Geophysical methods for reservoir safety investigations

By Calum Park, MSc

September 2017

Commissioned by the Environment Agency and

British Dam Society

Abstract

With aging water management infrastructure, and an increasing number of safety and flooding incidents occurring, there is a demand for more thorough and advanced safety monitoring of dams and other flood risk management assets in the UK. One answer to this often posited is the use of geophysical methods for sub-surface investigation. This paper reviewed the latest available geophysical methods and mapped them to asset types and the important processes of failure that might require detection, as well as their strengths and weaknesses in terms of suitability, cost, ease of use/deployment and interpretation. Asset types were principally characterised as permanently impounded structures (i.e. steady state seepage conditions) and flood defence dikes/levees/ storage (i.e. transient seepage conditions) with sub-categories for location (urban/rural/coastal).

The fact that many geophysical survey methods are well-researched and long established as a cost-effective alternative to traditional investigation techniques begs the question - Why have these practices not yet been adopted commercially on a significant scale? Rather than researching applications/ experimenting with new techniques, it is suggested that work should be focussed on producing clear implementation information for engineers/surveyors perhaps in the form of a field manual/guideline, and includes a suggested process and look up table that can be used to quickly identify the most appropriate geophysical technique for asset type/location/detection or investigation requirement.

Acknowledgements

The utmost thanks to my technical mentor Martin Hewitt, for his guidance and support throughout this research. I would also like to thank Dr Manousos Valyrakis, who's continued support throughout this project and in academia generally has been invaluable, as well as Dr Panagiotis Michalis and Jamie Menzies for taking the time to lend me their geophysical expertise and advice.

Contents

Abstract 2
Acknowledgements 3
1. Introduction 6
1.1 Motivations 6
1.2 Asset Characterisation 7
1.3 Failure Modes and Early Signs 10
1.4 Study Constraints 11
2. Analysis of Geophysical Methods 13
2.1 Electromagnetic Profiling 13
2.2 Electrical Resistivity Tomography (ERT) 14
2.3 Self Potential Method 16
2.4 Ground Penetrating Radar 17
2.5 Seismic Methods 18
2.6 Temperature Methods 19
2.7 Micro-Gravimetry 20
2.8 Magnetic Profiling 21
2.9 Other Methods 21
4. Comparative Summary of Analysis 22
4.1 Example of Geophysical Selection Method. 24
5. Conclusions and Proposed Research 26
5.1 Proposed Investigation Outline 26
5.2 Theory to Implementation 28
6. Appendices 29
a. Underlying Theory of Geophysical Methods 29
b. Geotechnical Investigations 33
c. Inverse Processing 33
d. A Note on the Advancement of Remote Sensing Techniques 34
References 35

Table of Figures

Figure 1- Schematic of two generalised asset categories 7
Figure 2- Surveyed Properties of UK embankment dams (Johnston et al., 1990) 9
Figure 3- Approaches to embankment monitoring (Fauchard and Mériaux, 2007) 12
Figure 4- EM measurement processed data (Fauchard and Mériaux, 2007) 13
Figure 5- EM data collection (Morris W. et al, 2008) 13
Figure 6- ERT electrode setup (RSK Geophysics, 2016) 14
Figure 7- 2D tomography from an ERT survey of Mugdock Dam (Michalis, Sentenac and Macbrayne, 2016) 14
Figure 8- Collation of 2D mappings into pseudo-3D contour plot (RSK Geophysics, 2016) 15
Figure 9- Colour contour plot produced by SP method for a reservoir (Frontier Geosciences, 2016) 16
Figure 10- Field Implementation pictorial and example of processed data from a GPR study. (A) highlights the top surface of a hidden underground storage tank (RSK Geophysics, 2016) 17
Figure 11- Diagram highlighting the different seismic waves and there travel path in the sub-surface (Royet et al., 2013) 18
Figure 12- Schematic sketch of the ground temperature sounding technique (Royet et al., 2013) 19
Figure 13- Contour Plot data using (Kappelmeyer GTC, no date) sounding method 20

