ROZWÓJ METODY TERMOMONITORINGU PROCESÓW FILTRACYJNO-EROZYJNYCH W WAŁACH i ZAPORACH

DEVELOPMENT OF THERMAL METHOD OF DETECTION AND ANALYSIS OF LEAKAGES AND INTERNAL EROSION IN LEVEES AND DAMS

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### Why Internal Erosion Detection and Monitoring Are Important?

Statistics of dams and levees collapses due to internal erosion

<table>
<thead>
<tr>
<th>Type</th>
<th>Failures</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth dams (World, of several years)</td>
<td>46%</td>
<td>Foster, 2000</td>
</tr>
<tr>
<td>Flood protection dikes / levees (Poland, flood 2010r)</td>
<td>30%</td>
<td>Kledyński et al., 2012</td>
</tr>
</tbody>
</table>

Collapse of dike in Cracow during flood of Vistula river in 2010

- The failure occurred at night
- No recent signs of danger
WHY INTERNAL EROSION DETECTION AND MONITORING ARE IMPORTANT?

**SUFFUSION**

Risk of piping

**CONTACT EROSION**

**BACKWARD EROSION**

High risk of piping

**CONCENTRATED LEAKS**

1976, 100m high Teton dam collapse
Visual inspections, spot geotechnical studies, classical 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 LEVEES

- The necessity to minimize the probability of disaster of dikes protecting valuable areas particularly urban and industrial ones
- 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 monitoring and automatic detection of internal erosion threats during flood defence
- 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

One of the PRINCIPAL PROBLEM is RELIABLE LEVEE FOUNDATION MONITORING AND CONDITION ASSESSMENT
BASIC CONCLUSION FOR DESTRUCTION PROCESS DETECTION AND MONITORING FOR DAMS, LEVEES AND GEOTECHNICAL ENGINEERING APPLICATION

SOME OF THE MAIN PROCESSUS / PARAMETERS THAT SHOULD BE MONITORED

- Leakages and Seepage
- Internal Erosion
- Displacements

PRINCIPALES PROBLEM WITH MONITORING

- Large scale of the structures limits the range of application of monitoring technologies
- Cost

NEW IDEAS FOR MONITORING METHODS AND TECHNOLOGIES AND FOR THEIRS APPLICATION METHODOLOGY
1) Identification and analysis of characteristic features of thermo-hydraulic influence of internal erosion
2) Development of innovative temperature measurements instruments
3) Development of data analysis methods
4) Development of methodology of thermal method application
5) Development of methodology of complex, multi-methods destructive processes investigations, monitoring and condition assessment
INTRODUCTION TO THERMAL METHOD

DIFFUSION-ADVECTION EQUATION

\[ C_\Theta \frac{\partial T}{\partial t} + C_f \bar{q} \frac{\partial T}{\partial x} - \lambda_\Theta \frac{\partial^2 T}{\partial x^2} = 0 \]

SYSTEM NONDIMENTIONAL

\[ \bar{q} = \text{const.} \]

\[ \bar{x} = \frac{x}{L} \quad \bar{t} = t \frac{L^2}{D_\Theta} \quad D_\Theta = \frac{\lambda_\Theta}{C_\Theta} \]

\[ \frac{\partial T}{\partial \bar{t}} + P e \frac{\partial T}{\partial \bar{x}} - \frac{\partial T}{\partial \bar{x}^2} = 0 \]

Peclet number

\[ P e = \frac{\text{advection}}{\text{conduction}} = \frac{C_\Theta \bar{q} L}{\lambda_\Theta} \]

Conduction domination \quad Advection domination

\[ P e < 1 \quad P e > 1 \]
INTRODUCTION
ACTIVE AND PASSIVE THERMAL METHOD

PASSIVE METHOD
Natural temperatures measurements

ACTIVE METHOD
Heat emission measurements

Schematic extent of the leak detection zone for spot measurements
IDENTIFICATION AND ANALYSIS OF CHARACTERISTIC FEATURES OF THERMO-HYDRAULIC INFLUENCE OF INTERNAL EROSION
IDENTIFICATION OF RELATIONS BETWEEN DIMENSIONS OF PIPING / BACKWARD EROSION PROCESS DEVELOPMENT AND ITS INFLUENCE ON HYDRO-THERMAL FIELD OF SOIL

Example of pipe influence:

on water velocity field

on temperature field

Radzicki and Bonelli (2009)
Examples of some results:

