Quantifying Seepage Flow Velocities in Embankment Dams from Optical Fibre Distributed Temperature Measurements

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Abstract

Seepage flow velocities are a key parameter to assess the risk of internal erosion in embankment hydraulic structures, such as embankment dams, canal embankments or levees. Accurate orders of magnitude of these seepage flow velocities are difficult to assess via conventional monitoring technologies or numerical modelling. EDF and geophyConsult have developed for 15 years an innovative technology of seepage detection using optical fiber distributed temperature measurements. This technology has already demonstrated its capability to locate seepages through embankment hydraulic structures using passive temperature measurements without any constraint of the optical fiber cable location with respect to the ground water table elevation. The next step was to use this technology to quantify the seepage flow velocities after having located them. A specific numerical modelling and analysis of optical fiber temperature data was developed and applied to a canal embankment experiencing seepage. After having presented the main geometrical and geotechnical characteristics of this canal embankment and its foundation, this paper presents the optical fiber monitoring installation. Then, the hydraulic behaviour of this canal embankment is discussed, based on visual inspections and piezo metric measurements. In its third part, this paper presents the optical fiber temperature measurement analysis, allowing seepage location detection and seepage velocity quantification. This innovative technology still needs to be tested and implemented on other case studies but it has already shown a promising potential to significantly improve internal erosion assessment from monitoring data.

Keywords: embankment dams, monitoring, seepage flows, temperature measurements, optical fiber.

1. INTRODUCTION

Seepage flow velocities are a key parameter to assess the risk of internal erosion in embankment hydraulic structures, such as embankment dams, canal embankments or levees. Accurate orders of magnitude of these seepage flow velocities are difficult to assess via conventional monitoring technologies or numerical modelling. EDF and geophyConsult have developed for 15 years an innovative technology of seepage detection using optical fiber distributed temperature measurements. This technology has already demonstrated its capability to locate seepages through embankment hydraulic structures using passive temperature measurements without any constraint of the optical fiber cable location with respect to the ground water table elevation ([1], [2], [3], [4], [5], [6]). The next step was to use this technology to quantify the seepage flow velocities after having located them. A specific numerical modelling and analysis of optical fiber temperature data was developed and has been applied to an 800m-long portion of a canal embankment where seepages occurred at the downstream toe.

After having presented the main geometrical and geotechnical characteristics of this canal embankment and its foundation, this paper presents the optical fiber monitoring installation. Then, the hydraulic behaviour of this canal embankment is discussed, based on visual inspections and piezo metric measurements. In its third part, this paper presents the optical fiber temperature measurement analysis, allowing seepage location detection and seepage velocity quantification.

2. CANAL EMBANKMENT DESCRIPTION

The 15-km long canal embankment of interest is located on the right bank of the intake channel of an EDF's hydraulic power plant located in the South-East of France. Figure 1shows a view of this canal from the top of the embankment.

Figure 1: View of the canal embankment

The embankment's height above natural ground varies until 15m. Dam crest is 9m wide, downstream and upstream slopes are 3H/1V. The foundation is made of silty sandy alluviums. The embankment body includes a watertight upstream fill made of clay, sand and lime. The central and downstream part of the embankment body are made of sandy gravels. In some parts of the embankment, diaphragm walls have been realized from the crest to the upper part of the foundation (Fig. 2). However, this canal embankment which was originally built in the years 1890' has suffered for decades of seepages and low kinetics types of internal erosion (suffusion and contact erosion).