1. Introduction

1.1 Motivations

The average age of UK reservoir impounding dams is well over 100 years, and the number of safety incidents occurring at dam and dike sites each year is on the rise (Mitchell, C, Brown, A & Morris, no date) with more thought to be going unreported. This is likely due not only to structures coming to the end of their lifetime, but also added pressure being exerted on flood safety assets due to an increase in the regularity of flooding conditions and extreme weather events. There is a clear need for detailed assessment of these assets in terms of their internal structuring and integrity and yet, the vast majority of dam inspection in the UK is merely visual. Visual inspections consist of checking for external indicators that an issue exists within the asset, such as cracking, movements or increased seepage flow. Although dam failure is rare, this form of assessment is reactive and may not identify an issue that is driven by internal processes until they are in progression. More detailed studies are sometimes carried out in the form of geotechnical investigation, but geotechnical methods are intrusive and costly when used over an entire site.

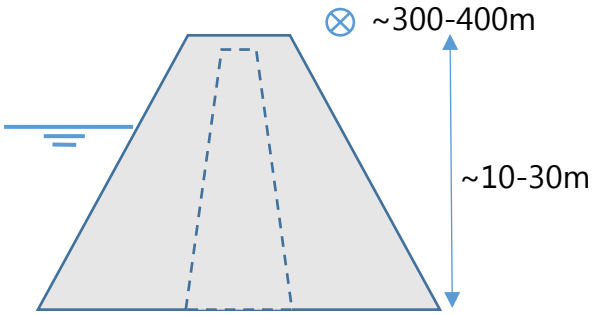
Geophysical methods have the potential to offer a comprehensive and cost-effective way of assessing the performance of dams and dikes non-intrusively that is complimentary to other surveying techniques and can be applied across large areas of sub-surface. This report is an overall analysis of the principle geophysical methods in existence that have potential for use in reservoir and flood safety assessment. It will include a review in terms of their respective strengths and weaknesses with a focus on resolution, cost, ease of use/deployment and interpretation. Each method is examined in terms of its application and suitability across a range of needs by first categorising potential sites by dimension, composition and environment, as well as the failure modes and requirements of the stakeholder. The summarised collation of this examination is in the form of a set of two tables of analysis, that can be utilised as a quick-reference comparison of the geophysical techniques. As different techniques have site-specific advantages and limitations, this will be valuable for selecting the most appropriate method for an investigation.

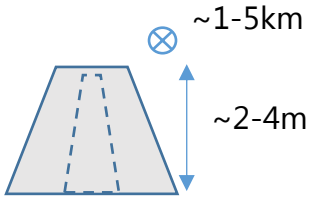
Care will be taken to present analysis in a digestible and concise manner accessible to someone with limited scientific expertise. Discussion will also provide an outline of a possible methodology for the most widely applicable investigation, an example of how to apply geophysical methods to a real site, and propose steps forward to better integrate these strongly scientific practices with large-scale engineering implementation.

1.2 Asset Characterisation

A proper characterisation of the sites and environments that stakeholders aim to monitor is necessary to make an informed analysis of the advantages and limiting factors of each respective geophysical technique. Table 1 is an extract of a report concerning asset typology from the Environment Agency Asset Information Management system (AIMs). It delineates the different man-made and natural Flood and Coastal Erosion Risk Management (FCERM) assets. It is assumed that all of these assets should be considered as potential sites for geophysical investigation.

Figure 2 is a table from 'An engineering guide to the safety of embankments in the UK' (Johnston *et al.*, 1990) (an industry standard) that categorises impounding dams by composition and size. It is worth noting from this the large number of dams with unknown internal structures. For the purposes of this investigation, it is useful to generalise FCERM's as broad categories of the most common/important asset types. This was done using the aforementioned documents and grouping assets in terms of their size and use, and then looking at the different environments and external factors that may impede an investigation. The majority of dams and dedicated flood defences are embankment structures (Johnston *et al.*, 1990) so this report will primarily deal with applicability of geophysical techniques on two different types of embankment:





Reservoir Impounding Dams

- Constantly under load.
- Steady state seepage
- Will likely contain internal structures such as cores, transition zones, pipework, culverts

Flood Storage Dikes/Levees

- Dry the vast majority of the time, only in use during flooding events.
- Transient seepage
- May contain a core or internal

Figure 1- Schematic of two generalised asset categories

The dimensions shown in Figure 1 are approximations that serve to highlight the required depth of investigation necessary for a geophysical technique to be suitable, and infer the speed of data acquisition a technique would need to be efficient for a site. There are of course sites that exceed these dimensions, with some impounding dams as high as 100m (Berga, 2006).

