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Geophysical and geotechnical methods for fluvial levee investigation : a review

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Abstract

Fluvial levees are assets of major importance for protecting human lives and activities. To prevent the risk of failures and to assess their stability, survey campaigns involving geophysical and geotechnical methods are needed. These two types of methods play highly complementary roles and provide information of different natures, uncertainties and spatial distributions. In this work, we first present the function of fluvial levees and describe the associated physical properties that may become pathological and lead to failure mechanisms. Then for each presented investigation method, we introduce : its basic principles, its ability to characterize specific physical properties (or characteristics) of fluvial levees, and then its advantages and drawbacks under specific environmental conditions. It should be emphasized that geophysical and geotechnical methods are placed on an equal footing in order to assist agencies and levee managers in selecting the most relevant ones to assess the condition of their levees and characterize potential weak zones, according to a specific type of pathology and to the environmental constraints. Throughout this review, we introduce a certain amount of literature that is believed to be of potential interest to the research community as well. We also draw attention to some lack of information on the application of specific methods to levee investigation. Finally, we discuss some complementarities of the presented methods and we propose a dedicated comparative table, leading us to suggest new method combinations for levee investigation.

Keywords : Levee, condition assessment, near surface geophysics, geotechnical engineering.

1 Introduction

Fluvial levees are manmade structures built up for flood protection [Brierley et al., 1997]. They are considered as hazardous structures that can fail and lead to disastrous consequences such as human or material loss and economic disasters [van der Veen et al., 2003]. To prevent the risk of failure, it is required to carry out survey campaigns in order to assess the stability of levees. Fluvial levees are very various: their age, history, structure and composition materials make each one unique [Foster et al., 2000b] and more or less subject to failure in weak zones under specific loads. The purpose of the assessment is to verify the levee serviceability level in comparison with design serviceability level. It is firstly based on technical surveys able to establish if specific pathologies that could lead to failure mechanisms are present in the levee structure. In order to perform a reliable assessment, it is required to be aware of the relations linking these pathologies to the different existing failure mechanisms.

There are globally acknowledged methodologies for levee assessment [Royet et al., 2013] that include a phase of investigation involving geophysical investigation methods [Kearey et al., 2013] and geotechnical investigation methods [Look, 2014]. Geophysical methods provide physical information on large volumes of subsoil with potentially important related uncertainties. These associated uncertainties are notably due to

1 the resolution of inverse problems and to the indirect and integrative aspects of the methods. These methods
2 are non-intrusive, unlike geotechnical investigation methods that provide more punctual and more accurate
3 information. The aim of this paper is to place on an equal footing these two types of methods in order to
4 assist agencies and levee managers in selecting the most relevant methods to characterize the vulnerability
5 of a levee, according to a type of pathology and to the environmental constraints, in an effective way. In
6 this work, we confine ourselves exclusively to fluvial levees and to survey campaigns excluding monitoring
7 and well logging methods. Even though monitoring techniques bring a lot to fluvial levee diagnosis [Bièvre
8 et al., 2018; Sjödaahl et al., 2008], these methods are more efficient for levees exposed to constant hydraulic
9 loads.

10

11 This review has the double aim of creating interest in the levee managers (decision makers) and in the
12 research community as well. The large number of introduced methods and their abilities to characterize
13 a specific property or characteristic, under particular conditions, can be a useful tool for a levee manager
14 willing to set up a levee investigation or to departments looking for references. The great number of bibli-
15 ographic references can spotlight the potential lack of information concerning specific methods, inform on
16 the advantages and drawbacks of the methods for the levee investigation, work on the methods complemen-
17 tarities and suggest new method combinations.

18

19 First, we introduce the role of fluvial levees and describe the failure mechanisms and associated patho-
20 logical physical properties and characteristics. Then, in the first instance we present the role of geophysical
21 investigation methods for characterizing these pathologies and as a second step, geotechnical investigation
22 methods are presented equally. The order of presentation of the investigation methods depends on their phys-
23 ical fields. Finally, we discuss the lack of information about specific investigation methods and introduce
24 references on studies combining different kinds of investigation methods.

25 **2 Fluvial levees and related pathologies**

26 **2.1 Fluvial levees**

27 The primary function of flood embankments is to retain a water volume. According to the type of structure,
28 the intended goal can be different: water storage (dams), channeling (canal dike) or protection of a delimit-
29 ed area (flood embankments). The two essential properties of flood embankments are a) the mechanical
30 resistance and b) the watertightness. The mass, as well as the composition and morphology of the levee
31 determine its capacity to resist to the hydraulic charge, which is a function of the water quantity. A part of
32 the embankment is made of impervious materials (clays, silts) guaranteeing the watertightness.

33

34 Foster et al. [2000b] present twelve kinds of flood embankments. There, a distinction is made between
35 the homogeneous embankments and the zoned and more recent ones. For homogeneous embankments, the
36 same materials guarantee simultaneously the watertightness and mechanical resistance functions. A low
37 compactness often characterizes these structures [François et al., 2016]. The zoned embankments frequently
38 include a clayey core to guarantee the watertightness with a coarser material around it to ensure the stability.
39 In addition, many different ways to reinforce the structure can be found such as rock fill, drains, sheet piling,
40 concrete layers... [Foster et al., 2000b].

41

42 Each flood protection embankment is unique, since many different materials and construction methods
43 exist, the nature of its structure goes hand in hand with its environment [Sharp et al., 2013]. Geographically,
44 the structure type can be very variable according to the different materials available, loads, history, culture
45 and economy of the region. Because of important floods, various levees have been submitted to successive

1 heightenings, filling of breaches, rockfillings or drains adding. These modifications may be responsible of
 2 unequal and heterogeneous composition of the construction work in terms of granulometry and compactness
 3 [Dion, 1961].

4 2.2 Failure mechanisms and associated physical properties and characteristics

5 Four types of mechanisms [Fauchard and Mériaux, 2007; François et al., 2016] can lead to the failure of a
 6 flood protection embankment: overflowing, sliding instability, external erosion and internal erosion. These
 7 mechanisms are unfortunately not exclusive and may be responsible for the formation of a breach leading to
 8 the failure of the levee [Nagy, 2012]. Failure scenarios consisting of combinations and sequences of failure
 9 mechanisms must be considered. In this work, we will only be considering the slope instability phenomenon
 10 and the four different types of internal erosion (backward erosion, concentrated leak erosion, contact erosion
 11 and suffusion). To characterize the sensitivity of a soil to external erosion processes, the JET (jet erosion
 12 test) [Marot et al., 2011] and MoJET (mobile jet erosion test) [Henensal and Duchatel, 1990] can be used
 13 in laboratory or in-situ. Most of the times, a visual inspection can identify the indicators of external erosion
 14 while the overflowing mechanism corresponds to the overflowing of the crest by the water, which depends
 15 on geometrical criteria [Herrier et al., 2014].

16
 17 Complete information concerning internal erosion can be found in [Fell and Fry, 2007; François et al.,
 18 2016; Fry, 2012; Morris, 2012; Sharp et al., 2013], while information on the slope instability mechanisms is
 19 available in [Jia et al., 2009; Rinaldi et al., 2004; Sharp et al., 2013; Varnes, 1978].

20
 21 Various physical material properties (hydraulic permeability, compactness...) and levees characteristics
 22 (presence of heterogeneities within the levee body and foundation, presence of man-made pipes...) associated
 23 with specific pathologies (low compactness, high hydraulic permeability, low shear strength...) characterize
 24 these mechanisms and increase their probability of occurrence (Figure 1).
 25

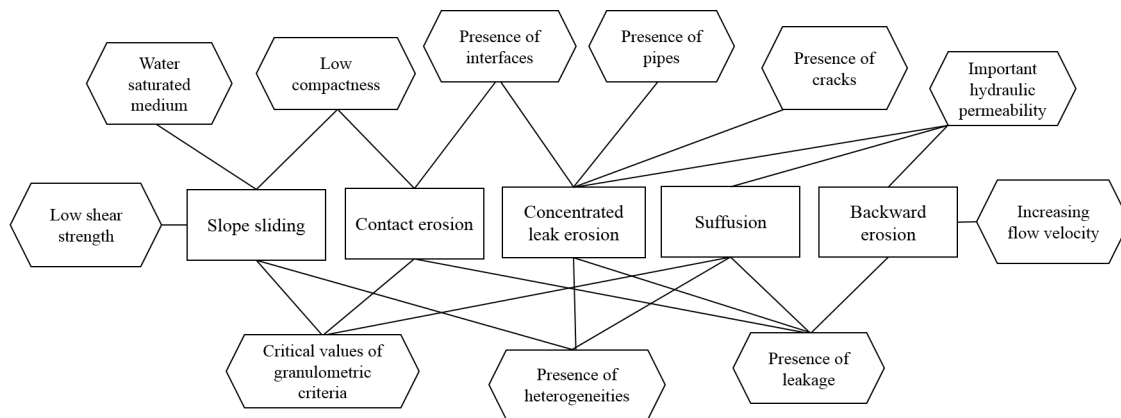


Figure 1: Diagram displaying the links between pathologies (in hexagons) and mechanisms that may lead to levee failure (slope sliding and four internal erosion mechanisms, in rectangles), after Dezert et al. [2017].

26 For large dams, failure statistics up to 1986 are proposed by Foster et al. [2000a] (Table 1). External
 27 erosion mechanisms are not expressly presented since they can lead to piping (internal erosion), slope insta-
 28 bility or overtopping which are included in the table. Danka and Zhang [2015] propose others statistics of
 29 observed failure mechanisms, relying on 1 000 levee failure cases while Nagy [2012] summarizes various
 30 authors' works on statistics of mechanisms of dikes and dams damage and failure. Globally, the overflowing

1 (or overtopping) mechanism is responsible of about 50% of levee failures.