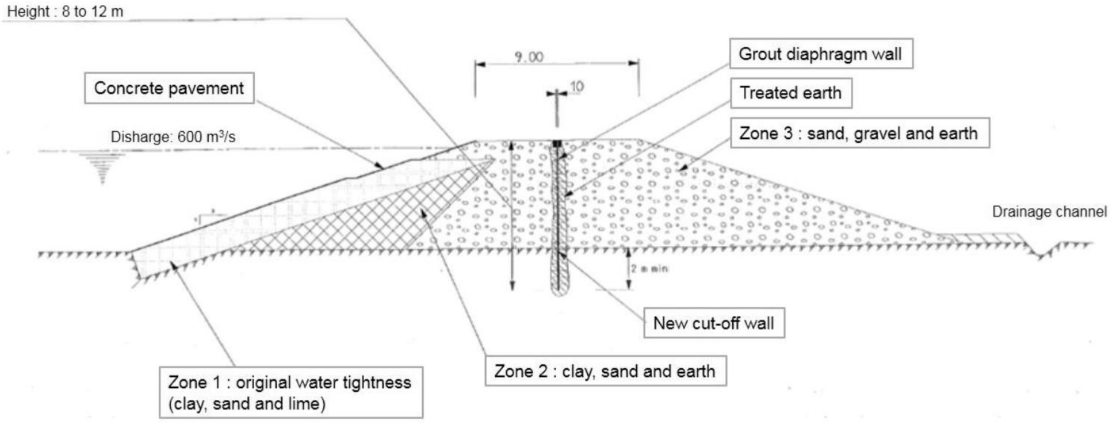


Figure 2: Cross section of the canal embankment before its rehabilitation 3

As this canal embankment is located in a high-density urban area where a breach due to internal erosion is a major safety issue, rehabilitation works have been carried out in 2014, following a safety assessment study. These works included the realization of a continuous diaphragm wall from the embankment crest to the upper part of the foundation and the rehabilitation of the drainage at the downstream toe of the embankment. The rehabilitation of the drainage included the recalibration and reinforcement of the existing drainage channel in addition to the realization of a new drainage ditch at the downstream toe of the embankment, in order to improve the resistance of the embankment against internal erosion and to enhance seepage monitoring. Taking advantage of the undergoing construction, optical cables were installed during the works of the new drainage ditch and the existing drainage channel (Fig. 3). The goal of this fiber optic monitoring system is to monitor the spatial distribution of seepages and to quantify the seepage flow velocities.

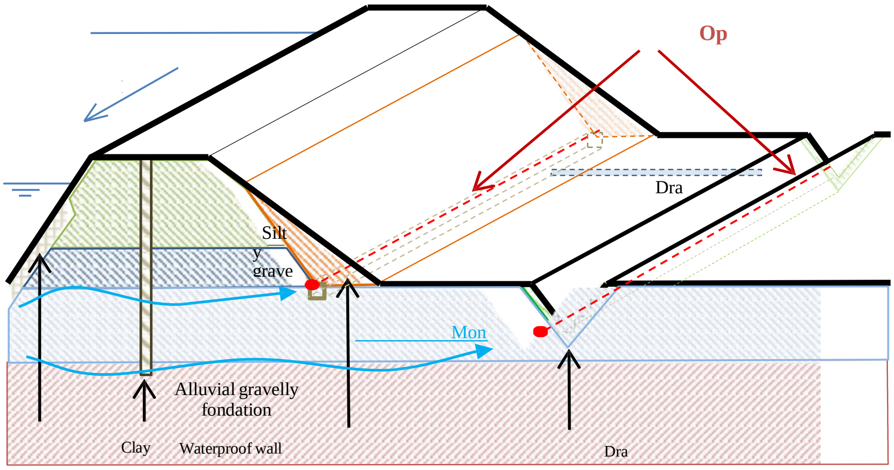


Figure 3: 3D view of the canal embankment after its rehabilitation

The monitoring system of this canal embankment includes piezometers which are located along the crest, behind the cut-off wall and along the berm between the downstream toe of the embankment and the drainage channel, flow weirs which measure drainage flows at drainage exits and optical fiber distributed temperature measurements located along the drainage ditch and channel.

The main potential failure mode of this embankment identified by the safety assessment study is contact erosion in the upper and lower part of the silty-sand layer associated with a defect in the cut-off wall. Through thermo-hydraulics modelling of seepages induced by this physical process, it was concluded that two optical fiber cables parallel to the embankment were needed to detect it. The first cable is located at the base of the draining ditch, just above the draining trench. The draining ditch is located at the base of the downstream slope. Flow from seepages, if any, is drained into the trench and then routes through the outlets along the berm to end up in the drainage channel. Some outlets are equipped with water flow sensors. The second cable is located parallel to the drainage channel, which is roughly 20 meters from the toe of the downstream slope.

These two optical fiber cables are connected to the optoelectronic instrument, configured for hourly data acquisition. Distributed temperature is computed using Raman spectra method.