Although not limited just to Environment Agency assets, and applies also to FCERM assets that might be captured elsewhere, e.g. by Local Authorities, the Environment Agency's (EA) Creating Asset Management Capacity (CAMC) programme provides a set of definitions that can be used to describe and classify different asset types. These definitions have been adopted by this study as they are inclusive of the range of FCERM assets across different agencies and environments.

Both man-made and natural FCERM assets are considered, but it does not include all types of asset associated with water management; for example, water supply and waste services, or reservoirs. The CAMC inventory system adopts a system of asset classification, with FCERM assets identified as follows (Table 2.2):

Table 2.2 CAMC Asset Type Categories

Asset Types				
Channel	Defence	Structure	Instruments	Buildings
Channel Crossing	Land	Beach Structure	Aids to Navigation	Major Civils

However, this higher-level classification was determined to be insufficiently refined to enable meaningful assessment of impacts, and consideration is necessary at the CAMC sub-asset level, listed below in Table 2.3. ***For the purposes of this study, these asset subtypes are simply referred to as the 'assets'***.

Table 2.3 Asset Sub-Types

Asset Subtypes classification		
Asset Sub-type	**Asset Sub-type**	**Asset Sub-type**
Open Channel	Saltmarsh	Groyne
Simple Culvert	Mudflats	Breakwater
Complex Culvert	Washland	Slipway
		Steps
Bridge	Screen	Ramp
Utility Services	In channel stoplogs	
	Control gate	Instruments - Active Monitoring
Embankment	Outfall	Instruments - Passive Monitoring
Wall	Weir	
Flood Gate	Spillway	Beacon
Demountable	Stilling basin	Buoy
Bridge Abutment	Draw-off tower	Signal
High ground	Fish pass	Signage
Quay	Hydrobrake	Dolphin
Beach	Inspection chamber	
Dune	Jetty	Pump House
Barrier beach		
Promenade		Abutment
Cliff		Central Pier

Table 1- Extract from E.A. Asset Typology

Table 1 Survey of UK embankment dams (Millmore and Charles, 1988)

		Information obtained from: inspecting engineers No	%		undertakers No	%	
Number of dams reported on		757	100		651	100	
of which:	impounding	687	91		516	79	
	non-impounding	70	9		135	21	
Date of completion:	before 1900	533	70		431	66	
	1900–1940	139	18		147	23	
	1940–1960	36	5		29	4	
	after 1960	49	7		44	7	
Height:	under 15m	594	78		397	61	
	over 15 m	163	22		254	39	
Core/membrane:	puddle clay	273	36	(65)	447	69	(77)
	rolled clay	38	5	(9)	25	4	(4)
	upstream membrane	12	2	(3)	20	3	(4)
	other	23	3	(5)	37	6	(6)
	homogeneous	75	10	(18)	53	8	(9)
	unknown	337	44	(–)	70	10	(–)
Cut-off:	puddle clay	159	21	(59)	331	51	(65)
	concrete	40	5	(15)	94	14	(18)
	rolled clay	30	4	(11)	6	1	(1)
	grout curtain	26	3	(9)	25	4	(5)
	other	3	0	(1)	3	0	(1)
	none	13	2	(5)	53	8	(10)
	unknown	501	65	(–)	144	22	(–)
Unprotected outlet pipes in embankment:	upstream control valve	118	16		173	27	
	control within dam	53	7		65	10	
	downstream control valve	225	30		56	9	
Purpose:	water supply	348	46		–	–	
	ornamental lake	228	30		–	–	
	industrial process	59	8		–	–	
	flood control	20	2		–	–	
	agriculture	13	2		–	–	
	power generation	17	2		–	–	
	other	73	10		–	–	

Notes: Figures in brackets for core and cut-off refer to percentages expressed as a proportion of only those dams where the construction is known.
Where a dam includes more than one type of core or cut-off, each type has been shown in the table.