Mode of failure	% of total failures
Piping through embankment	31
Piping through foundation	15
Piping through embankment to foundation	2
Slope instability	4
Overtopping	46
Earthquake	2

Table 1: Failure statistics for large dams up to 1986 considering each failure mechanism [Foster et al., 2000b]

2 2.2.1 Slope instability

3 Sharp et al. [2013] explain that: "the instability occurs when the active strengths of soil particle movement
4 exceed the resistant strengths." There are various processes associated to the slope instability mechanism
5 such as superficial or rotational sliding, settlement or liquefaction. All these processes can occur on both
6 sides of a flood protection embankment.

7
8 Superficial and rotational sliding (Figure 2) tend to occur when the shear strength of the materials consti-
9 tutive of the levee body and/or its foundation, is insufficient to keep its geometry in its original configuration
10 [Poulain et al., 2015]. Settlement is associated to the lowering of the crest level. Liquefaction is deeply
11 associated with the seismic activity, causing the loss of resistance of a sandy water saturated material, with a
12 great increase of the interstitial pressure [Bertil, 2007].

13

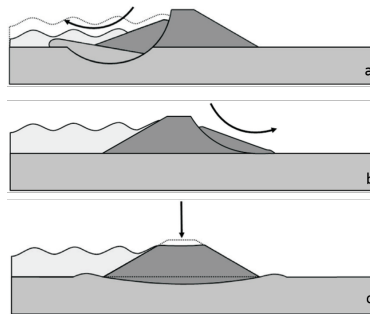


Figure 2: a) Deep rotational sliding of a levee. b) Shallow rotational sliding of the landside of a levee. c) Settlement of a levee on a soft soil foundation [Sharp et al., 2013]

14 Varnes [1978] explains that these mechanisms need a water-saturated medium to occur. They are pro-
15 moted when the levee slope is steep, when there is a low compactness and/or high charge and when there is
16 little draining and presence of heterogeneities. The granulometric criteria also play an important part in the
17 slope sliding mechanism since it is directly linked to the material shear strength and to its ability to be well
18 compacted or not [Sharp et al., 2013]. Finally, this phenomenon can be reinforced by a rapid receding water
19 level.

20 2.2.2 Internal erosion

21 The pullout of particles and their migration within the levee or its foundation characterize the internal erosion
22 process [Sharp et al., 2013]. This phenomenon tends to occur when the hydraulic forces are strong enough
23 to initiate the movement of the soil particles and when the porosity and hydraulic permeability are great

1 enough to allow them to migrate [Bonelli et al., 2012]. Four types of internal erosion processes are defined :
 2 backward erosion, concentrated leak erosion, contact erosion and suffusion.

3 2.2.2.1 Backward erosion

4
 5 Morris [2012] describes the backward erosion process as a detachment of soil particles occurring when a
 6 seepage exits to an unfiltered surface. A pipe is formed regressively from downstream to upstream with an
 7 increase of the flow velocity and hydraulic gradient (Figure 3). This erosion process is only made possible
 8 in non-plastic soils [Richards and Reddy, 2012]. van Beek et al. [2011] and Sellmeijer et al. [2011] experi-
 9 mentally validate a model for the characterization of the backward erosion mechanism.

10
 11 The presence of leakage, an increasing flow velocity and an important hydraulic permeability are sus-
 12 ceptible to lead to a backward erosion phenomenon [François et al., 2016; Sharp et al., 2013].

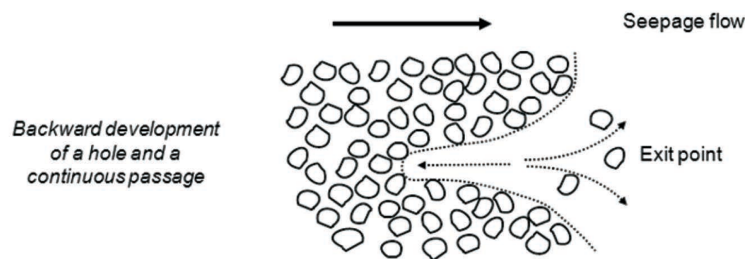


Figure 3: Principle of backward erosion [Sharp et al., 2013]

13 2.2.2.2 Concentrated leak erosion

14
 15 Concentrated leak erosion occurs in the interstices of the levee, which could correspond to worm gal-
 16 leries, open cracks, voids left by roots, spaces around man-made pipes, etc... It can also occur in a permeable
 17 area for a critical shear stress value, induced by flows [Sharp et al., 2013]. The particles are pulled out from
 18 the void sides, increasing its diameter (Figure 4).

19
 20 Historically, Wan and Fell [2002, 2004a,b] propose the first interpretation of concentrated leak erosion
 21 with a laboratory test: the Hole Erosion Test (HET). Bonelli and Brivois [2008] and Benahmed and Bonelli
 22 [2012] work on a new model to interpret with greater accuracy the HET results. The HET is the only test able
 23 to evaluate the concentrated leak erosion risk by giving the critical shear stress value (Pa) and the coefficient
 24 of erosion ($s.m^{-1}$). The change of scale of these results, from the laboratory test to a real levee is still under
 25 study.

26
 27 François et al. [2016] indicate many characteristics that could potentially foster the development of this
 28 kind of internal erosion process such as presence of interfaces, man-made pipes, cracks and heterogeneities.
 29 The presence of leakage can be indicative of such a mechanism. Finally, an important hydraulic permeability
 30 would also be conducive to concentrated leak erosion.

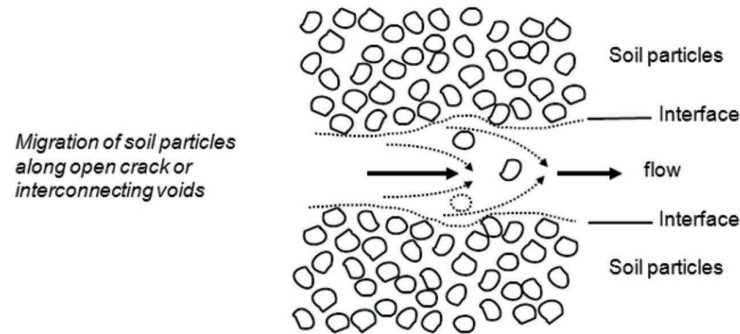


Figure 4: Principle of concentrated leak erosion [Sharp et al., 2013]

2.2.2.3 Contact erosion

This process takes place at the interface between two materials with distinct granulometry and with the presence of a parallel water flow. Fine particles are pulled out and transported through the coarser material (Figure 5). This kind of erosion can also be observed between two layers, one of which is fractured. To make this phenomenon possible, a geometric condition and a hydraulic condition must be fulfilled. The geometric condition consists in having pores large enough to let the fine particles pass through while the hydraulic condition consists in having a water flow strong enough to pull out these particles [Chevalier and Bonelli, 2017]. To deepen this topic, we suggest the work of Guidoux et al. [2009] and Beguin [2011].

The presence of multiple interfaces and poorly compacted materials (geometric condition) tend to foster the development of contact erosion. Beguin et al. [2012] state the possibility for leakage to emerge on the levee slope. The granulometric criteria is an essential parameter too since the triggering of the mechanism is related to the grain size difference between the two layers.

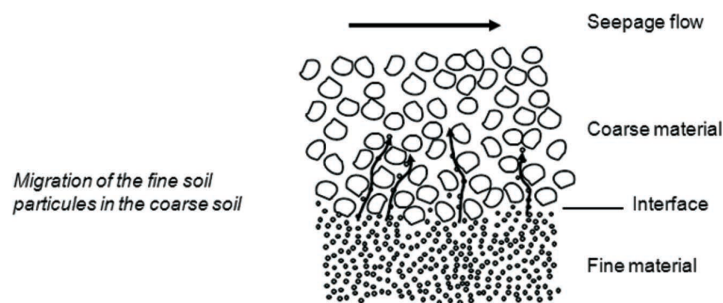


Figure 5: Principle of contact erosion [Sharp et al., 2013]

2.2.2.4 Suffusion

This fourth internal erosion mechanism consists in the most fine particles' migration within a matrix of coarser particles (Figure 6). This phenomenon happens in cohesionless soils [Sibille et al., 2015] and tends to increase the medium's permeability without modifying its volume. This process is quite slow but increases with the presence of heterogeneities.

Thus, the presence of heterogeneities as well as leakage [François et al., 2016] can be judged as warning

1 signs for the progress of suffusion. The increase of permeability and decrease of compactness are also
 2 alarming. The initiation of suffusion is only made possible under specific granulometric conditions [Kenney
 3 and Lau, 1985; Seghir et al., 2014; Wan and Fell, 2004a].



Figure 6: Principle of suffusion [Sharp et al., 2013]

4 3 Geophysical investigation methods

5 A geophysical investigation campaign consists in acquiring physical data on the levee structure from the
 6 variations of a measured physical field. The acquisitions can be carried out from the surface or with several
 7 boreholes techniques [Keys, 2017]. Regarding the levee problematic, we can briefly distinguish these acqui-
 8 sition techniques which are either non-intrusive and covering a certain length (surface techniques), or little
 9 intrusive and dedicated to the detailed investigation of more limited areas (drilling techniques). The geo-
 10 physical information is often interpreted in a complementary way with geotechnical data according to the
 11 physical property. In some contexts, quantification of a property can be made requiring that the investigated
 12 materials are already known, tested in laboratory, and present little variations through space. Niederleithinger
 13 et al. [2012] propose the evaluation of some geophysical methods dedicated to dike investigation.

14
 15 Most geophysical investigation methods need the resolution of inverse problems [Menke, 2018; Taran-
 16 tola, 2005]. The inversion is a processing method that aims to find the "best" model explaining geophysical
 17 measurements performed on the levee. More precisely, various inversion scheme exist based on the mean-
 18 ing of "best", concerning mainly the minimization criterion. In the following sections, a special focus is
 19 performed for each method using an inversion procedure.

