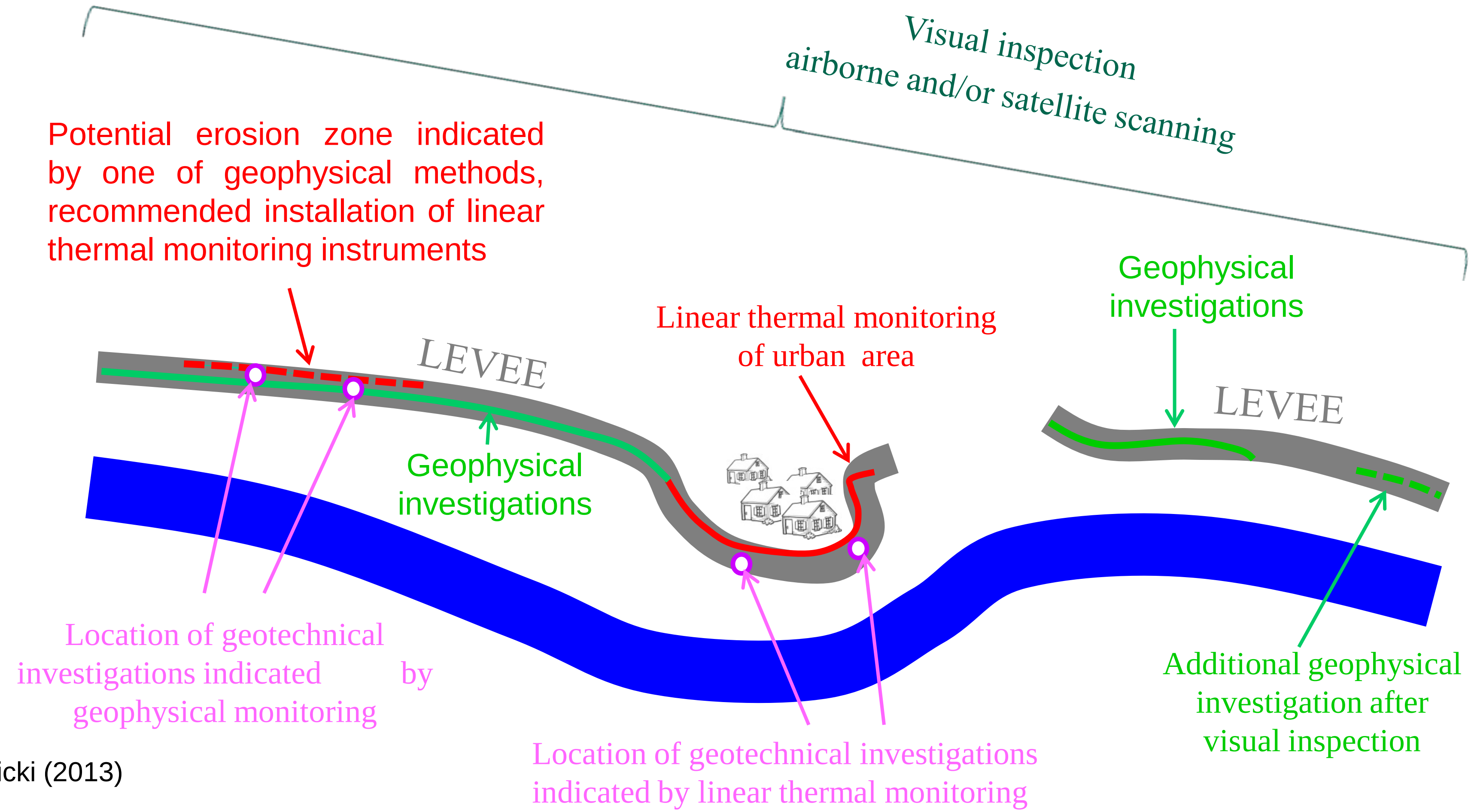
This scenario reproduce with a good accuracy the real temperature measurements carried out in the body and the foundation of dam

High value of information, low cost of the solution

The first levee in Poland instrumented in thermal monitoring system including linear thermal monitoring – 2016



Example of methodology of levees state assessment



Radzicki (2013)

KEY FEATURES OF THERMAL MONITORING METHOD

- MONITORING OF LEAKAGES AND INTERNAL EROSION PROCESSES IS CONTINOUS ALONG DAMMING CONSTRUCTION
- EARLY DETECTION OF LEAKAGES AND INTERNAL EROSION PROCESSES
- IT ALLOWS TO EVALUATE DYNAMIC OF THE PROCESSE AND SPATIAL DYSTRIBUTION OF LEAKAGES AND INTERNAL EROSION PROCESSES
- POSSIBILITY OF AUTOMATIC DETECTION OF LEAKAGE AND THE RISK OF EROSION

APPLICATION RESULTS OF THERMAL MONITORING

- MINIMIZATION OF THE FAILURE PROBABILITY DUE TO THE DEVELOPMENT OF INTERNAL EROSION (PIPING ESPECIALLY) AND/OR LEAKAGE
- MINIMIZATION OF THE SCOPE AND COSTS OF RENOVATION THROUGH ACCURATE DIAGNOSIS AND RELIABLE ASSESEMENT OF DYNAMIC AND SPATIAL DYSTRIBUTION OF LEAKAGES AND INTERNAL EROSION PROCESSES

Thank you for your attention

Krzysztof Radzicki Ph.D Eng
radzicki@hotmail.fr tel. +48 694 443 923