Figure 2- Surveyed Properties of UK embankment dams (Johnston *et al.*, 1990)

The type of environment in which an asset is situated is also a major aspect that influences the effectiveness of geophysical monitoring techniques. Many techniques are susceptible to interference or attenuation by various external sources of noise. We define three categories of environment; rural, coastal and urban. Rural and coastal areas typically have much fewer sources of noise than urban environments. The majority of reservoir impounding dams are found in rural areas. Coastal areas are mainly defined by the presence of salt water, and the types of structures found there are sea walls, piers and the other sub-types defined as 'beach structures' and 'aids to navigation' in table 1. Urban environments here could also refer to urban/coastal environments (densely populated areas located by the sea). Table 2 delineates each

environment type by the likelihood of the presence of factors that would impede certain geophysical techniques, in the style of a risk matrix. These environments are then referred to again in table 4, showing the applicability of the major geophysical methods for each.

	Environment		
Limiting Factor	**Rural**	**Coastal**	**Urban**
Metallic disturbances	Possible	Possible	Likely
Potential/EM sources	Possible	Possible	Likely
Vibrations from traffic etc	Unlikely	Unlikely	Likely
Water type	Fresh	Salt	Fresh/Salt

Table 2- Matrix of limiting factors present in 3 different environments

1.3 Failure Modes and Early Signs

There are many different processes by which an asset can fail. Failure can arise from hazards at virtually any region of a structure and modes include but are not limited to: catastrophic overtopping, dam breach, structural failure, instability, uncontrolled seepage and foundation failure. These issues are discussed in more detail in "Modes of dam failure and monitoring and measuring techniques" (Almog, Kelham and King, 2009) along with the wide array of hazards and how they can progress to a failure event. The main hazards that occur in FCERM assets and that geophysical monitoring has the potential to detect are defined here, and considered in table 4:

Seepage is the flow of water through the subsurface of an asset. It occurs naturally from any impounded body of water and may become hazardous if there is increased or concentrated flows occurring, or if the seepage flow is carrying sediment or any other material with it which is often a sign of suffusion/internal erosion (Fannin and Slangen, 2014)

Damage caused by environmental factors may be present but not yet resulting in significant seepage flow. Desiccation is a common issue of this nature, occurring in soils and in clay cores, where dryness results in cracking or fissuring which weakens the integrity of the embankment. (Jones, Zielinski and Sentenac, 2012) defines soil as desiccated when it "has either (i) soil suction in excess of that which would be expected, or (ii) a moisture deficit." Other examples of structural damage include

issues from vegetation growth on the surface of or beside an asset, most notably root penetration.

Burrows and Voids are essentially internal holes that are often present within a site and pose a challenge to detect. Even smaller burrowing animals leave networks behind that can be extensive enough to severely compromise dam integrity. Voids can arise from internal erosion and have a similar effect and occur both within the body of a dam and at or beneath dam foundations. Voids left by the dissolution of soluble material (limestone etc.) are known as karst.

1.4 Study Constraints

When selecting a method of investigation, three factors that must be considered alongside the properties of the site are: time, budget and study objectives. Time and budget heavily influence decision-making and each geophysical technique must be analysed in terms of its efficiency and cost-effectiveness. Of course, a governing factor in decision making is also the reason for the investigation itself. The objectives of the study will influence time constraints and budget allocation, and dictate the type of survey technique most effective for the situation.

We define two broad reasons for instigating an FCERM asset safety assessment:

General Investigation: An exploratory, knowledge gathering study. As discussed, assets in the UK are often aging and a large percentage are of unknown structure/composition. A general investigation is broad in its scope, trying to identify as many features and properties of the asset as possible. There may be the option of long-term monitoring of a site as part of a maintenance routine.

