Active and Passive Defences against Internal Erosion of Dikes

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Abstract

A reliable early localization and warning system for both gradual and catastrophic dam and dike failure is being developed. This monitoring system is based on the combination of geosynthetic functions, integrated fibre optic sensors and a related instrumentation to detect the first steps of internal erosion processes and hydraulic works instability. The detection of the leaks, early stage of the internal erosion process, is assessed through temperature changes measurement using the passive method without heating. The GeoDetect® system has been tested on several 1:1 scale experimental works and real dikes in-use. The results from 2 of them are very promising.

1 Improved Hydraulic Structure Safety

Owners of dams and dikes are managing a wide number of works with a large variety of ages and stages. The problem facing the dike owner today is to limit the impact of this aging phenomenon and the most serious task is to eliminate the risk of failure and repair costs. In the last decade a large number of dam and dike failures occurred, causing several hundreds of billions of Euros in damages.

For this purpose, a technical solution that detects and localizes malfunctions (erosion, blocking, breaches, sliding, settlements), which are the precursors of failure was developed.

2 Seepage Detection by Thermometry in Unsaturated Dikes

Fibre optic distributed measurements now make it possible to measure temperatures and deformations over lengths of up to 30 km (Selker, 2006). The two following methods are based on temperature measurements and are used for seepage detection (see chapter 6 of this document).

The active method (or heat-pulse method) is used for determining the saturation level and the rate of flow of the fluids in the structure with high accuracy (Perzlmaier, 2006). However, the use of this method implies the consumption of between 3 and 10 W/m power for seepage detection and the estimated seepage flow rate, respectively.

The passive method (or gradient method) also allows a seepage location to be detected and the flow to be measured, and without heating the fibre. But this method is based on the hypothesis that the fibre has to be in the groundwater and that the effect of the air temperature on it is negligible (Johansson, 1997).

There is a shortcoming in the case of the gradient method (because they are more economical or able to supply the necessary heating power) performed on dry dikes and also to take advantage of the reinforcement (refilling) works to instrument a structure. In this case, the fibre can be outside the groundwater and near the surface, with an influence of air temperature on that of the fibre, meaning a need for suitable analyses. For the instrumentation of a structure during reinforcement, the advantage of coupling a distributed measurement system with the geotextile used, as already done for deformation measurement in civil engineering structures, becomes obvious

3 The GeoDetect® system.

The purpose of the Eureka E!3361 SafeDike project is to develop a technical solution which is a practical answer to the problems of dike owners, who have to manage the risk of failure of their work, either due to internal erosion or due to overall instability.

Concerning internal erosion, the first defence level for a hydraulic work is the use of a filtration system which stabilizes the soil particles of the dike body. The purpose of the GeoDetect® system is to combine this first classical level made of a geotextile filter with a second monitoring level with optical fiber sensors increasing the global level of safety by early detection of leaks for instance.

GeoDetect® is a full system which includes both the hardware (product, sensors, instrumentation) and the related software based on the data analysis methodology described hereafter.

The partners of this project are: Cemagref, Cetmef, EDF, FOS&S, Grenoble University and TenCate Geosynthetics.

4 Associated Analysis Methods (of Outside Groundwater)

The principles

In theory, there are many environmental variables: Outside temperatures (air, water), radiative effects, wind, precipitation. When the fibre is placed in a saturated zone, the Johannson approach can be generalized by integrating these variables to detect and quantify a rate of seepage. Conversely, when the fibre is based in an unsaturated zone (outside the groundwater during normal operation), because of the influence of the hydric condition of the ground, evaluating a seepage rate is now an open question. However, we are going to demonstrate that detection is possible.

We have used two methods of analysis. The first (STa) is derived from the HST Thermic method (PENOT, 2003), developed to explain that the movement of arch dams under the effect of phenomena like hydrostatic effects, time and effects related to temperature. The STa model informs us that some physical parameters, especially the delay times of OF measurements compared to those made in the air, may be linked with the presence of seepage. When flow variations appear, statistical parameters like the residuals (differences between measurements and model) or the sum square errors (SSE) can also be seepage detection and quantification parameters.