20 3.1 DC-Electrical Resistivity methods

21 The 2D-electrical resistivity tomography method (ERT) allows the acquisition of apparent electrical resistiv-
 22 ity values with correctly aligned electrodes. These values can then be turned into real electrical resistivities
 23 after inversion processes in order to get two dimensional (2D) sections of levees. Electrodes can also be
 24 considered in boreholes or in 3D configurations. The inversion processes can thus be made in 2D or in 3D
 25 and more information can be found in Loke [2011]; Loke et al. [2013]; Pidlisecky et al. [2007]. However,
 26 the 3D configuration is rarely used for levee issues, considering large scale investigation campaigns. 3D
 27 configuration is more likely to be used for high resolution studies. The electrical resistivity is expressed in
 28 [$\Omega.m$]. Even though ERT is commonly used for the investigations of levees, it still has some limitations.
 29 Actually, the method can be disturbed by the presence of sheet piling, temperature, rainfall and 3D effects
 30 [Besson et al., 2008; Fargier, 2011; François et al., 2016; Keller and Frischknecht, 1966]. Topography is
 31 not a limitation but transverse topographic variations need to be considered for longitudinal tomographies.
 32 Variations of topography can limit the results interpretation for longitudinal acquisition [Busato et al., 2016;
 33 Rucker et al., 2006]. Moreover, the ERT needs important resistivity contrasts to work properly. The method
 34 capability to characterize levee properties is presented in Table 2.

1 The method consists in injecting an electrical current, that can be assimilated to a direct current, with a
 2 known intensity in the soil by means of two "current" electrodes. Two other "potential" electrodes are used
 3 to measure the electrical potential drop, which is a function of the material's characteristics and distribution.
 4 The acquisition can be done as a vertical electrical sounding (to investigate vertical variations of resistivity)
 5 or as a continuous resistivity profiling (to investigate lateral variations of resistivity). The combination of
 6 these two acquisition modes leads to ERT. The investigation depth and the resolution are function of the
 7 spacing of the electrodes, the device's length, the acquisition array (Wenner, Schlumberger...) and the soil's
 8 nature [Kearey et al., 2013]. The resolution decreases as the depth of investigation increases. If galvanic
 9 contact is difficult to achieve, the capacitive resistivity technique can be used [Kuras, 2002; Kuras et al.,
 10 2006]. Many more information concerning the ERT method can be found in [Friedman, 2005; Kearey et al.,
 11 2013; Keller and Frischknecht, 1966; Loke et al., 2013; Samouëlian et al., 2005; Ward, 1990].

12
 13 ERT is a preferred method for levee investigation and many studies refer to it [Burns et al., 2006; Chinedu
 14 and Ogah, 2013; Fargier et al., 2014; Johansson and Dahlin, 1996; Jones et al., 2014; Lin et al., 2013; Lopes
 15 et al., 2012; Royet et al., 2013; Sjö Dahl et al., 2005].

16

Levee properties and characteristics	Characterization ability
Water content	Decrease of the electrical resistivity when water content increases. Keller and Frischknecht [1966] propose a relation for coarse-grained materials. and [Gunn et al., 2015; Kalinski and Kelly, 1993; Schwartz et al., 2008] for clays.
Interfaces	The ability to detect interfaces increases with the resistivity contrast of the two materials involved [Kearey et al., 2013].
Granulometry	The electrical resistivity goes down with the increase of clay content [Giao et al., 2003; Tabbagh et al., 2007; Waxman et al., 1968] and coarse materials imply a higher electrical resistivity [Keller and Frischknecht, 1966]. Abu-Hassanein et al. [1996] point out a relation between the particles size and the electrical resistivity for a known water content.
Cracks	Samouëlian et al. [2003] characterize soil cracks at centimetric scale such as Tabbagh et al. [2007]. It depends on the cracks size and whether they are filled or not.
Heterogeneities	It depends on the size, depth and resistivity contrast with the surrounding material [Kearey et al., 2013; Samouëlian et al., 2005; Weller et al., 2006].

Table 2: The ERT method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Man-made pipes	It depends on their nature and on their resistivity contrast with the host material. For metallic pipes, a very low value of apparent resistivity will be measured and the pipes will easily be detected [Liu and Kleiner, 2013]. For PVC pipes, the detection is complicated. Vickery and Hobbs [2002] propose a method for removing the effects of subsurface conducting pipes.
Cavities	Interesting for the detection of conductive cavities (filled with clay or water) but not for the empty ones [Fauchard et al., 2004]. Is directly function of its size, depth and resistivity contrast with the host material [Chalikakis et al., 2011]. [Butler et al., 1994; Gautam et al., 2000]
Compactness	The porosity can be estimated using Archie's law for saturated rocks [Archie, 1942]. Robain et al. [1996] link high electrical resistivity to porosity. Abu-Hassanein et al. [1996] establish that the electrical resistivity decreases when the compactness increases for a constant water content and Beck et al. [2011] propose interpretation of the dry density influence on the resistivity of a fine-grained soil.
Hydraulic permeability	For glacial outwash materials, Kelly [1977] develops an empirical relation. Huntley [1986] suggests a relation between permeability and apparent formation factor (ratio of measured total resistivity to the fluid resistivity) in a granular aquifer [Bolève et al., 2011]

Table 2: The ERT method ability to characterize levee properties and characteristics.

1 3.2 Self potential method

2 The self-potential (SP) method is a passive electrical method with no current injection. It consists in mea-
 3 suring electrical potential differences, [V], naturally present in the ground. The two main origins of these
 4 electrical sources are the electrofiltration potential, linked to the water circulation in a porous medium or in
 5 fractures network, and the redox potential. The investigation depth depends on the intensity of the source
 6 and on the extension of the measurement [Kearey et al., 2013]. The potentials can fluctuate depending on
 7 the temperature. The method is very sensitive to anthropogenic noises (man-made pipes, reinforced con-
 8 crete, electricity network...), to bio electrical potentials (tree roots) and to magnetotelluric phenomena such
 9 as storms [François et al., 2016]. Ahmed et al. [2013] propose the use of SP2DINV code and detail the inver-
 10 sion of the self-potential data using Tikhonov regularization and weighting depth and smoothness constraints.

1 The self-potential method is mainly used for the detection of water leakage in levees [Al-Saigh et al.,
 2 1994; Bolève, 2009; Bolève et al., 2011; Kang et al., 2014]. Additional information about the SP method
 3 can be found in Fink et al. [1990] and in Jouniaux et al. [2009]. The method capability to characterize levee
 4 properties is presented in Table 3.

5

Levee properties and characteristics	Characterization ability
Cracks	Can possibly be detected according to their size, orientations and if there is water flow inside [Rozycki et al., 2006].
Man-made pipes	Buried metallic structures are source of redox potentials which can be detected [Castermant et al., 2008; Revil et al., 2001].
Cavities	Chalikakis et al. [2011] point out that cavities can be detected if they are filled with water [Jardani et al., 2006; Vichabian and Morgan, 2002].
Flow velocity	Bolève [2009] and Bolève et al. [2009] propose a method for the estimation of flow velocities focused on levee problematic.
Hydraulic permeability	Bolève et al. [2011] suggest a method for the hydraulic permeability estimation of the preferential fluid flow pathway with salt tracer injection.

Table 3: The SP method ability to characterize levee properties and characteristics.

6 3.3 Induced polarization method

7 The induced polarization method (IP) can be used in the spectral or time domain [Kaouane, 2016]. Used in
 8 time domain, it allows the determination of the apparent chargeability [mV.V^{-1}] [Slater and Lesmes, 2002]
 9 while used in frequency domain, it allows the determination of the frequency effect (differential polarization
 10 effect) and the phase (phase difference between the voltage and the injected current) [Kaouane, 2016]. The
 11 IP effect stems from a delay in the voltage response of the investigated material [Sumner, 2012]. Just as
 12 the ERT method, a current is injected by means of two electrodes while potential electrodes measure the
 13 electrical potential difference. A high chargeability can indicate the presence of sulfides, oxides, graphite or
 14 cation-rich clays [Pflug et al., 1997]. It is easier to set up the IP method in the time domain but a specific
 15 decision needs to be taken concerning the signal integration windows for the chargeability computation [van
 16 Schoor et al., 2009]. Furthermore, non polarizable electrodes are required for the potential drop measure-
 17 ments except in limited cases [Leroux et al., 2007], and much care is needed when handling cables in order

1 to avoid electromagnetic coupling. The spectral induced polarization method is complex to implement since
 2 the accurate measurement of low frequency signals requires time-consuming acquisitions [Ingham et al.,
 3 2014] and because of electromagnetic couplings between the ground and the cables. Research teams are
 4 currently working on the signal transformation from the time domain to the spectral one [Ingham et al.,
 5 2014]. As for the ERT method, the investigation depth increases as the spacing of the electrodes increases
 6 [Sarma, 2014]. This investigation method is long to set up and the presence of man-made pipes, cables or
 7 electric transformers prevents from using it. The intercalation of too resistive or conductive layers can mask
 8 the underlying layers. Details of electrical induced-polarization inversion approaches are proposed in Binley
 9 and Kemna [2005]; Karaoulis et al. [2011].

10

11 Kaouane [2016]; Kemna et al. [2012] and Sumner [2012] give complete information about the IP method
 12 principles. In levee problematic, Mary et al. [2016] and Zanetti et al. [2011] use the IP method to map tree
 13 root systems. The method capability to characterize levee properties is presented in Table 4.