Issue Prompted Investigation: External indicators identified that require further site analysis i.e. increased drainage flow, seepage, sediment appearance downstream, deformation, external cracking. Issue prompted investigations may well be more urgent than a general study, having a greater time pressure and higher budget if the issue is seen as serious but the full extent and origins of it are not yet known. A specific example would be a visual assessment of an embankment noticing a burrowing animal presence, which prompts an investigation to determine the extent of the burrow network and the hazard it poses to the integrity of the embankment.

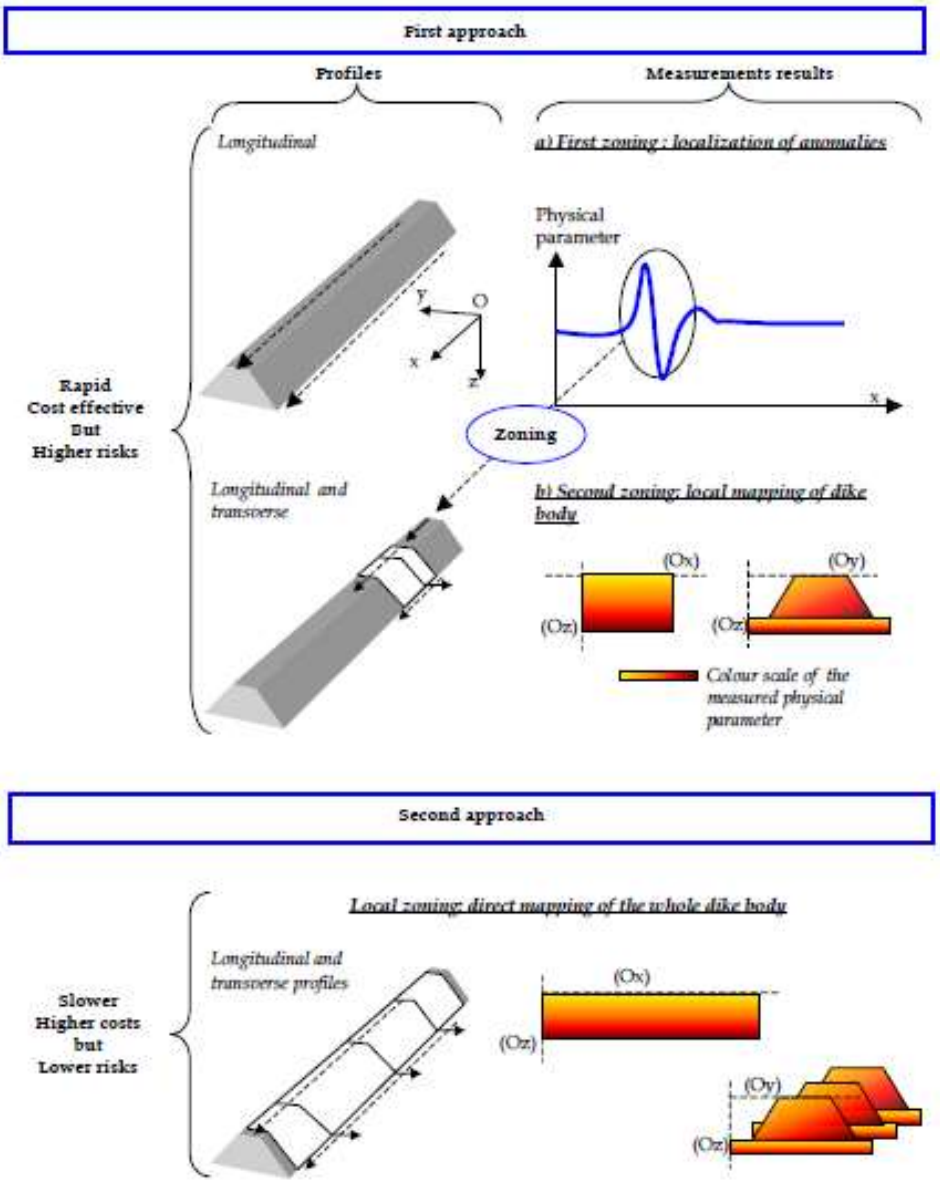


Figure 3- Approaches to embankment monitoring (Fauchard and Mériaux, 2007)

Figure 3 describes two approaches to embankment monitoring suggested by (Fauchard and Mériaux, 2007) for dikes. The first approach is to use a faster, overall form of mapping that will highlight anomalies requiring further investigation by more detailed technique. The second approach is simply to use the detailed technique across the entirety of the asset. This gives a fuller assessment of the asset but is slower and more costly. This approach becomes less viable for larger sites such as the dikes and levees characterised in section 1.2. Part of this study will be to identify a pair of techniques suitable for the first approach (one for overall and one for detailed investigation) that are particularly effective when used together and are widely applicable in terms of site, environment and detection requirements.

