Effectiveness of distributed temperature measurements for early detection of piping in river embankments

REPLY TO COMMENTS BY REVIEWER 2

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I thank the reviewer for the suggestions that I found very useful. In the following I answer all his comments also on behalf of the co-authors.

 # The order of chapters should be changed. Description of model and theory concerning the geothermal Péclet number should be presented before the trial test description.

 # The title of chapter 2 "Early detection of internal erosion" should be changed. It does not correspond well to the content of this chapter.

 # p.3, row 8 "The use of DTS for early detection of internal erosion is nowadays common practice in dam monitoring" Remark: Bibliographic references to confirm this conclusion should be included

 # The authors presented in the introduction some information about previous research concerning mechanical aspect of piping process and failure criteria. However they did not mentioned the existing research results concerning main goal of the paper, i.e., about the thermal influence of internal erosion on soil/damming-structure temperature field, and particularly of the backward erosion and piping thermal influence. Relevant information can be found in a thesis of Guidoux (2008), a thesis of Radzicki (2009), two papers of Radzicki and Bonelli from 2010 and Bonelli and Radzicki (2012). Moreover, a similar test, like described in this paper, was carried out in 2009, also in the framework of the IJkdijk project that gave some interesting and important results. This test is not mentioned in the reviewed paper.

The structure of the paper has been changed, also upon suggestion of the other reviewer. Previous section 5.1 and part of 5.2, introducing the Peclét number, are now in section 2. Section 2 contains theory and methods, the latter consisting in the description of the field test.
The content of previous chapter 2 "Early detection of internal erosion" has been moved to the Introduction chapter in the section 1.3 "the thermometric method". This section will also include references that confirm that "The use of DTS for early detection of internal erosion is nowadays common practice in dam monitoring" and previous research about data interpretation methods and thermal influence of internal erosion on soil/damming-structure temperature field.
Comparison with the 2009 IKdijk experiment, which dynamic was a bit different, could be made in the discussion of the data.

 # The chapter 3.3 contains some information that could have been presented] in chapter 3.4, and conversely]. I suggest to merge them in one chapter.

I agree it was confusing. I limited 3.3 to the presentation and basic interpretation of the data. I moved the interpretation in previous section 3.4 to a new section 4 containing a conceptual model of detection of piping by means of temperature measurements.

 # The authors use often the words "erosion" or "internal erosion". It would be more clear if there be an explanation what the internal erosion is and that piping (backward erosion piping) is one of the internal erosion processes.

I added:
"Backward erosion piping is a specific kind of internal erosion. Internal erosion is the removal and transport of soil particles operated by seepage flow within an embankment or its foundation."
And a foot note:
"For the sake of brevity the term *piping* is used in the paper to indicate backward erosion piping. In the literature the term piping is also used as a synonym of internal erosion or to indicate other types of internal erosion, as concentrated erosion (f.i. the formation of a pipe through the core of a dam) or contact erosion (see ICOLD, 2015)"

 # p.1, rows 9-11 "This work investigates the effectiveness of DTS for dike monitoring, focusing on early detection of backward erosion piping, a mechanism that affects the foundation layer of structures resting on permeable, sandy soils." Remark: Reader may think that the piping always affects the foundation layer only. I propose to write for example "...focusing on early detection of backward erosion piping for the case of a mechanism that affects the foundation layer: : :"

 # p.3, row 8 "The use of DTS for early detection of internal erosion is nowadays common practice in dam monitoring" Remark : Bibliographic references to confirm this conclusion should be included

I added: "Backward erosion piping consists in the formation of a thin pipe below a roof provided by a layer of cohesive soil or a rigid structure. It mostly occurs in the foundation of water retaining structures when the foundation soil consists of uniform, fine to medium sand (ICOLD, 2015). […] Backward erosion piping can also occur, although less frequently, under revetments (Galiana, 2005) or in riverbanks and dike bodies with sandy inclusions (Hagerty, 1991)."

 # p.3, rows 23-27 "Among these are electrical resistivity, self-potential and temperature (Sheffer et al., 2009). These methods have a common feature: they provide spatially distributed measurements. Unfortunately they also have a common shortcoming: they measure quantities that are influenced by a large number of variables besides the occurrence of internal erosion, which makes data interpretation not straightforward and ambiguous." Remark: Indeed, the electrical resistivity and self- potential measure quantities that are particularly influenced by a large number of variables. Contrary, the thermal method is influenced mostly by humidity variation and water flow.