The second method is the Impulse Response Function Analysis (IRFA). This model has been designed to simulate the pore pressures measured in and around dams, which are influenced by the reservoir and rainfall levels (Bonelli and Radzicki, 2007), or to simulate temperature measured in dams as a function of air and water temperature (Bonelli and Felix, 2001). This is a two-parameters analysis. The first parameter, α (dimensionless), characterizes the damping. The second parameter, η, is a characteristic diffusion time: the system has some memory of the previous values of the loading time series. The role of this parameter is given by harmonic analysis: if the input is $\sin(\omega t)$, the output will be $\alpha\sin(\omega(t-\eta))$, under slowly varying loading conditions ($(\omega\eta)^2 << 1$). The characteristic time η quantifies the time elapsing between the onset of the loading and the response.

5 Experimental Sites

5.1 Oraison

The Oraison canal was built between 1959 and 1962; its main characteristics are as follows:

- Maximum height on natural ground: 27 m – Length: 21,430 m
- Coating: Sealed of un-reinforced concrete (redone in asphalt concrete in some areas).
- Volume of materials: 5,400,000 m^3 excavation, 6,300,000 m^3 backfill
- Foundation land: Valensole pudding on the left bank and forming an embankment, Durance alluvial matter containing pudding lenses and marl passages with a high void index on the right bank

Figure 1: Aerial view of Oraison canal

- In 2002, the optical fibre was buried at the toe of the dike over a length of 2300 m upstream of the plant, and to a depth of 0.80 m.
- Over the first 1000 m, the optical fibre is in a low location at the foot of the dike near the counter canal. After 1000 m, the optical fibre is in a high location on the shoulder of the dike (**Figure 2**).

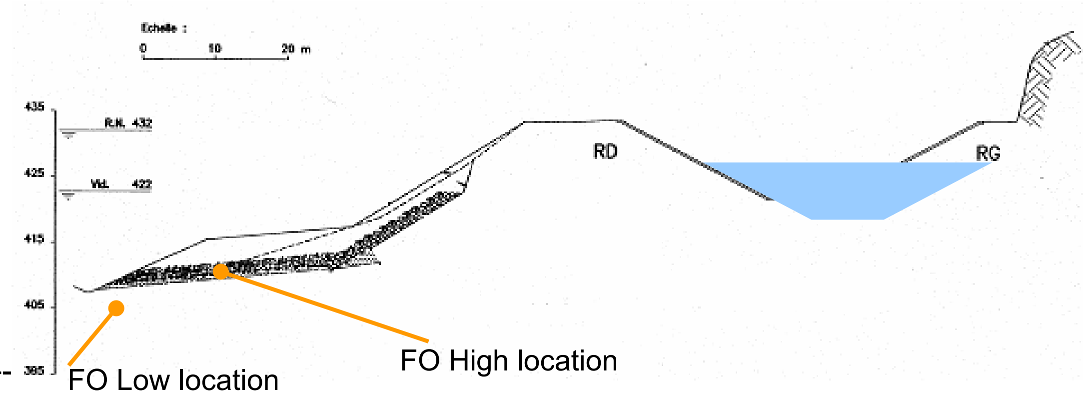


Figure 2: Sectional view of dike

5.2 Aix-en-Provence Experimental Basin

To test and validate the GeoDetect system, as well as other equipment and methods dedicated to detecting and quantifying leaks from a real structure, an experimental basin was built during the second quarter of 2006 on the Cemagref site in Aix-en-Provence, France (Guidoux, 2007).