Levee properties and characteristics	Characterization ability
Water content	Used in clay-rocks [Ghorbani et al., 2009] and sandstones [Titov et al., 2010]. The chargeability tends to decrease when the water content increases but a normalisation is needed. The direct link between chargeability and water content has not been made for embankments.
Interfaces	Interfaces between distinct materials are detectable if the chargeability contrast is enough [Vaudelet et al., 2011].
Granulometry	Revil and Florsch [2010] find out that the granulometry is linked to the distribution of the relaxation times for a polarization of the Stern layer being the dominant mechanism in the integrated frequency window.
Cracks	Is a function of the nature of the surrounding material and the nature and size of the fractures. Schmutz et al. [2011] use the spectral IP method to detect cracks and make a distinction between clay-filled and open fractures.
Heterogeneities	Heterogeneities with an important chargeability contrast with their surrounding materials will be detectable if they are not too deep and large enough [Vaudelet et al., 2011].

Table 4: The IP method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Man-made pipes	Is sensitive to the presence of metallic materials. Mao et al. [2016] bring to light that it is better to plot the chargeability rather than the normalized one to visualize a metallic pipe. The presence of long metallic structures such as pipes or cables can make the method useless because of the generated noise.
Compactness	Weller et al. [2010] propose a constrained relation between parameters obtained from IP acquisition and pore surface area.
Hydraulic permeability	Revil and Florsch [2010] relate the hydraulic permeability of a granular material to its spectral IP properties [Koch et al., 2012].

Table 4: The IP method ability to characterize levee properties and characteristics.

3.4 Low-frequency near-field electromagnetic induction method (Slingram)

The low-frequency near-field electromagnetic induction (EMI) method is an active method giving information on the field apparent electrical conductivity $\sigma_a [S.m^{-1}]$ and on the magnetic susceptibility. The method consists in using vertical and/or horizontal coils in which an alternating current is flowing with a known frequency, inducing a primary magnetic field H_P [McNeill, 1980]. The encountering of this magnetic field with a conductive anomaly generates a secondary field H_S . Thanks to a coil, the total field H_T is measured, corresponding to the sum of H_P and H_S . The Slingram method is a specific EMI method with short distance coils [Delefortrie et al., 2014]. Under the low induction number approximation [McNeill, 1980], the investigation depth is function of the distance s between the coils and of the acquisition mode. When the coils are coplanar and horizontal, the investigation depth is about $s/2$ while when they are vertical, the investigation depth is about $3s/2$ [Fauchard and Mériaux, 2007]. These kinds of methods, when used qualitatively, allow a quick (cost-effective) assessment over the whole levee length (flood protection system). They are often used for preliminary field studies. Nabighian [1991] explains that power lines and cables can cause electromagnetic perturbations in the Slingram acquisitions and that the temperature changes can cause drift or errors in the in-phase readings such as topographic effects. Thiesson et al. [2017] propose a 3D linear inversion method for the processing of magnetic susceptibility variation data derived from the method of moments. In this work, 1D non-linear inversion scheme is first applied, point by point, to identify the vertical distributions of magnetic susceptibility and electrical conductivity.

Inazaki and Hayashi [2011] use the Slingram method to obtain an apparent electrical conductivity map all around a levee on which they conduct geophysical methods. Sentenac et al. [2017] use the Slingram method all along an earth dam axis to obtain resistivity profiles and characterize anomalies. Tezkan [1999] proposes a review concerning different electromagnetic methods using a magnetic dipole or coils, such as Slingram, or electromagnetic methods using a remote plane-wave source of excitation, such as radio magnetotelluric. The

- 1 latter is not presented in this paper because it does not appear much in the literature about levee investigation.
 2 Additional information on the method can be found in Everett [2012]; Nabighian [1991] and recent use for
 3 hydrogeological studies in Calamita et al. [2015] and in Boaga [2017]. The method capability to characterize
 4 levee properties is presented in Table 5.

Levee properties and characteristics	Characterization ability
Water content	The electrical conductivity increases along with water content [Brevik et al., 2006; Hanson and Kaita, 1997; Kachanoski et al., 1990; Khakural et al., 1998].
Interfaces	Can detect vertical conductivity interfaces caused by changes along the levee such as the presence of a zone including a repaired breach [Morris, 2012]. Sherlock and McDonnell [2003] use the Slingram method to estimate a water table depth.
Granulometry	Used to delineate clay lenses [Cockx et al., 2007], to estimate depth to claypans [Doolittle et al., 1994] or to map sand deposits [Kitchen et al., 1996].
Heterogeneities	Can be detected, especially conductive anomalies but Thiesson et al. [2009] show the ability of the method to detect resistive features in a conductive medium. The method is often used in archaeological problematics to detect a target.
Man-made pipes	Recommended for the buried metallic structure detection [Huiming et al., 1990; Tabbagh and Verron, 1983].
Cavities	Used to characterize the lateral karst extension in rock areas [Vogelsang, 1987]. Depends on size, depth and if the cavities are filled or not. Bibliographic references concerning the cavities detection in levee problematic remain sparse [Fauchard et al., 2004].

Table 5: The low-frequency near-field EMI method ability to characterize levee properties and characteristics.

5 3.5 Ground penetrating radar method

- 6 This method is an electromagnetic high frequency method (from 10 MHz to 1 GHz) [Kearey et al., 2013].
 7 The ground penetrating radar (GPR) measures a round trip propagation time of the radar wave pulse in the

1 ground and variations of amplitude and phase of this wave. If the medium is globally homogeneous with
 2 presence of reflectors, value can be deduced, informing on interfaces depth and other reflectors [François
 3 et al., 2016]. Di Prinzio et al. [2010] use a 250 MHz central frequency antenna to monitor river embankments
 4 and display the values of maximum spatial resolution and penetration depth for some nominal frequency val-
 5 ues.

6
 7 Waves are issued from an antenna and propagate through the ground. When the wave encounters a di-
 8 electric permittivity contrast, [$F.m^{-1}$], a part is transmitted and a part is reflected back to the surface and
 9 recorded by the radar. The investigation depth depends on the chosen central frequency of the antenna and
 10 on the electrical conductivity of the levee materials. The presence of very resistive materials or the use of low
 11 frequency allows a deeper investigation depth (with a lower resolution). The depth can vary from 0 m in very
 12 conductive materials to 50 m for very low conductivity material (less than $1 mS.m^{-1}$) [Smith and Jol, 1995].
 13 While 2D full waveform inversion of ground penetrating radar data is effective [Lavoue, 2014], the 3D full
 14 waveform inversion is still under research [Watson, 2016]. For further insight concerning the method and the
 15 data processing as well as the inversion, complementary and complete information are available in Annan
 16 [2005]; Benedetto and Pajewski [2015]; Daniels [2005]; Jol [2008]; Lai et al. [2018]. To take benefits of it,
 17 the GPR needs a material with a resistivity value greater than $100 \Omega.m$ [Bièvre and Maurin, 2002] and with
 18 a low water content since it affects the GPR velocities and attenuation [Antoine et al., 2015]. The method is
 19 disturbed by metallic and/or emitting structures such as power lines, metal walls, radio transmitters...

20
 21 This investigation method is not often used for levee diagnostic since they are usually too conductive
 22 (presence of clays, high water content...) to allow a deep investigation [Fauchard and Mériaux, 2007]. How-
 23 ever, hereafter are a few works dealing with the GPR method on levees: [Antoine et al., 2015; Carlsten et al.,
 24 1995; Johansson and Dahlin, 1996; Marcak and Golebiowski, 2014; Tanajewski and Bakula, 2016]. As
 25 done in Busato et al. [2016], the GPR is often used in bi-static configuration to improve the highlighting of
 26 anomalies and water content differences. The method capability to characterize levee properties is presented
 27 in Table 6.

28

Levee properties and characteristics	Characterization ability
Water content	For all soils, the apparent permittivity significantly increases with the value of water content [Topp et al., 1980]. West et al. [2003] and Kuroda et al. [2009] quantify water content while Huisman et al. [2003] propose a complete review dedicated to the estimation of soil water content [Turesson, 2006].
Interfaces	According to the type of materials, interfaces can be characterized [François et al., 2016]. An interface between a sandy material and a subjacent clayey one will for example be striking [Kearey et al., 2013]. The detection is eased with a large dielectric contrast.

Table 6: The GPR method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Cracks	Is sensitive to voids and technically able to detect cracks in the levee materials if they are large enough and depending on the antenna's frequency. Xu et al. [2010] detected cracks in sloping clay core and Grasmueck [1996] uses this method for imaging fractures in gneiss.
Heterogeneities	Is a function of the size, depth, nature of the heterogeneity and of the host material. Biavati et al. [2008] detect repaired areas, construction levels and hidden elements in embankments. However, the detection of pluri-centimetric rocks in a fine-grain material seems complex and depends on the investigation depth which is function of the frequency.
Man-made pipes	Metallic pipes and cables can easily be detected [Pettinelli et al., 2009; Royet et al., 2013].
Cavities	Air filled, water filled and clay filled cavities can be detected if there is no clayey cover masking the cavity. Xu et al. [2010] detect voids inside levees. Di Prinzio et al. [2010] and Chlaib et al. [2014] detect small scale burrows of animals.
Compactness	An increase of the soil compactness induces an increase of the dielectric permittivity [Scholte et al., 2002]. However, it is very complex to determine precisely the compactness or porosity value. [Araujo et al., 2016; Golebiowski, 2010].

Table 6: The GPR method ability to characterize levee properties and characteristics.