Despite these rehabilitation works, seepages were observed along the downstream toe of the canal embankment during visual inspections performed during fall 2015 on an 800m-long section. In order to better understand the physical processes through a characterization of this seepage, an analysis of the optical fiber temperature measurements has been performed with the goals to quantify this seepage.

In this section of the embankment, the core is composed of different gravelly and silty-sand soils. A 1-meter-tall layer of silty-sand supports the core. The foundations are composed of sandy-silty-gravel (see Fig. 3).

3. EMBANKMENT HYDRAULIC BEHAVIOUR

To study the consistency of the optical fiber data processing results, conventional monitoring conclusion is previously presented. Visual inspection, piezometer and flow discharge data, as part of the conventional monitoring, give an insight of the embankment's hydraulic behaviour in this specific section.

First of all, during the optical fiber installation works in 2014, a 600-meter long area of saturated soil with the presence of very slight seepages has been highlighted during excavation of the draining ditch between locations KP (Kilometric Point) 9.5 and KP 10.1. Figure 3 is a picture of the draining ditch being excavated. A high water table level was also identified during drainage channel works in this area.

Figure 4: Picture of the draining ditch being excavated during works in 2014 (left picture), observation of humid soil (right picture).

During standard operation of the canal, a visual inspection is carried out along the whole embankment on a 15-day basis. During visual inspections in 2016 and 2017, areas of humid soil at the toe of the downstream slope around locations KP9.5 and 9.7 and a 180-meter wide area of high water level on the side of the drainage channel were identified.

The piezometers along the embankment, during the period from 2014 to 2015, are extremely stable in the area of interest and further with a standard deviation of about 20 cm. Figure 5 shows a piezo metric profile at location KP 9.670 compiled with a 2-year dataset. Maximum, minimum and average piezo metric levels are displayed in the French national reference unit. 5

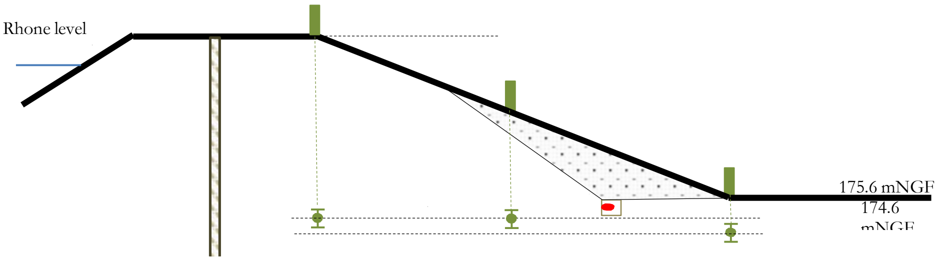


Figure 5: Piezo metric profile at KP 9.670. mNGF unit refers to the topographic level in the French national reference.

At location KP 9.670, the piezo metric profile shows that the optical fiber is located around 30 cm above the highest water line. At location KP 9.940, the water level is slightly above the level of the optical fiber, submerging it.

The draining ditch is composed of two drainage sub-sections as shown in Figure 6. The first sub-section drains the draining ditch from location KP 9.46 to 9.7 with an outlet located at KP 9.58. The average water discharge over the years 2015 and 2016 was 220 L.min$_{-1}$ with a maximum up to 400 L.min$_{-1}$. The second sub-section spans from KP 9.7 to KP 10.1 with a non-monitored outlet located at KP 9.7. The visual inspection of March 2017 gave an estimated discharge of about 100 L.min$_{-1}$.