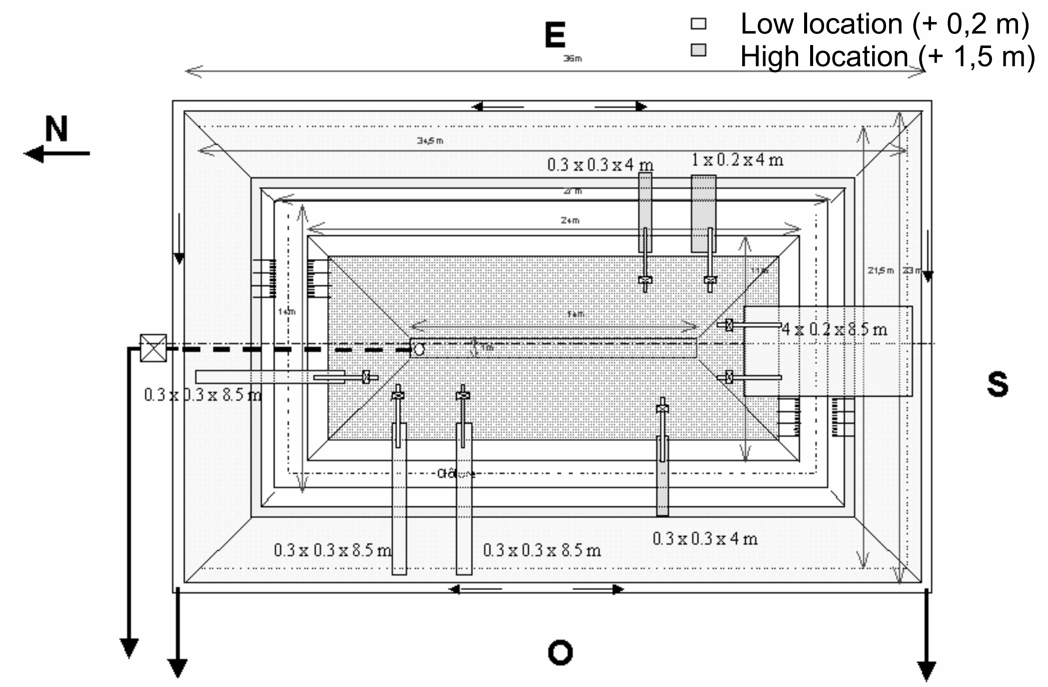


Figure 3: View of experimental basin

The main characteristics of the experimental basin (**Figure 3**) are as follows:

- Volume of materials: Approximately 1200 m^3 of clayey materials (permeability at saturation of 10^{-11} m/s) for the dikes, approximately 225 m^3 for refilling.
- Perimeter: 118 m at the foot, 78 m at the head.
- Coating: None (for the data investigated here; a geo-membrane was installed subsequently in December 2006)
- Approximate water volume: 200 m^3

Among the various materials, a device (associated with a geotextile) for measurements of temperature distributed along an optical fibre (OF) was tested. This device consists of an OF arranged on a geotextile having three levels (referred to as T2, M2 and B2, respectively for top, middle and bottom) along the downstream embankment. The geotextile and the OF retained by a refill (**Figure 4**).

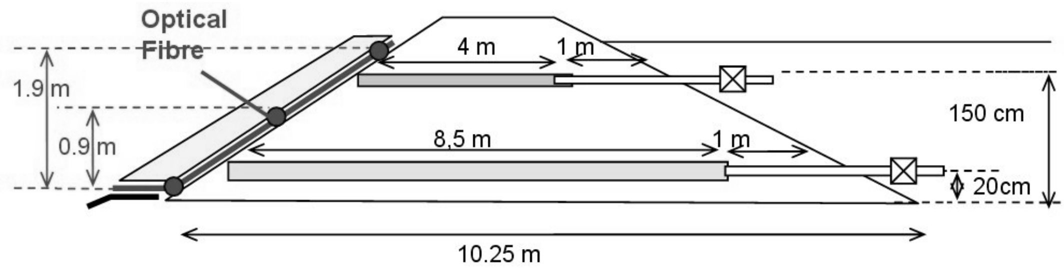


Figure 4: Sectional view of one face of basin

There are several devices situated at two different heights: Between OFs T2 and M2 and between OFs M2 and B2, fitted to the structure. These comprise geotextile envelopes filled with sand and connected on the upstream side by a PVC tube terminating in a valve designed for qualitative and quantitative control of seepage (**Figure 4**). This provides a maximum flow rate of approximately 10 l/min.

6 Results Obtained

6.1 Oraison: Case of Abrupt Leakage

From of the canal air and water temperature data, FE modeling was carried out to represent the temperature measured at the OF. This modeling reveals good correlation between the results of the model and the measured values (using the hypothesis of zero flow through the model). These simulations were reproduced for various flow rates (1, 10 and 100 l/min/m). The data analysis model was tested on these modeling results.