1 3.6 Nuclear magnetic resonance (NMR) method

2 The nuclear magnetic resonance (NMR) method can be used as a laboratory, borehole or field method
3 [Behroozmand et al., 2015]. A magnetic field is generated, at a specific frequency, by means of a loop
4 disposed on the levee surface, in order to perturb the equilibrium state of the hydrogen protons composing
5 the water molecules. Once the magnetic field is shut down, the protons come back to their equilibrium state
6 and a magnetic field is induced by the relaxation of the excited protons. This phenomenon is called the
7 NMR response. The NMR response gets more significant as the amount of excited protons gets larger. That
8 is why it can directly be correlated to the water content in the subsoil, to the thickness of the groundwater
9 table and to the hydraulic conductivity [Hertrich, 2008; Legchenko et al., 2002; Yaramanci et al., 1999]. The

1 depth of groundwater detection with this method depends on the measurement conditions but an average
 2 depth of investigation of about 100 m can be estimated [Legchenko et al., 2002]. One of the limiting factors
 3 is the electrical conductivity of the studied structure. Indeed, the investigation depth strongly decreases for
 4 resistivity values below 10 Ω .m [Baltassat and Legchenko, 2003] and if the magnetic field intensity is low.
 5 A special attention must also be given to all electromagnetic field disturbers such as electrical transformers,
 6 high-voltage lines, storms...

7
 8 Irons et al. [2014] used the NMR method to monitor internal erosion and piping in an earthen embank-
 9 ment. Detailed and complete information are available in Behroozmand et al. [2015]; Legchenko et al.
 10 [2002]; Weichman et al. [2000], as well as reviews of the advances in data processing, forward and inverse
 11 modelling and hydrological parameter estimations from NMR method. The method capability to character-
 12 ize levee properties is presented in Table 7.

13

Levee properties and characteristics	Characterization ability
Water content	Especially dedicated to the detection and estimation of water content, even though the discrimination between free and bound water remains complex [Legchenko et al., 2002].
Granulometry	According to the nature of the materials, the relaxation times are different. These are dependent of the pore size and of the surface relaxivities or large magnetic susceptibilities [Behroozmand et al., 2015; Legchenko et al., 2002].
Cavities	A water-filled cavity is detectable whereas an air-filled one is not [Chalikakis et al., 2011].
Compactness	Porosity can be evaluated in a saturated media [Chang et al., 1994; Grunewald and Knight, 2011; Kenyon, 1997; Legchenko et al., 2002].
Hydraulic permeability	Relation exists between the relaxation times and the hydraulic permeability [Kenyon, 1997]. For saturated media and if the porosity is well constrained [Chang et al., 1994; Legchenko et al., 2002]).

Table 7: The NMR method ability to characterize levee properties and characteristics.

3.7 Seismic refraction tomography method

Seismic refraction and seismic reflection methods can be used to characterize the sub-surface. However, we do not detail the seismic reflection method since it requires specific technologies to be used on a small scale problematic such as levee investigation. The characterization of the first 10 meters could be done with high-resolution seismic reflection method, but it still remains under study.

The seismic refraction method uses P-waves (or S-waves) arrival times to determine the seismic velocities, v [$\text{m}\cdot\text{s}^{-1}$], of different layers and their associated thicknesses. The equations governing the propagation of these waves are those used in optics (Snell-Descartes principles). A seismic source is generated at various locations and geophones are aligned on the surface, recording the seismic waves arrival times. The body waves are refracted on the interfaces of two layers of different mechanical impedance. With the arrival times, seismic velocities can be determined [Kearey et al., 2013] and a 2D cross section can be obtained [Dérobert and Abraham, 2000; Hagedoorn, 1959]. In order to use this method, the seismic velocities are required increasing with the depth. Many unwanted noise sources (vehicles, wind, storms...) are susceptible to alter the data quality. If a water table is present, the P-waves velocity will be modified and the interpretation will be tougher unless the expert is looking for the groundwater table. The seismic refraction tomography uses the interfaces' depths determined by the seismic refraction method. Its goal is to obtain a clearer image using inversion process. White [1989] proposes a tomographic inversion process for the 2-D velocity structure determination from first-arrival traveltimes while Zelt and Barton [1998] compare two tomographic methods for the determination of 3D velocity structure. In particular, Boschetti et al. [1996] implemented an algorithm to solve the inverse problem with several sets of synthetic seismic refraction data. Sheehan et al. [2005a] also evaluate and compare various methods and available software for seismic refraction tomography analysis.

The investigation depth of the seismic refraction method is function of the nature of the seismic source, the length of the profile and the nature of the investigated materials [Hilbich, 2010]. For a source consisting of a hammer and a plate, 10 meters is a rather good investigation depth.

The seismic refraction method has been used for earth dams investigation in Heiland [1940]. However, apart from its combined use with geophysical methods [Cardarelli et al., 2014] or to detect the bedrock's top. Its single use remains quite unusual in levee problematic. Detailed information concerning this method can be found in Palmer [1980] and in ASTM [2011a]. The method capability to characterize levee properties is presented in Table 8.

Levee properties and characteristics	Characterization ability
Water content	Can be used to estimate the groundwater level [Haeni, 1988; Zohdy et al., 1974] but not for the estimation of soil water content.
Interfaces	If the acoustic impedance contrast between two layers is large enough, can determine the depth of such an interface [Bell, 2007; Kearey et al., 2013].

Table 8: The seismic tomography method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Cavities	Animal burrows can have a very small effect on the data acquisition, but their characterization is almost impossible [Kneibler, 1985]. Can detect larger cavities such as karsts. The presence of a layer of high seismic velocity can still be an obstacle to the detection of cavities [Chalikakis et al., 2011; Sheehan et al., 2005b].
Compactness	The P-waves velocity tends to increase with the compactness [Eaton and Watkins, 1967; Yu et al., 2016].

Table 8: The seismic tomography method ability to characterize levee properties and characteristics.

1 3.8 Multi-channel analysis of surface waves (MASW) method

2 The Multi-channel Analysis of Surface Waves (MASW) method was introduced in the late nineties [Park
3 et al., 1999] and [Xia et al., 1999]. It consists in studying the surface wave's dispersion (waveform defor-
4 mation) in order to determine the shear wave's velocity. The array implementation is similar to the one used
5 for the seismic refraction method. About the two-thirds of the seismic energy is transmitted by the surface
6 waves, they are less impacted by the environmental noises [Miller et al., 1999]. Park et al. [1999] break
7 down the method into three stages: (a) the data acquisition, (b) the determination of the Rayleigh disper-
8 sion curve, and (c) the inversion process with the determination of the shear velocities. These velocities can
9 be constrained during the inversion process using information on the P-waves velocities and the interfaces
10 depth, obtained by the seismic refraction method. The investigation depth is function of the wavelength of
11 the source signal and of the array length, about a quarter of the array length according to Lagabrielle [2007].
12 The investigation depth increases along with the decrease of the source frequency and can go deeper with
13 natural sources. In order to be correctly used, this method requires a flat topography and a horizontally lay-
14 ered medium. An important acoustic impedance contrast between the different media is also needed to be
15 able to distinguish them. The resolution is directly related to the inter-geophone spacing.

16
17 Many complementary information about the MASW method are presented in Park et al. [1999, 2007];
18 Socco et al. [2010]; Xia [2014]; Xia et al. [1999]. Surface waves have been used by Karl et al. [2011] in ac-
19 tive mode and by Le Feuvre et al. [2015] in passive mode to characterize river or sea levees. Lin et al. [2004]
20 present the use of MASW for assessing the soil liquefaction potential which can lead to the levee failure.
21 "Although the model used to solve the inverse problem in surface-wave method is always one dimensional"
22 as written in Socco et al. [2010], some authors take into consideration some side effects to improve their 1D
23 model Strobbia and Foti [2006]. Bohlen et al. [2004] propose 1.5D model by concatenating 1D model with
24 lateral constraints in the inversion. The method capability to characterize levee properties is presented in
25 Table 9.

26

Levee properties and characteristics	Characterization ability
Interfaces	The acoustic impedance contrast must be big enough between two layers [Karl et al., 2008; Lane Jr et al., 2008].
Cracks	Presence of fractures in the subsoil modifies the acquired signal [Chalikakis et al., 2011; Parker Jr and Hawman, 2012] but, to our best knowledge, the size and extension of the cracks cannot be precisely determined.
Heterogeneities	Is a function of their size and nature. If the heterogeneity dimension is below the resolution level, it cannot be detected. Lin and Lin [2007] use the lateral variation of surface waves velocities to detect lateral heterogeneities.
Cavities	Large cavities can be detected [Chalikakis et al., 2011; Nolan et al., 2011], but the MASW method is usually combined with one or more methods. [Debeglia et al., 2006] combine it with microgravimetry to detect karsts in an urban environment. The use of MASW to detect cavities is still under study and remains a tough problem [Bitri et al., 2016]. To our best knowledge, animal burrows would not be detected into a fluvial levee.
Compactness	Yu et al. [2016] bring out the effects of porosity on seismic velocities and elastic modulus for solid materials and rocks. The porosity/compactness value of a levee cannot be precisely determined but zones of deconsolidated soils can be detected [Morris, 2012].
Shear strength	The seismic velocities are linked to the dynamic shear and Young's modulus [Karl et al., 2011]. Privileged geophysical method to characterize the shear strength of the levee material.

Table 9: The MASW method ability to characterize levee properties and characteristics.

1 3.9 Acoustic method

2 The acoustic method is a passive method that consists in recording the pressure variations on hydrophone
3 membrane induced by acoustic waves. These waves are assigned to potential water leakage inside the levee
4 or dam. As for internal erosion processes with water leakage, the grains movement provokes acoustic waves
5 with a frequency from 15 to 20 Hz [Bolève et al., 2012], potentially audible and measurable. François

1 et al. [2016] distinguish two measurement methods : (1) direct leakage estimation by an expert ear or (2) a
 2 posteriori data processing after recording the acoustic signal. Many recordings need to be carried out close to
 3 the abnormal area in order to determine its extent [Bolève et al., 2012]. Rittgers et al. [2014] use geophones
 4 instead of hydrophones for acoustic emissions localizing. Koerner et al. [1981] propose a review paper on
 5 acoustic emission behavior in soils, having the dam and levee as a case study. This method can be affected
 6 by parasitic noises such as storms or rainfall [François et al., 2016].