External thermal influence of pipe in relation to its length and radius

Adimensional temperature differences in the pipe outlet flow versus adimensional length of the pipe for different radius of the pipe

Principal effects of piping hydro-thermal influence were defined

One of the most important conclusions: There is a possibility to estimate the length of pipe by analysis of temperature measurements of water at outlet of the pipe

Results presented e.g. in: # 2009, Radzicki & Bonelli, Evaluation of piping erosion by means of temperature analysis, Studia Geotechnica et Mechanica, # 2009, Radzicki, PhD rapport, Analyse retard des mesures de températures dans les digues avec application à la détection de fuite # 2010, Radzicki K., Bonelli S., (2010). Proceedings Of the 8th Icold European Club Symposium Dam Safety, A Possibility to Identify Piping Erosion In Earth Hydraulic Works Using Thermal Monitoring
Examples of some results:

A) Dam without suffusion

B) The hydraulic conductivity of the suffusion layer $K=1e^{-4}$ m s$^{-1}$; Suffusion layer developed to the half of the cross-section

C) The hydraulic conductivity of the suffusion layer $K=1e^{-3}$ m s$^{-1}$; Suffusion layer developed to the half of the cross-section

D) The hydraulic conductivity of the suffusion layer $K=1e^{-4}$ m s$^{-1}$; Suffusion layer crosses all the cross-section length

E) The hydraulic conductivity of the suffusion layer $K=1e^{-3}$ m s$^{-1}$; Suffusion layer crosses all the cross-section length

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.

Principal effects of suffosion hydro-thermal influence were defined.

Some results are presented e.g. in paper:

# 2012, Radzicki & Bonelli, Monitoring of the suffusion process development using thermal analysis performed with IRFTA model, International Conference on Scour and Erosion
DEVELOPMENT OF INNOVATIVE MEASUREMENTS INSTRUMENTS - quasi LINEAR TEMPERATURE SENSORS
SOME REFERENCES TO THERMAL METHOD

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.>

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.>
METHODS OF TEMPERATURE MEASUREMENTS

Linear temperature measurements sensors are crucial for thermal monitoring methods. Continuous measurements all along the structure brought about a quality change in the monitoring of seepage, leakages and erosion processes compared with the point monitoring carried out only at selected places of the structure.

*Temperature perturbations caused by leak*

*Vertical temperature profile measurements (including temperature measurements in piezometers)*
DFOT (Distributed Fibre Optic Temperature) SENSING

Fiber optic temperature sensing:
- Spatial resolution 1m
- Resolution ± 0.1°C
- Measurement distance - up to 30km with one fiber optic cable

Spectral analysis of backscattered light
PROBLEMS WITH INSTALLATION OF DFOT SYSTEMS

COST OF APPLICATION
- Cost of fiber optic cable installation (particularly if earth works are required)
- Costly technology for short distances of measurements due to relatively high cost of sensing unit (DTS unit)

SAFETY PROBLEMS
- Earthworks affect body or foundation of the structure. They must be carried out very carefully. There is a risk of creation of preferential seepage paths by these works
- In the case of high water level in the body of earth damming structure the risk of piping appearance due to affection the soil by installation of fiber optic cable can be very high

OTHER PROBLEMS
- Permission of earthworks usually is necessary
- There must be an access for vehicle along the structure (problem particularly for levees)
- Limited depth for foundation monitoring

IN CONSEQUENCE: DFOT is recommended to be installed on new dams or levees or during their renovations, for their long sections (more than some hundreds meters), where cost of earthworks is already included

DFOT system is not optimal for temporal (up to several years), short distance (up to some hundreds meters) monitoring, particularly in the cases where urgent investigation is necessary or for the problem of deep (more than 2m) foundation investigation?
These are typical problems for the case of levee investigation or monitoring

Presented problems and conclusions were described e.g. in paper: 2015, Radzicki K., Siudy A., Stoliński M., An innovative 3D system for thermal monitoring of seepage and erosion processes and an example of its use for upgrading the monitoring system at the Kozłowa Góra dam in Poland, Q. 99 – R. 7, 25th International Congress on Large Dams,
**MPointS - INNOVATIVE LINEAR TEMPERATURE SENSOR**

**Multi POINTS Sensor (MPointS)** is linear thermal passive and active sensor for quasi continuous detection and monitoring of leakages and internal erosion.