The first graph (**Figure 5**) illustrates a case without leakage and we see that the level of the residuals values is low (< 0.3 °C) and stable in the course of time.

The second graph (**Figure 6**) illustrates this case with the appearance of leakage of 1 l/min/m during the second year of measurement. We also see a definite increase in the residuals values (> 1.5°C).

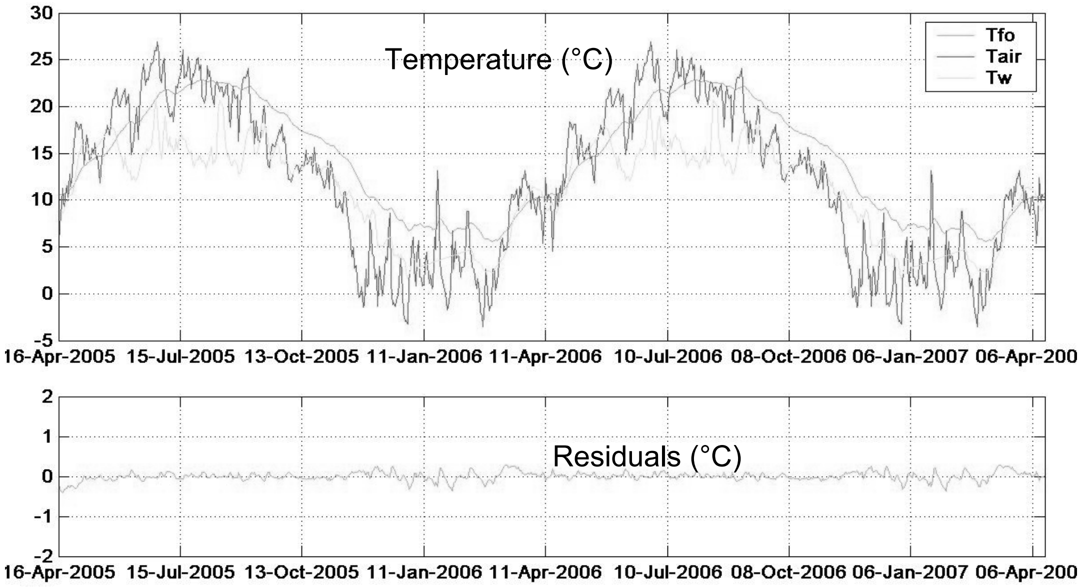


Figure 5: Results of modeling and analysis – Case without leakage

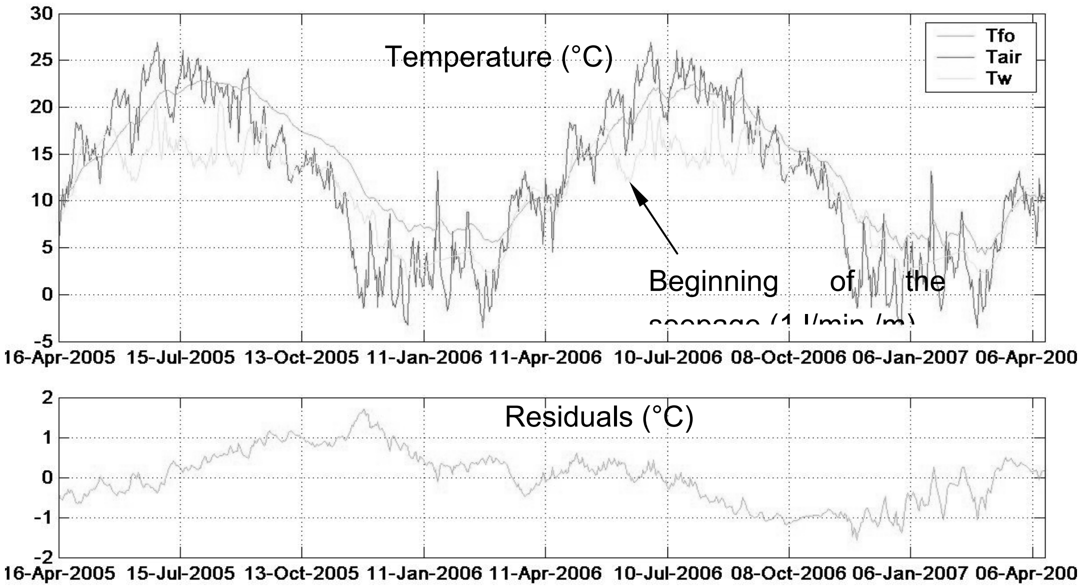


Figure 6: Results of modeling and analysis – Case with leakage

Similar tests were performed for flow rates of 10 l/min/m and 100 l/min/m. For each result, the sum square error (SSE) was calculated and we see that there is apparently a relationship between the SSE and the leakage flow rates (when a leak appears) (**Figure 7**).