7 3.10 Micro-gravimetry method

8 Results of a micro-gravimetry campaign are expressed as gravity field anomalies, named Bouguer gravity
 9 anomaly [gals]. This investigation method relies on the study of gravity field variations associated to un-
 10 derground mass anomalies (positive or negative), using a micro-gravimeter. These mass anomalies can be
 11 associated to density variations. The smallest significant anomaly that can be measured is about 10 μ gal
 12 according to Yule et al. [1998] and about 20 μ gal according to Lagabrielle [2007]. No true investigation
 13 depth can be given since the detection of an anomaly is function of the nature, dimension and depth of the
 14 anomaly, except if the hypothesis of a cylindrical anomaly is made. A very deep but large and contrasting
 15 anomaly could thus be sensed. However, since the measures are inverted, the extension of the measurements
 16 and of the gravimetric investigation has an impact on the investigation depth. Li and Oldenburg [1998]
 17 display two methods for the surface gravity data inversion in order to recover a 3-D distribution of density
 18 contrast. For the use of micro-gravimetry method, measurements need numerous corrections (drifting of
 19 device imputed to the change of latitude, luni-solar tide, surrounding reliefs...) detailed in Nowell [1999].
 20 Elevation values must be recorded precisely for each point using a digital elevation model. Fauchard et al.
 21 [2004] point out the dimension of the measurement mesh : an optimized mesh is essential to get relevant re-
 22 sults. The work of Debeglia and Dupont [2002] presents some critical factors for microgravity investigations.

23
 24 The micro-gravimetry method is not often used for levee problematic. However, Blížkovský [1979];
 25 Butler [1980]; Kearey et al. [2013] and Torge [1979] provide additional general information about gravity
 26 surveying. The method capability to characterize levee properties is presented in Table 10.

27

Levee properties and characteristics	Characterization ability
Heterogeneities	Positive (higher density) or negative (lower density) anomalies are detected if the density contrasts are high enough [Butler, 1980].
Cavities	Historically adapted method. Many works have been carried out concerning the detection of cavities in karst areas [Butler, 1984; Styles et al., 2005]. Empty cavities are easier to detect than the filled ones [Chalikakis et al., 2011]. Depends of the size, density contrast and depth.
Compactness	Tuckwell et al. [2008] use this method to characterize low-density ground.

Table 10: The micro-gravimetry method ability to characterize levee properties and characteristics.

3.11 Temperature based method

The infrared (IR) thermography method can estimate the temperature of a targeted object from its IR emission intensity, using an IR camera [Gaussorgues, 1999]. The measurement precision is around a tenth of a Celsius degree [François et al., 2016]. Unfortunately, this method cannot provide information on the internal levee structure since the maximum investigation depth is about a few centimeters. It is necessary to choose the correct time to do the investigation in order to have a correct lighting without shadow. Measurements cannot be done under rainy conditions or a too sunny weather. Vegetation density has to be very limited [Armbruster et al., 1989] and it shall be ensured that there are no warm bodies around likely to generate radiation interference (pylons, concrete walls...) [Mériaux et al., 2000].

The temperature contrast on the surface of a levee allows the detection of water leakage [Armbruster et al., 1989; Huang et al., 2010]. The IR thermography investigation method can be done on foot, by car, plane, helicopter or even with drones [Miquel et al., 2016]. Intrusive methods based on temperature acquisitions are also used for levee assessment. Dornstädter and Heinemann [2012] for example, use temperature probes and fibre optic temperature sensing for levee monitoring, detecting water flows inside the structure. The method capability to characterize levee properties is presented in Table 11.

Levee properties and characteristics	Characterization ability
Water content	Deitchman and Loheide [2009] bring to light the limit between saturated and non-saturated areas on sides of a drainage ditch. They were able to monitor the groundwater discharge process and distinguish different discharge rates. Grinzato et al. [2011] study the water content of buildings' walls.
Cavities	Can be useful for detecting animal burrows, only if they are inhabited [Boonstra et al., 1994]. But it does not provide information concerning the galleries' extension. Fauchard et al. [2004] explain that the airborne method can inform on the presence of potentially large cavities, but does not seem relevant for application to levees.
Flow velocity	Deitchman and Loheide [2009] are able to establish a qualitative link between temperature and hydraulic permeability at leakage position.

Table 11: The IR thermography method ability to characterize levee properties and characteristics.

4 Geotechnical investigation methods

The objective of a geotechnical investigation campaign is to provide punctual information on the levee structure, informing on the presence of interfaces and anomalies. These information can then be used to calibrate the geophysical data and to improve the characterization of the levee, informing on the mechanical properties of the different layers. Thanks to these geotechnical methods, geotechnical models of levees can be generated and then used to model scenarios of rupture. These investigation methods can be divided into two categories : (a) laboratory testing on soil sample and (b) in-situ testing. Concerning the detection of cavities and man-made pipes, obviously all in-situ testing are able to determine their presence if the borehole has been done through, if not, no relation can be made.

4.1 Laboratory testing on soil samples

The material extractions allow the identification of the soil and the understanding of its mechanical behavior as well as the lithology determination. The extraction can be made by using an auger or by coring. Laboratory testing have the benefit to provide very accurate information, however they do not study the in-situ sample and consequently some environmental parameters are not taken into account. That is why it is important to carry out laboratory testing to characterize a soil even if the measured parameters can differ from the in-situ ones. The article focuses on in-situ methods, explaining why we will not detail them. Moreover, these methods exclusively characterize one soil property. A non-exhaustive list of laboratory testing techniques usually used for levee investigation is proposed below.

Identification tests :

- Atterberg limits (plasticity indexes, clay content) [ASTM, 2017c]
- Methylene blue test (clay content) [ASTM, 2014]
- Particle size analysis [ASTM, 2017d]
- Sedimentation size analysis (particle size below 75 μm) [ASTM, 2017b]
- Void ratio test (relative density) [ASTM, 2017a]
- Water content test [ASTM, 2010]

Mechanical characterization tests :

- Compaction test (Proctor) [ASTM, 2012]
- Unconfined Compressive Strength test [ASTM, 2016]
- Hydraulic permeability test with a permeameter under constant or variable applied load [ASTM, 2015b]
- Oedometer test (soil's consolidation properties) [ISO, 2017b]
- Shear test (Casagrande shear box test) [ISO, 2017a]
- Triaxial compression test [ASTM, 2011b]
- Hole Erosion Test (critical shear stress value and coefficient of erosion) [Fattahi et al., 2017]
- Jet Erosion Test [Marot et al., 2011]

4.2 Drilling parameters recordings

When a geotechnical survey is executed, many parameters are recorded in order to characterize the levee mechanical properties and to take advantage of the executed borehole. The drilling rig can drill through the levee with an established depth and diameter. While drilling, the device is cooled by a drilling fluid. Accord-

ing to Cailleux [1986] and then updated Reiffsteck [2010] and François et al. [2016], the drilling parameters can be classified into four categories:

3

4 - parameters imposed by the device and the method, unrelated to the acquired data (device dimensions,
5 fluid injection, drilling rig limits);

6 - instrument parameters fixed by the user (thrust applied on the device, rotational speed, fluid flow);

7 - parameters related to the environment (rotational couple, injection pressure, progress speed, fluid flow
8 return);

9 - independent evolving parameters (modification of the fluid composition, deterioration of the device).

10

11 In order to have correct drilling parameters, it is necessary to maintain constant the thrust applied on the
12 device, the injection flow, the rotational speed [Reiffsteck, 2010]. Corrections also need to be made in order
13 to take into account the deterioration of the device and the modification of the fluid composition. Riechers
14 [2012] presents the impact of drilling in embankment dams, in particular the associated risks. Complementary
15 information about the drilling parameters recordings can be found in Gui et al. [2002]; Pfister [1985]; Reiff-
16 steck et al. [2012].

17

18 Girard et al. [1986] and Reiffsteck [2010] point out the relations between the drilling parameters and
19 the soils characteristics. Different media can present equivalent drilling parameters. Reiffsteck et al. [2012]
20 present the example of heterogeneous soils with coarse grains: the thrust applied on the device and the
21 rotational couple decrease considerably with the presence of water since the coarse grains are lubricated and
22 rejected by the drill. That is why it is necessary to combine the drilling parameters with other data in order
23 to constrain the levee model. The method capability to characterize levee properties is presented in Table 12.

Levee properties and characteristics	Characterization ability
Water content	To our best knowledge, the water content cannot be determined even though the amount of water affects the method values since it has an impact on the soil plasticity.
Interfaces	If the contrast of nature between two formations is strong, interfaces can be detected. Duchamp [1988] proposes the use of a complementary method using the entropy to enhance the interface detection. François et al. [2016] point out the use of drilling parameters to inform on the water table level.
Granulometry	Relative information can be obtained by comparing drilling parameters of different materials. The fluid injection pressure is related to the amount of fines [Reiffsteck et al., 2012].

Table 12: The drilling parameters recordings ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Compactness	The progress speed is directly related to the mechanical resistance of the penetrated formation. It is therefore possible for two media of same composition, to establish which one is more compacted. The effective thrust also differs according to the stiffness of the penetrated medium. The Soil Rock Sounding relation can as well be used to characterize the compactness of the soil: it is similar to the penetration resistance [Möller et al., 2004].
Hydraulic permeability	With the correct shape factor (below or over the water table), the relative hydraulic permeability can be estimated according to the variations of the fluid injection flow on the adjusted injection pressure [Reiffsteck et al., 2012].
Shear strength	The rotational couple can be associated to a shear test with the effective thrust being the vertical stress [Reiffsteck et al., 2012]. However Gui et al. [2002] show poor correlation between the undrained shear strength and the recorded drilling parameters.