For transient water flow and shallow measurements (i.e. measurements at the toe of an embankment or inside an embankment lower than 10 m) also the initial temperature distribution in/under the embankment influences the thermal response of the structure. Solar radiation, rain (see the work by A. Khan), wind also influence the temperature field in the shallow portion of the subsurface. So I believe the problem is rather complex, but, as you stated, less that complex than the inversion of resistivity and self-potential fields, see f.i. Rittgers et al. (2015)* for the analysis of a similar experiment at the IJkdijk test site.

By relating temperature measurements along the dam toe with measurements in the transverse direction (quasi 3D systems) I believe that some ambiguities could be resolved.

*J.B. Rittgers, A. Revil, T. Planes, M.A. Mooney and A.R. Koelewijn (2015) "4-D imaging of seepage in earthen embankments with time-lapse inversion of self-potential data constrained by acoustic emissions localization", *Geophys. J. Int.*, **200**, 758–772.

 # p.3, row 30 "Because of conduction...." Remark: It would be more precisely to write "In the case of only conduction heat transport in the soil (without water flow) ..."

It was rearranged as: "In the absence of seepage (or in presence of moderate seepage flow), the temperature distribution in the upper portion of the subsoil fluctuates seasonally in response to the variations of the air temperature".

 # p.4, rows 1-2 "While moderate seepage flow occurring in the soil does not affect the temperature field determined by heat conduction, significant seepage (rates higher than 10-7 - 10-6 m/s) produce variations in the soil temperature." Remark: Temperature distribution in soil, including changes of temperature field generated by seepage depend not only on water velocity but also on length of the seepage path, so we can say as well that temperature distribution depends on Péclet number that contains both these variables. The same water velocity results in different temperature field variation depending on the scale of a damming structure. In consequence, the authors should better explain their conclusion, referring it for example only to a limited range of the scale of damming structures.

This is correct, thanks for the remark. Since the basics of the thermometric methods are explained before introducing the Péclet number, I preferred to removed any value of Darcy velocity in that part.
Immediately after introducing the Peclet number I wrote: "Assuming a characteristic length of 10 m and typical values of the thermal properties of soils (see Table 1) the Péclet number is on the order of 1 when the Darcy velocity is on the order of 10-7 m/s"
The influence of the geometry is then further explained. In our theoretical model both the thickness of the sand layer and the size of the damming structure play a role.

 # p.4, rows 4-6 "Johansson and Sjödal (2009) observed that, in dams, the regions affected by internal erosion are typically characterized by a temperature similar to the reservoir water, while the temperature in the other regions of the flow domain is nearly unaffected by the reservoir temperature." Remark: It is not clear what the authors explain by this paragraph. If it is an example to confirm the previous sentence that "Since internal erosion promotes the formation of zones of higher permeability and, consequently, a local increase of seepage rate, it is expected that it also causes a local variation of the temperature field "

I agree on the fact that this sentence in that position was confusing. I will improve it.

they should add "for example Johansson and Sjödal (2009) observed that, : : :." There are different possible results of internal erosion development on temperature field. Research results of Radzicki and Bonelli (2012), Radzicki and Bonelli (two papers in 2010) explained that the thermal influence of internal erosion depends on: - the permeability of the soil which surrounds the zone of internal erosion - the type of internal erosion process and level of its development (geometrical and/or mechanical) - the scale of a damming structure For example, one of possible results of internal erosion development is that the water reservoir *temperature is transported only to the upstream side of the damming structure. In consequence, on one hand there is no effect of water reservoir temperature on the downstream side of damming structure temperatures. On the other hand, the transport of heat from the downstream slope into the body of the damming structure is affected by local acceleration of water flow due to the internal erosion development, which allows to detect leakages and internal erosion.*

I'll see where to include this in the text, whether in the introduction (Section 1) or in the conceptual model (Section 4).

 # p.8, rows 22-26 "For this reason, the mechanism that promoted the formation of piping-induced thermal anomalies was not, as commonly found in the literature, the prevalence of advection in the eroded regions in opposition to the purely conductive behaviour of the regions unaffected by piping. This occurs because the assumption of conductive behaviour in the unaffected regions (Johansson and Hellström 2001; Johansson and Sjödal 2009) only applies to low permeability bodies such as dam cores.." Remark : The thermal effect of piping development in soil, comparing with the case of soil without piping, was analyzed for different value permeability of soil and for different advection transport intensity (Péclet value from 0.1 up to 100) in the thesis of Radzicki (2009) and presented as well in Radzicki and Bonelli (2010).

I will certainly reformulate and include this. I think it is correct to say that the first models developed for leakage detection in dams, for which numerical methods are also available to quantify the water flow, assumed the conduction was dominant in the regions unaffected by piping. Later the thermal effect of piping development in soil was analyzed for different values of soil permeability and for different advection transport intensity (Radzicki, 2009; Radzicki and Bonelli, 2010).