2. Analysis of Geophysical Methods

The following outlines the general capabilities of the major geophysical monitoring techniques being discussed. The section omits much of the theoretical operation principles of the technology to aid in clarity of analysis, but more detail can be found in appendix a, and fully in "Applied Geophysics" (Telford, Geldart and Sheriff, 1991) and "Geophysics in engineering investigations" (McDowell *et al.*, 2002).

2.1 Electromagnetic Profiling

Electromagnetic Profiling is a fast, inexpensive and contactless method of dam investigation (Kirsch and Ernstson, 2006). It provides data on soil properties through soil electrical conductivity, making it suitable for identifying preferential seepage paths, changes in material composition, structural damage, and the presence of buried metallic objects (Rubin, Y., Hubbard, 2005). For shallower depths, data is gathered using a handheld boom-shaped device holding an Electromagnetic field transmitter on one end and a receiver on the other. This can be operated by one-person traversing along the surface of the embankment as shown in Figure 5. For greater depths, two person systems exist which are still very straightforward to

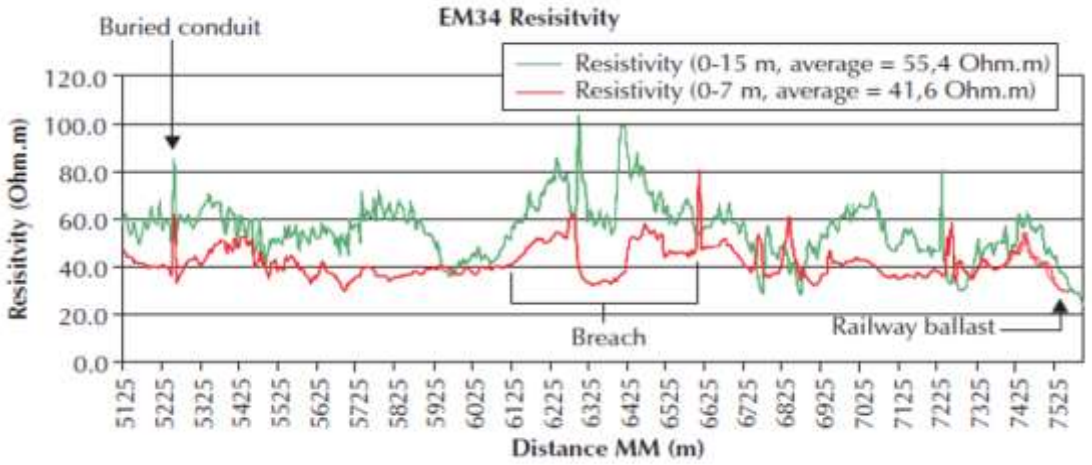


Figure 4- EM measurement processed data (Fauchard and Mériaux, 2007)

implement (Subsurface Surveys & Associates, 1988).

The data is outputted as singular conductivity values along the embankment for the area below the measuring device, which once processed can be presented in a similar manner to Figure 4. That is to say, a singular value will be given for the two-dimensional area extending down to the maximum depth of measurement and within the width of the boom. Conductivities directly below the ends of the boom will not be measured. This data is easy to process and very

Figure 5- EM data collection (Morris W. et al, 2008)

accurate (Rubin, Y., Hubbard, 2005) but its simplistic output means that little definitive information can be garnered, hence it is more useful as an initial study for identifying anomalies and areas of interest for further investigation. Electromagnetic profiling is easily disturbed by the presence of metal so care must be taken to account for this (Royet *et al.*, 2013).