MPointS is mounted without an excavation by inserting successive thermal sensors in a series, one after another, from the surface of terrain (for example from the crest of the berm).

MPointS can be fast and easily installed longitudinally or/and vertically in the foundation or/and body of damming structure to create linear or multidimensional monitoring system.

MPointS is much more cheaper, faster and easier to install monitoring solution than fiber optics technology particularly for the section of existing levee up to some hundreds meters or/and for deep foundation investigation.

MPointS technology was described e.g. in papers: 2015, Radzicki K., Siudy A., Stoliński M., An innovative 3D system for thermal monitoring of seepage and erosion processes and an example of its use for upgrading the monitoring system at the Kozłowa Góra dam in Poland, Q. 99 – R. 7, 25th International Congress on Large Dams, 2015, Radzicki K., The concept of quasi-3d monitoring of seepage and erosion processes and deformations in dams and dikes, considering in particular linear measurement sensors, Technical Transactions.
**MPointS – hybrid passive and active thermal leakage detection**

MPointS technology allows to use both passive and active thermal method due to integration of temperature sensors with microheaters.

**PASSIVE METHOD**
- Natural temperatures measurements

**ACTIVE METHOD**
- Heat emission measurements

Example of leakage detection with active thermal MPointS technology
INNOVATIVE QUASI-LINEAR TEMPERATURE SENSOR

**MCableS**

*Multipoint Cable Sensor to use for passive or/and active quasi continuous thermal monitoring*

MCableS is a cable inside which single temperature sensors and communication and supply cables have been placed and integrated. The main advantage of this solution for short measurement sections of up to several hundred meters is its cost which is even several times lower than that of a fibre optic-based thermal monitoring system.

MCables can be applied in water temperature measurements in piezometers. Given its small diameter, a “multi sensor cable” does not prevent manual periodic measurements in a piezometer, which are more often than not required for dams in order to verify automatic pressure measurements.

MCables technology was described e.g. in papers: 2015, Radzicki K., Siudy A., Stoliński M., An innovative 3D system for thermal monitoring of seepage and erosion processes and an example of its use for upgrading the monitoring system at the Kozłowa Góra dam in Poland, Q. 99 – R. 7, 25th International Congress on Large Dams, 2015, Radzicki K., The concept of quasi-3d monitoring of seepage and erosion processes and deformations in dams and dikes, considering in particular linear measurement sensors, Technical Transactions.
2017 - First MPointS installation in Poland for levee monitoring
Second MPointS system will be installed in the beginning of 2018

MPointS – longitudinal, linear measurements of temperatures along the downstream toe in body and in foundation of levee

Leakage zones observed during the flood

MPointS - vertical temperature profile measurements
DEVELOPMENT OF QUASI 3D MONITORING DEFINITION AND METHODOLOGY INCLUDING LINEAR OR QUASI LINEAR SENSORS
Conception of quasi 3D thermal monitoring and displacement monitoring proposed e.g. for the largest, planned Polish dam, Racibórz dam
MPointS – Linear or multi-dimensional monitoring of body and foundation

Longitudinal monitoring of body and foundation

Cross-sectional monitoring of body and foundation

Conception of quasi-3D monitoring in hydraulic engineering and geotechnics is presented in the paper:

2015, The concept of quasi-3D monitoring of seepage and erosion processes and deformations in dams and dikes, considering in particular linear measurement sensors, Technical Transactions. Environment Engineering = CZASOPISMO TECHNICZNE. Środowisko, 2-Ś/2015, s. 129-139

2015, Krzysztof Radzicki, Innowacyjne, instrumentalne systemy pomiarowe quasi 3D monitoringu procesów filtracyjno-erozyjnych oraz odkształceń w zaporach i wałach, MATERIAŁY CERAMICZNE /CERAMIC MATERIALS/, vol.67, no1, 81-87,
QUASI 3D MONITORING SYSTEM ON KOZŁOWA GÓRA DAM
QUASI 3D MONITORING SYSTEM ON KOZŁOWA GÓRA DAM
QUASI 3D MONITORING SYSTEM ON KOZŁOWA GÓRA DAM

Flood in 2010
QUASI 3D MONITORING SYSTEM ON KOZŁOWA GÓRA DAM

**MCableS**
Measurements of vertical temperature profiles in the dam body in existing piezometers

**PASSIVE THERMAL METHOD**
QUASI 3D MONITORING SYSTEM ON KOZŁOWA GÓRA DAM

**MPPointS**

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

PASSIVE THERMAL METHOD
VERIFICATION AND DEVELOPMENT OF NEW OR EXISTING METHODS OF DATA ANALYSIS
NUMERICAL MODELLING OF DATA FROM KOZŁOWA GÓRA