Table 12: The drilling parameters recordings ability to characterize levee properties and characteristics.

1 4.3 Cone penetrometer test

2 The cone penetrometer test (CPT) consists in pushing rods into the soil, at a constant speed, with a conical
3 tip at the end [ISO, 2012a]. Different tip geometries exist. This test is often used for the determination of
4 the soils mechanical resistance properties. A piezocone can be added to the rod, giving information about
5 the interstitial pressure u [kPa], the test is then named CPTu. The two measured parameters are the tip re-
6 sistance q_c [MPa] and sleeve friction f_s [MPa]. Thanks to these parameters variations, the different subsoil
7 media are distinguishable. Robertson [1990] proposes a soil classification relying on the measured CPT
8 parameters. This classification is widely used in civil engineering. An update of this classification has been
9 proposed in Robertson [2016]. Concerning its limitations, the method is not workable in the presence of
10 stones (pluridecimetrics). Furthermore, it needs a heavy truck and a roadway which is why it can only be
11 used on the levee crest. The drill pipe inclination also needs to be taken into account and the test needs to be
12 calibrated with other tests.

13

14 Additional information concerning the CPT and CPTu tests can be found in Lunne et al. [1997], in the
15 dedicated standard [ISO, 2012a], in Robertson and Cabal [2015] and in Ameratunga et al. [2016]. For levee
16 investigation, the CPT method is usually not used alone but combined with other methods [Bélangier et al.,
17 2010]. The method capability to characterize levee properties is presented in Table 13.

18

Levee properties and characteristics	Characterization ability
Water content	The combined use of time-domain reflectometry (TDR) water content probe and CPT test shows that the modification of water content modifies both the tip resistance and the sleeve friction [Vaz et al., 2001; Zawadzki and Bajda, 2016]. Though, the impact of the water content seems to be a function of the material, consequently, it still remains difficult to evaluate the exact water content.
Interfaces	Easier to detect given that the contrast between the materials is strong (interface between clays and sands). The different sets of materials are quite easy to distinguish, Hegazy and Mayne [2002] propose the use of the cluster method in order to characterize them using data from the piezocone (CPTu).
Granulometry	Assuming a stone-free homogeneous medium, one can use Robertson's soil classification [Robertson, 1990, 2016].
Heterogeneities	Is able to characterize the vertical variations of stiffness and tip resistance.
Compactness	Tip resistance is directly related to the density and compactness of the penetrated material [Baghdad et al., 1993].
Hydraulic permeability	Can only be estimated with a CPTu, for a saturated medium, thanks to the interstitial pressure values. Van Baars and Van De Graaf [2007] propose the estimation of compressible soils' hydraulic permeability using a piezocone. Robertson and Cabal [2010] propose a permeability estimation using the Soil Behaviour Type (SBT).
Shear strength	Can be obtained from the tip resistance and constrained with the interstitial pressure (CPTu). It has been experimented for clays by Konrad and Law [1987] and Rémai [2013].

Table 13: The CPT method ability to characterize levee properties and characteristics.

1 4.4 Field vane shear test

2 The field vane shear test consists in imposing an in situ shear constraint in order to characterize the undrained
 3 shear strength (S_u) of the material. This test is described in ASTM [2015a]. A vane composed of 4 perpen-
 4 dicular plates is pressed into the ground. Once the vane is at the chosen depth, a torque is applied and the
 5 modification of the torsional moment [$\text{kN}\cdot\text{m}^{-1}$] is measured thanks to a torquemeter. These values can then
 6 be linked to the undrained shear strength S_u [kPa]. To do so, correction factors need to be taken into account,
 7 associated to the plasticity index and to the soil's state of consolidation [Bjerrum, 1972]. Different correc-
 8 tions factors have been proposed [Chandler, 1988; Morris and Williams, 1994]. This test is acknowledged
 9 for its robustness, simplicity and quick implementation [Ameratunga et al., 2016]. It is the recommended
 10 test to estimate a short-term embankment stability. This test is not adapted for all materials. It cannot be
 11 used within soils with undrained strengths below 200 kPa, neither in high permeability soils such as sands
 12 or gravels. Furthermore, intervals of 0.5 m minimum vertical depth are necessary between two subsequent
 13 acquisitions [ASTM, 2015a].

14
 15 Description of the method and associated physical relations can be found in ASTM [2015a] and in
 16 Ameratunga et al. [2016]. Azzouz et al. [1983]; Bjerrum [1972]; Jamiolkowski [1985] and Larsson [1980]
 17 are devoted to the use of the field vane shear test in embankments. This method is mostly used on terrains on
 18 which a levee is to be built. The method capability to characterize levee properties is presented in Table 14.

Levee properties and characteristics	Characterization ability
Interfaces	Is unable to characterize interfaces since an acquisition can only be made each 0.5 m. However, it can distinguish two media with different shear strengths [Roy and Leblanc, 1988].
Heterogeneities	A weakened zone can be detected if the shear strength is lower than in the surrounding material.
Compactness	The undrained shear strength informs on the plasticity index of the soil and thus on the state of cohesion. Ameratunga et al. [2016] propose relations between undrained shear strength and plasticity index for normally consolidated soils and over consolidated soils. However, to characterize compactness of a medium from its shear strength, the material needs to be known beforehand.
Shear strength	Best in situ method to characterize the shear strength of a medium, considering its limitations, as stated above.

Table 14: The field vane shear test method ability to characterize levee properties and characteristics.

4.5 Pressuremeter test

The test is described in ISO [2012b]. To be executed, a pre-drilling first needs to be made. It consists of a cylindrical probe lowered in the borehole. An increasing pressure is applied on the probe that in turn applies a stress on the walls' borehole, the radial deformation is then measured [François et al., 2016]. The relation between the applied pressure and the measured deformation allows the characterization of the soil mechanical properties. A stress-strain curve can be established, it can lead to the characterization of three parameters [Cassan, 2005]:

- the pressiometric modulus (E_M) defines the soil pseudo-elastic comportment;
- the pressure limit (P_{LM}) corresponds to the soil rupture stress;
- the creep pressure (P_f) is the boundary between the pseudo-elastic and the plastic state.

The pressiometric curve involves the angle of friction that can then be deduced [Monnet, 2012a,b]. The limits of the method concern the execution time and the fact that the pressiometric modulus is not an intrinsic mechanical characteristic of the soil. The admissible stress and the settlement foundation are not estimated precisely [Monnet and Khlif, 1994]. This method can only be used with a vertical spacing of at least one meter [François et al., 2016] and the vertical stress remains constant.

The detailed methodology can be found for sands [Hughes et al., 1977; Jewell et al., 1980], granular soils [Monnet, 2012a,b] and clays [Thevanayagam et al., 1994]. Cassan [2005] and Mair and Wood [2013] also propose a state of art concerning this method. The pressuremeter is very rarely applied to levee investigation. The method capability to characterize levee properties is presented in Table 15.

Levee properties and characteristics	Characterization ability
Granulometry	The fraction P_{LM}/P_f and E_M/P_{LM} (known as the rheological factor α) can be related to the grain size [Cassan, 2005; Fawaz et al., 2014].
Heterogeneities	By comparing different acquisitions, it is possible to determine if the medium is heterogeneous or not. However, characterizing precisely one or more heterogeneities is not practicable.
Compactness	Can inform on the relative stiffness of the different layers [Fahey, 2005]. It can also be related to the tip resistance by the relation $P_{LM} \leq 0.3 q_d$ [Lepetit, 2002].
Hydraulic permeability	Estimation from the pressuremeter curve have been published for clayey materials [Zentar, 1999] and [Rangeard et al., 2003] but they concern only pressuremeter equipped with an interstitial pressure sensor and for specific range of permeability.

Table 15: The pressuremeter method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Shear strength	Determines the shear modulus from the slope of the pressure-expansion curve [Mair and Wood, 2013].

Table 15: The pressuremeter method ability to characterize levee properties and characteristics.

1 4.6 Hydraulic permeability tests

2 4.6.1 Lefranc test

3 The Lefranc test [Lefranc, 1936, 1937] is a field hydraulic permeability test in borehole for aquifers, which
 4 has known many modifications since its first use. To be used, this test needs a borehole with an open cavity
 5 at the end of it or with a double packer system. Whether a water injection or water pumping, with a constant
 6 flow, is used to produce a hydraulic head difference between the borehole and the groundwater table. This
 7 hydraulic head difference generates the measured water flow on which will be deduced the hydraulic perme-
 8 ability value. Hvorslev [1951] proposes the calculation of the hydraulic permeability according to the shape
 9 factor function of the shape of the cavity. Since then, many additional relations came to characterize that
 10 shape factor [Chapuis, 1989]. The Nasberg test is a variant from the Lefranc test; it allows the determination
 11 of hydraulic permeability in non-saturated media [Nasberg, 1951]. The method capability to characterize
 12 levee properties is presented in Table 16.

13

14 Concerning its drawbacks, this test can only be used for permeable media with a hydraulic permeability
 15 above 10^{-6} m.s^{-1} [Cassan, 2005] and the water table level must be known. The quality of the acquisition
 16 depends on the quality of the realization of the cavity. Furthermore, the investigation radius around the
 17 cavity is about 5 meters long, which is why it is relevant to use this method at different locations in order to
 18 establish an average permeability.

Levee properties and characteristics	Characterization ability
Granulometry	There is a direct link between the hydraulic permeability of a medium and its grain size. Hazen [1893] first proposes an empirical relation between the permeability and the grain size (D_{10}) for isogranular sandy soils and for $D_{60}/D_{10} < 2$. Many other relations were proposed since [Alyamani and Şen, 1993; Carman, 1956; Rawls and Brakensiek, 1989], each one with their imprecisions and limitations. More generally, a high permeability is associated to a coarse grain medium while a low permeability is associated to fine materials such as clays.