$$SSE = \sum_{i=1}^{n} \varepsilon_i^{\,2} \quad (1)$$

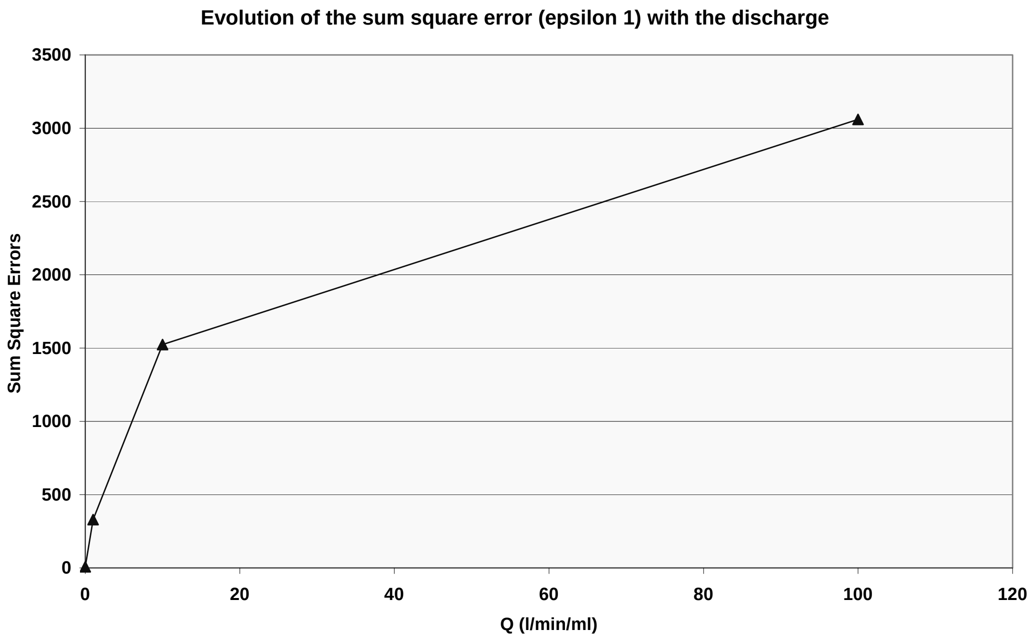


Figure 7: evolution of SSE according to leak flow rate

6.2 Aix-en-Provence Experimental Basin Diffuse Leaks

Experiments in the Aix-en-Provence basin, situated on the CEMAGREF site, made it possible to test the detection method on a real site.

We applied the method to the data measured on the West face between September and November of 2006 (**Figure 8**). There are three leakage devices on this face. The first is above OF M2 (leaks visible on OF M2 and B2 of figure 9) and the other two between the OFs M2 and B2.

Leak detection is possible from analysis of the residuals and the sum square error (SSE) (cf. **figure 9**).