High value of information, low cost of the solution

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

We proved that thermal method allows for very precise investigation of seepage and internal erosion. Only thermal method allowed in cost-effective way to investigate a foundation of Kozłowa Góra dam

Results are presented e.g. in:
# 2017, Radzicki K., Termomonitoring procesów filtracyjno-erozyjnych w zaporach i wałach przeciwpowodziowych, Gospodarka Wodna
# 2018, Radzicki K., Opaliński P, Bonelli S., Investigation of leakages and internal erosion at Kozłowa Góra dam using thermal method and HST model, ICOLD congress, accepted paper
DEVELOPMENT OF IRFTA (Impulse Response Function Thermal Analysis) MODEL

SOLUTION OF LINEAR PROBLEM WITH THE GREEN'S FUNCTION

Impulse response function to the air temperature influence

\[ T(x, t) = \theta_0(x) + h_{\text{air}}(x, t) * \theta_{\text{air}}(t) + h_w(x, t) * \theta_w(t) \]

Air temperature

Convolution product

\[ h(x, t) * \theta(t) = \int_0^t h(t - t') \theta(t') dt' = \int_0^t h(t') \theta(t - t') dt' \]

Water temperature

Simplest exponential approximation of the impulse response function

\[ h_i(t) = F_i(\alpha_i, \eta_i, t) \]

- damping factor
- characteristic time of the delayed system response

MODEL IRFTA (Impulse response function thermal analysis)

\[ \hat{T}(x, t) = \theta_0(x) + F_{\text{air}}(\alpha_{\text{air}}, \eta_{\text{air}}, t) * \theta_{\text{air}}(t) + F_w(\alpha_w, \eta_w, t) * \theta_w(t) \]
DEVELOPMENT OF IRFTA (Impulse Response Function Thermal Analysis) MODEL

System

Model

\[
\theta_{\text{air}} \quad \theta_{\text{w}}
\]

\[
\alpha_{1\text{air}}, \eta_{1\text{air}}, \alpha_{1\text{w}}, \eta_{1\text{w}}, R_1^2 \quad \alpha_{2\text{air}}, \eta_{2\text{air}}, \alpha_{2\text{w}}, \eta_{2\text{w}}, R_2^2
\]

Coefficient of determination

Damping factor

Time of delayed response

\[
R^2 \sim 1
\]

\[
\alpha_{\text{air}}, \eta_{\text{air}} \quad \alpha_{\text{w}}, \eta_{\text{w}}
\]

Damping factor

Time of delayed response
DEVELOPMENT OF
IRFTA (Impulse Response Function Thermal Analysis) MODEL

Very successful application of IRFTA model for thermal leakage detection and analysis of seepage process on French damming structures. E.g. we proved e.g. that even, only changes of moisture of soil (without water flow) is enough to detect a leakage by IRFTA model using sensors located in downstream toe of structure.

Results presented e.g. in:
• 2009, Radzicki, PhD rapport, Analyse retard des mesures de températures dans les digues avec application à la détection de fuites.

PEERINE experimental basin

Zones of artificial leaks

dike of canal of EDF
DEVELOPMENT OF THERMAL METHOD APPLICATION METHODOLOGY AND MULTI-METHODS APPLICATIONS METHODOLOGY
COMPLEX METHODOLOGY OF MULTI-METHODS APPLICATIONS FOR LEVEES INVESTIGATIONS, MONITORING AND CONDITION ASSESSMENT

Potential erosion zone indicated by one of geophysical methods, recommended installation of linear thermal monitoring instruments.

Linear thermal monitoring of urban area indicated by linear thermal monitoring.

Location of geotechnical investigations indicated by geophysical investigation.

Location of geotechnical investigations indicated by linear thermal monitoring.

Geophysical investigations.

Visual inspection, airborne and/or satellite scanning.

Additional geophysical investigation after visual inspection.

Concept is presented e.g. in paper:

# 2014, Radzicki K., (2014). The important issues of levees monitoring with special attention to thermal-monitoring method application, South Baltic Conference on New Technologies and Recent Developments in Flood Protection.
Thank you for your attention

Dziękuję za uwagę

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