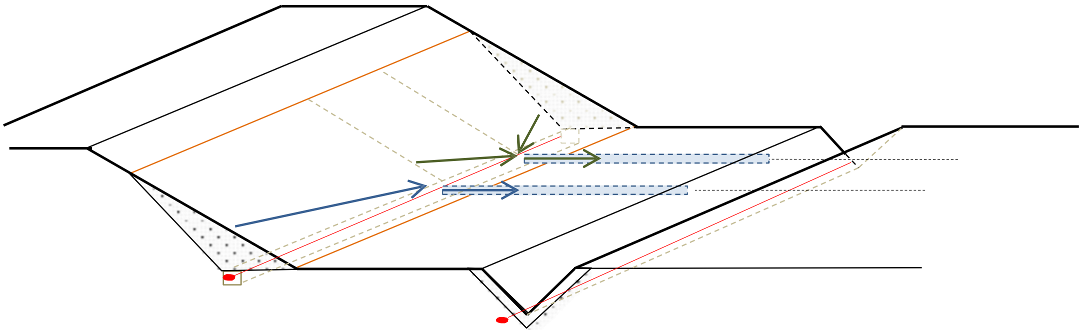
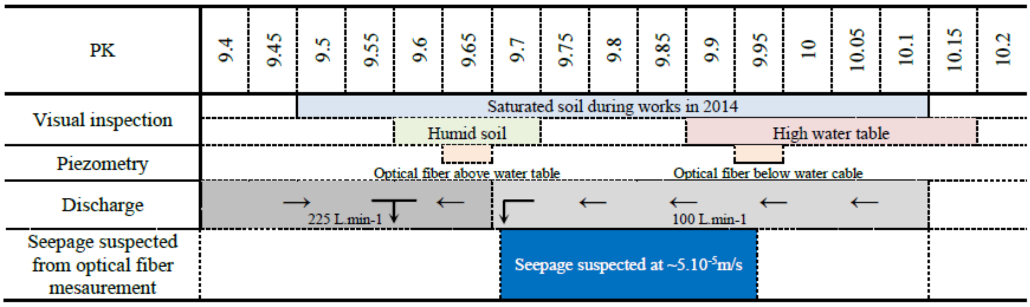


Figure 6: 3D view of the drainage slopes and outlets layout

The conventional monitoring concluded that the water table is generally high, as described by piezo metric data and visual inspections. At KP 9.94, the water level was higher than the location of the optical fiber. The non-zero water discharge at the outlets showed that a flow ran in the draining trench and gave an insight on the potential presence of seepage in the area of interest. The conventional results are summarized in Table 1. 6



PK	9.4	9.45	9.5	9.55	9.6	9.65	9.7	9.75	9.8	9.85	9.9	9.95	10	10.05	10.1	10.15	10.2
Visual inspection			Saturated soil during works in 2014														
					Humid soil						High water table						
Piezometry						Optical fiber above water table						Optical fiber below water cable					
Discharge	→ 225 L.min-1 ↓ ←						↓ ← ← 100 L.min-1 ← ←										
Seepage suspected from optical fiber mesaurement							Seepage suspected at ~5.10^{-5}m/s										

Table 1: Summary of the conventional monitoring results in the area of interest.

4. SEEPAGE FLOW VELOCITY QUANTIFICATION METHOD

The seepage flow velocity quantification method is a physically-based seepage detection method analyzing at each measurement point the optical fiber temperature measurements, using:

- A 1D energy numerical model to compute the temperature induced only by thermal advection as energy transportation process from the water in the canal to the location of the optical fiber. The water temperature and the distance between the canal and the optical fiber are the inputs of the computation. The model calculates the seepage flow velocity in order to optimize the modelled temperature with the temperature measured by the optical fiber.

- A 1D energy numerical model to compute the temperature induced only by thermal conduction as energy transportation process from the ground surface to the depth of the optical fiber. The air temperature and the optical fiber depth are the inputs of the computation. The model estimates the thermal parameters of the soil so that the computed temperature fits best with the measured optical fiber temperature.

An offset and a ratio correction are allowed as means to take into account the limitations of the models, such as the absence of solar radiative flux, the non-coupling of water and air effect, 2D or 3D problems, water and air temperature measured potentially far away from onsite location…etc.

These two temperature numerical models are compared together in terms of their performance to reproduce the measured optical fiber temperatures. When the air-based model gets less convincing, and the water-based model becomes better, a seepage flow from the canal is likely to exist. Figure 7 presents the example of a post-processing graph.