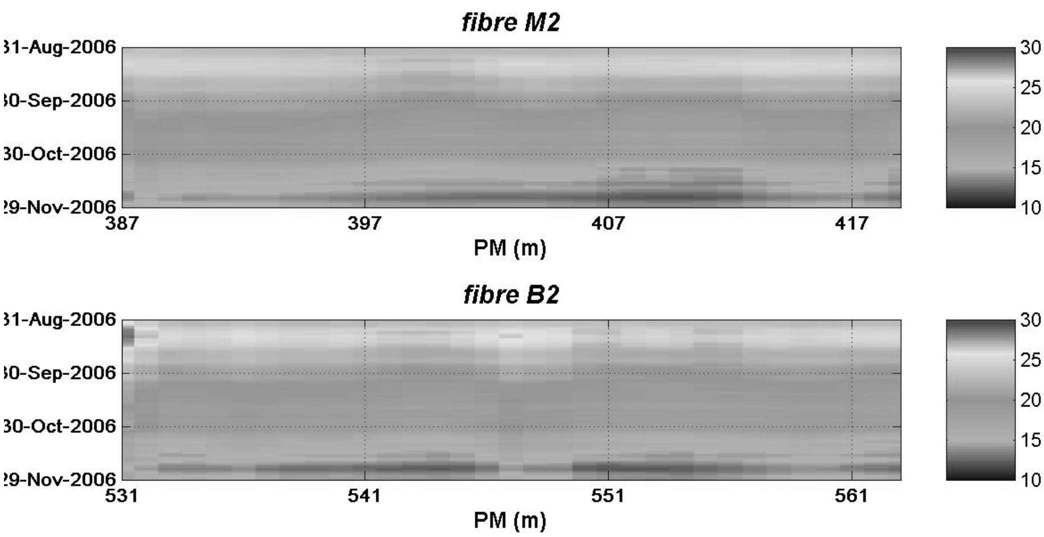


Figure 8: Evolution of temperatures measured along the OF – West Face

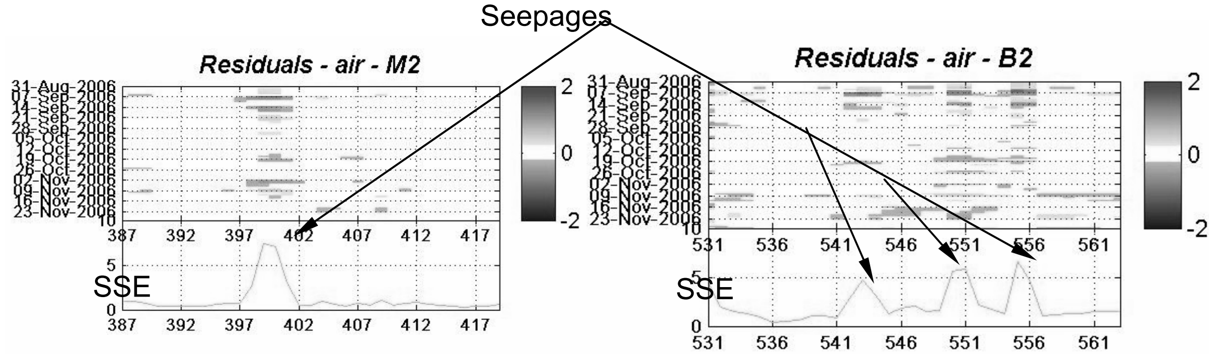


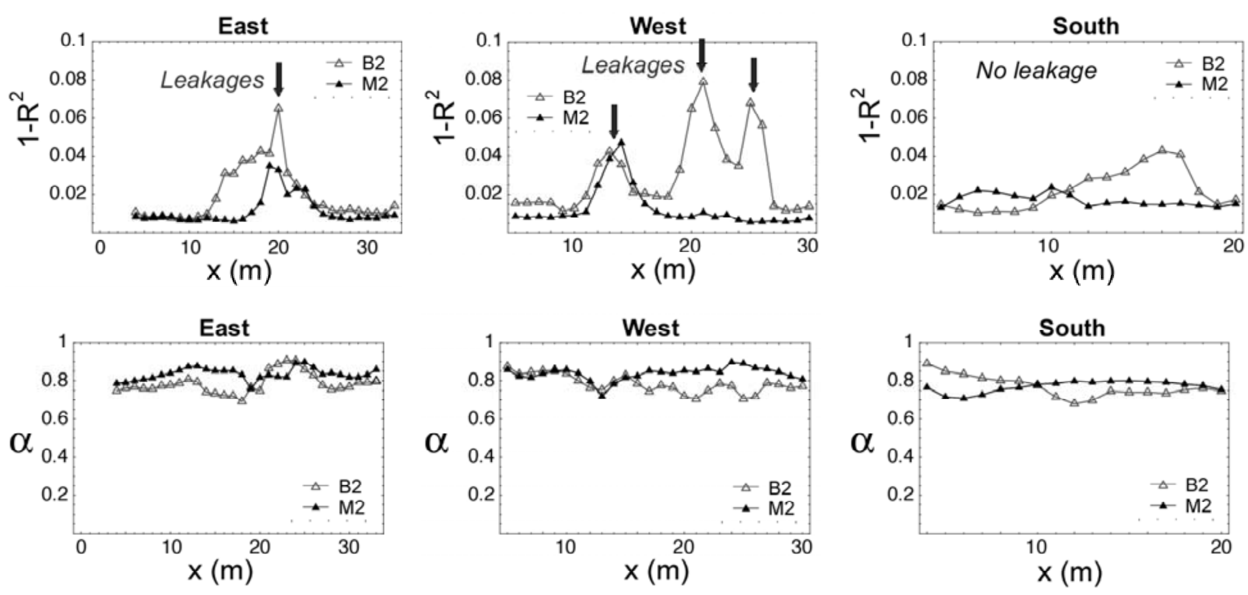
Figure 9: Residue after analysis and SSE – West Face

The Impulse Response Function Analysis (IRFA) has been applied in two steps. Firstly, the three OF temperature measurement has been expressed a delayed response of the air temperature. For conciseness, results are not detailed. The delay η is about 15 days for B2 and M2, and 5 days for T2.

Secondly, B2 and M2 has been expressed a delayed response of T2. This technique has several advantages: 1) the air temperature is not necessary, 2) the top temperature is here considered as an explanatory variable, accounting for all the complexity of the system (air convection, radiation, inhomogeneity of the soil, pluviometry, ...). As a consequence, the parameters (α, η) should be x-independent. In other words, a local variation may be interpreted as the influence of a local leakage.