Table 16: The Lefranc test method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Hydraulic permeability	Can be determined, even though the method provides an average value with an investigation radius of 5 meters. Consequently, it gives a mean local hydraulic permeability value.

Table 16: The Lefranc test method ability to characterize levee properties and characteristics.

1 4.6.2 Permeafor test

2 The objective of the Permeafor [Ursat, 1992] is to perform a well logging permeability thanks to the ham-
3 mering of a tip specifically known. This method has exclusively been used in France. The benefit of this
4 method is to allow the detection of vertical variations of permeability. The vertical resolution is fixed by the
5 operator (10 to 50 cm). This test does not require to perform a pre-drilling contrary to the Lefranc test and
6 the use of a packer. The measurement is fast and the results exploitation is automated. A percussion drill rig
7 is required to drive the device into the soil. The permeability measurements are then performed for chosen
8 depths (usually each 20 cm) by imposing a constant hydraulic load for a duration that is fixed by the user
9 [Fargier et al., 2013]. The flow of injected water is known and the progressive insertion of the Permeafor's
10 tip informs on the compactness of the penetrated medium. One of the Permeafor's limitation is its range of
11 use, indeed it can only inform on the soil permeability for an hydraulic permeability lying between 10^{-3} and
12 10^{-7} m.s⁻¹ [Fargier et al., 2013]. The radius of influence is about a few centimeters around the strainer,
13 which is much less than the one for the Lefranc test.

14
15 Larrabee [2010]; Reiffsteck et al. [2009] describe in a more exhaustive way the modus operandi of the
16 device while Bièvre et al. [2017] and Fargier et al. [2013] show the benefit of using such a device for the
17 assessment of levees. The method capability to characterize levee properties is presented in Table 17.

Levee properties and characteristics	Characterization ability
Interfaces	The interface between two different layers can be approximately established [Bièvre et al., 2017] from a change of hydraulic permeability and/or resistance to penetration,
Granulometry	The relation between grain size and the hydraulic permeability measured with the Permeafor are the same as the ones explained in the Lefranc test part.

Table 17: The Permeafor test method ability to characterize levee properties and characteristics.

Levee properties and characteristics	Characterization ability
Heterogeneities	If a stiff heterogeneity is encountered, the Permeafor will be able to detect it thanks to the change in the penetration resistance value [Fargier et al., 2013].
Compactness	The penetration resistance given by the Permeafor's tip can inform the user on the compactness of a layer relatively to another if the material is known [Bièvre et al., 2017].
Hydraulic permeability	Its estimation is the main function of the device [Fargier et al., 2013; Larrabee, 2010; Reiffsteck et al., 2009]. However, it has some limitations, as explained above (range of use, clogging risk...).

Table 17: The Permeafor test method ability to characterize levee properties and characteristics.

5 Discussion

This work presents on a same level the use of geophysical and geotechnical methods for the assessment of levee properties and characteristics. However, the use of certain methods does not preclude the indispensable preliminary examination of the levee (visual inspection, historical research, topographical survey, morphodynamic, geological and hydrological). Furthermore, instead of considering them separately, the geophysical and geotechnical methods are treated equally in order to suggest their joint use. The adequacies of the presented geophysical and geotechnical methods to characterize levee physical properties or characteristics, thanks to the literature given in the precedent sections, are respectively summed up in Table 18. As mentioned already, concerning the detection of cavities or man-made pipes, all in-situ testing are able to determine their presence if the borehole has been done through, if not, no relation can be made.

Many studies already integrate several geophysical and/or geotechnical methods to characterize the subsoil. Concerning the geophysical methods, the ERT is a privileged one and often employed with other geophysical methods [Inazaki and Sakamoto, 2005; Turesson, 2006] or for joint inversion with seismic data [Gallardo and Meju, 2003, 2004; Karaoulis et al., 2012; Saunders et al., 2005] or SP data [Song et al., 2005; Tsourlos and Ogilvy, 1999] for example. However, geophysical investigations do not necessarily include ERT and can combine specific methods according to the purpose of the study : SP and acoustic methods for leakage localizing [Bolève et al., 2012] or MASW and microgravimetry methods for karst detection [Debeglia et al., 2006] as examples. Jardani et al. [2007] use joint inversion of SP and conductivity values to detect the preferential infiltration pathways in sinkholes while Cygal et al. [2016] use this technique with seismic and gravity data in a geological characterization problematic. Concerning the geotechnical methods, the CPT is a common technique often combined with at least the ERT method [Alvin et al., 2016; Sudha et al., 2009] or more methods such as the GPR [Bélanger et al., 2010] or seismic data [Shan et al., 2014]. Finally, some authors combine as much information as possible from several geophysical and geotechnical

1 methods to characterize an environment : Cosenza et al. [2006] for example simultaneously use the dynamic
2 penetrometer, the vane shear test, ERT, GPR and seismic refraction while Giao et al. [2008] use drilling
3 parameter recordings, cone penetrometer, field vane shear test, laboratory results and resistivity data.

4
5 This work brings to light the lack of references concerning the use of the IP method, micro gravimetry,
6 NMR, pressuremeter and permeability methods for levee problematic. This review spotlights the advantages
7 of these methods for characterizing particular levee properties and suggests their use for levee issues, accord-
8 ing to their respective limitations. Furthermore, we highlight the fact that some additional studies need to be
9 made concerning relations between some physical properties and the measured physical parameters. Indeed,
10 some relations have been proposed but are confined to laboratory experiments [Ghorbani et al., 2009; Giao
11 et al., 2003] or can only be used for solid materials and rocks [Titov et al., 2010; Yu et al., 2016]. From a
12 practical point of view, the fact that the methods are not necessarily made available for the levee managers
13 must be emphasized (e.g., Permeafor).

14
15 It also must be taken into consideration that the different described methods are more or less popular
16 for characterizing one or more levee physical property or characteristic. For example, the ERT and CPT
17 methods are commonly used for survey campaigns while the Permeafor use is still unusual. This popularity
18 influences the ability to execute a specific method. It often depends on multiple questions such as : what
19 feedback from previous experiences do we have ? For how long the method has been used to quantify such
20 property ? Is it cost-effective ? Is such equipment available in the country where the study takes place ?
21 Even though these are essential questions, we have not been able to classify the properties' characterization
22 popularity according to the executed method with enough reliable references. The cost, required time, and
23 the instrumentation availability have neither been detailed here since these topics are very variable according
24 to the country and location of the levee. The list of the detailed methods is not exhaustive and the laboratory
25 and in-situ tests meet national standards.

Geophysical and geotechnical method	Water content	Interfaces	Granulometry	Cracks	Heterogeneities	Man-made pipes	Cavities	Compactness	Hydraulic permeability	Shear strength	Flow velocity
Geophysical method	ERT	+++	++	+	+++	+++	+++	++	+	0	0
	SP	0	0	+	0	+(+)	+(+)	0	+	0	++(+)
	IP	+	++(+)	+	+++	+++	0	+	++	0	0
	Slingram	++	++(+)	0	+++	+++	+	0	0	0	0
	GPR	++	+++	0	++	+++	+++	+	0	0	0
	NMR	+++	(+)	+(+)	0	0	(+++)	++	++	0	0
	Seismic refraction tomography	+	+++	0	0	0	+	++	0	0	0
	MASW	0	++	0	+	(++)	(++)	(++)	0	+++	0
	Acoustic	+	0	0	0	0	0	0	0	0	(+)
	Micro-gravimetry	0	0	0	0	+	0	+++	+	0	0
	IR thermography	+	0	0	(+)	0	0	+	0	0	+
Geotechnical method	Drilling parameters recordings	+	++	0	+			++	+	+	0
	CPT	+	+++	0	++			+++	++	++	0
	Field Vane Shear Test	0	+	0	+			++	0	+++	0
	Pressuremeter	0	0	0	+			++	+	++	0
	Lefranc test	0	0	0	0			0	+++	0	0
	Permeator	0	++	0	+			++	+++	0	0

Table 18: Ability for geophysical and geotechnical methods to characterize a levee physical property or characteristic in most appropriate conditions given the literature used in this work. +++ corresponds to a strong relation between a parameter and a levee property, ++ corresponds to a reasonably good estimation of a property, + is associated to the existence of a very restricted sensitivity or to a method little employed or still under study while 0 means that the method is unable to characterize the property or that there is a lack of information in the browsed literature. Crosses in brackets are here to symbolize the lack of application of a specific method for characterizing a specific property on levees. Such symbols highlight the unexplored potentials for levee application.

6 Conclusion

In this paper, we highlighted the relations between pathologies and existing fluvial levee failure mechanisms. These pathological physical properties or characteristics can be assessed thanks to different investigation methods during a survey campaign. We presented the most commonly used geophysical and geotechnical methods and detailed their abilities to inform on each potential fluvial levee pathology under specific conditions. This work placed on an equal footing these two types of methods in order (a) to assist agencies and levee managers for selecting investigation methods thanks to the proposed sum up tables and (b) to interest the research community with the large quantity of bibliographic references proposed. It appears that ERT and CPT, a geophysical and a geotechnical method respectively, are the most likely to inform on a large number of levee properties. Conversely, more unusual methods, such as NMR or Permeafor, can inform more precisely on fewer but more specific properties. For each method, we pointed out their respective limitations and the potential lack of information or lack of application on fluvial levees. In the future, it would make sense to look for pertinent combination of information methods in order to take maximum advantage of both geotechnical and geophysical data. These combination methods would have to take into account the specificities of each kind of data (different natures, associated uncertainties, spatial distributions) in order to propose the best possible levee diagnosis.

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