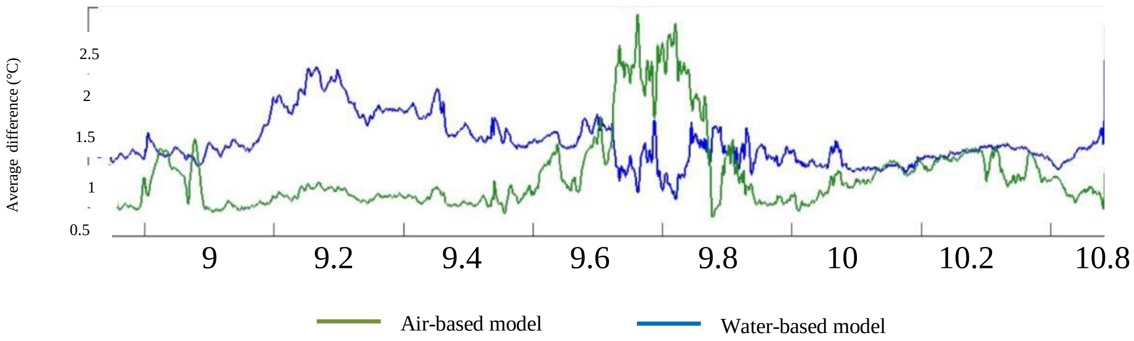


Figure 7: Temperature difference between the water-based model and the optic fiber temperature (blue line) and between the air-based model and the optic fiber data (green line)

This graph shows the average temperature difference between numerical results and measured temperatures, along the position of the optical fiber cable. Between KP 9.7 and 9.9, the average temperature difference between water-based model and measured temperature drops whereas the air-based model tends to divert from the measured temperature. This area is highlighted as a potential area of seepage.

Between KP 9.7 and KP 9.9, the water-based model fits the measured temperature with a seepage flow velocity of about 5.10^{-5} m.s^{-1} over a span of about 150 meters. Figure 8 shows the time evolution of the water-based model at PK 9.797 at the center of the area highlighted.

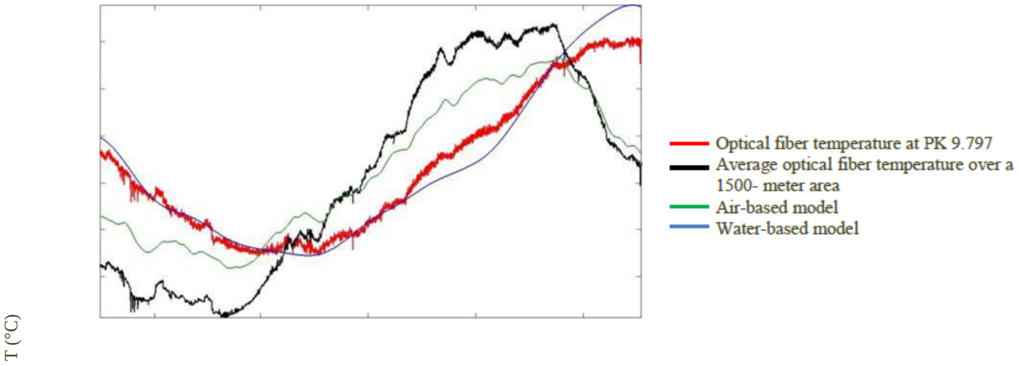


Figure 8: Air-based and water-based model temperature evolutions at PK 9.797 compared to optical fiber temperature evolution.

The seepage flow rate can be estimated from the width of the detected leaking area, from the estimation of the flow velocity and assuming a height of the seepage path in the dyke. If a 0.2 to 2-meter average height is assumed for the seepage, a total flow rate between 100 L.min^{-1} and 900 L.min^{-1} is calculated. This result is consistent with the estimated water discharge at the outlet 1 (100 L.min^{-1}). The monitoring of the water discharge at the outlet 1 would give better confidence in this comparison.

The seepage flow velocity quantification method detected an area of temperature disturbance, explained by the presence of seepage around KP 9.7 and 9.9 consistent with the conventional measurements. The analysis of the optical fiber temperature measurements gathered between KP 9.4 and 9.7, where a significant flow-rate is also collected from the drainage ditch is currently in progress.

5. CONCLUSIONS

A new method of quantification of seepage flow velocities by optical fiber temperature measurements has been used on a real case of seepage on a canal embankment operated by EDF. This method doesn't require to heat the optical fiber nor to locate the optical fiber cable below the water table. Being able to provide seepage flow velocities every one meter all along the embankment downstream toe, this method enables to envisage at short term to assess automatically in real time and at low cost the risk of internal erosion along canal embankments or levees for flood protection. This method is currently tested with data from other embankments in order to characterize properly its domain of use.

6. REFERENCES

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