Obtained results confirm the validity of this approach. All the (artificial) leaks have been clearly identified on the east and west sides, while no leakage has been detected on the south side (**Figure 10**).

Deep analysis of the mechanical equations shows that η is as a function of (*S*,*Pe*), while α is a function of *Pe* only, *S* being the saturation degree and *Pe* being the Peclet number (leakage velocity/thermal velocity). In the present situation, values of *Pe* around the OF (near the ground surface) are almost zero. We conclude that local variation of η may be interpreted as the consequence of *S* (actually on the local thermal diffusivity).



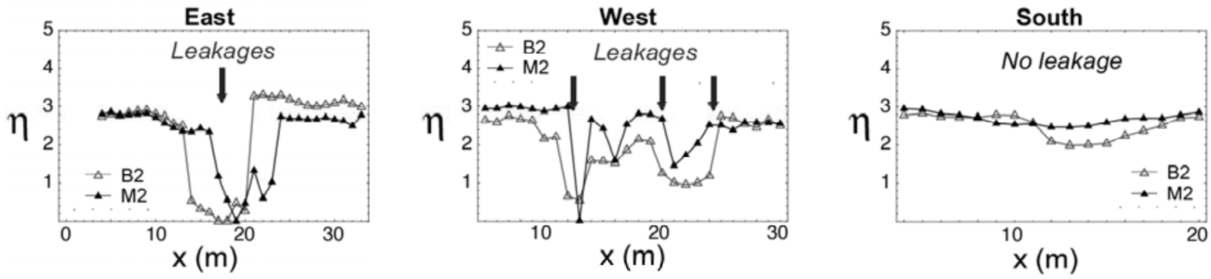


Figure 10: results of IRF analysis of bottom temperature (B2) and middle temperature (M2) as a function of top temperature (T2) (η in days)

7 Conclusions - Perspectives

The passive method used here is associated with a geotextile designed to detect leaks in the case of an OF placed outside the groundwater. There are a few remaining validation steps to render the overall system operational.

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