EM profiling's fast and simple field implementation leads to a high acquisition speed, which combined with the simplicity of the data processing, results in a very low cost, thus lending itself as an ideal method for initial, overall and complimentary tool (Royet *et al.*, 2013). For extremely rapid data acquisition over very large areas, airborne devices are also available, and are discussed further in appendix d.

2.2 Electrical Resistivity Tomography (ERT)

ERT is one of the most well-established, and widely applicable geophysical techniques for detailed investigation (Sentenac G; Zielinski, M.; Tarantino, A, 2013). Measuring material resistivity (inverse of conductivity), ERT studies have similar detection capabilities to EM- soil properties, geological structure, seepage detection, cracking, presence of metallic objects- though in much greater detail.

Figure 6- ERT electrode setup (RSK Geophysics, 2016)

Field implementation is straightforward but fairly time consuming and can be problematic- it involves installing a large array of electrodes at a depth of up to 15cm as in Figure 6, and it is not uncommon for an electrode to spoil the data by having poor ground contact, or not being properly connected. The acquisition time is longer for this process in comparison to EM, largely due to time setting up and calibrating electrode arrays. An ERT array can be configured to map the entirety of almost any site/ dam size, and advanced equipment is available that allow for

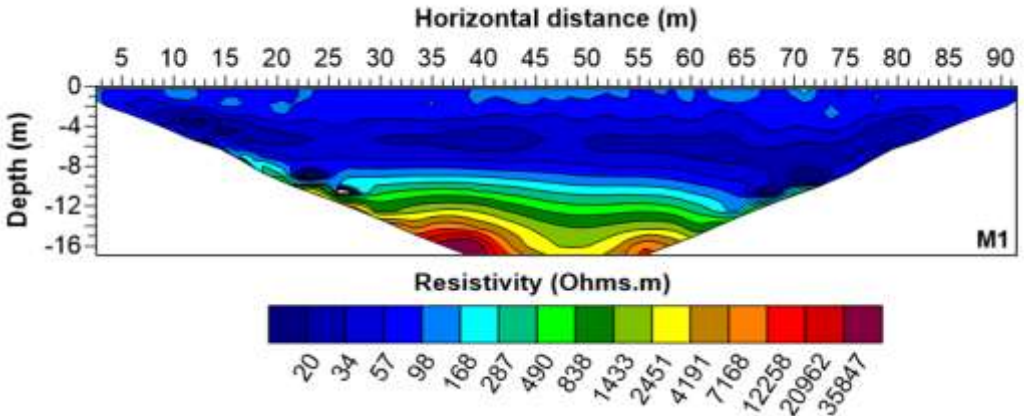


Figure 7- 2D tomography from an ERT survey of Mugdock Dam (Michalis, Sentenac and Macbrayne, 2016)

analysis across full frequency spectrums or incorporates complimentary geophysical surveying methods such as self-potential and induced polarisation (Kirsch and Ernstson, 2006).

The data produced from this method is of high resolution, presented as 2D resistivity models that can be collated as pseudo 3D maps. Figure 8 highlights how a pseudo 3D map is often produced, with a 2D tomography shown in more detail in Figure 7. Raw ERT data is processed using a method known as inverse processing. This is discussed further in appendix c but the key issue with inverse processing is that it has a non-unique set of results (Royet *et al.*, 2013). That is to say, one person's assessment of the data from an ERT survey can garner different information about the site compared to another's. This ambiguity adds a new element of uncertainty to the results, and for this reason some geophysical methods such as ERT are not as effective if employed as a standalone technique and need corroboration from other methods/types of investigation generally (Mériaux, Lino and Royet, 2000). That said, resistivity tomography can and is regularly carried out effectively, providing a substantially detailed picture of the site, and is resolved enough to identify features such as small animal burrows, and desiccation in any area of a dam (Jones, Zielinski and Sentenac, 2012).

As with electromagnetics, care must be taken to account for metallic objects and other artefacts that could influence the data. There are also variations of traditional ERT surveys such as capacitive methods, which produce more noisy data but do not require ground contact, which allows for easier and quicker field work (British Geological Survey, 2010). A popular two-electrode variant that uses an AC current rather than DC is often used alongside a traditional survey, and is suggested to be

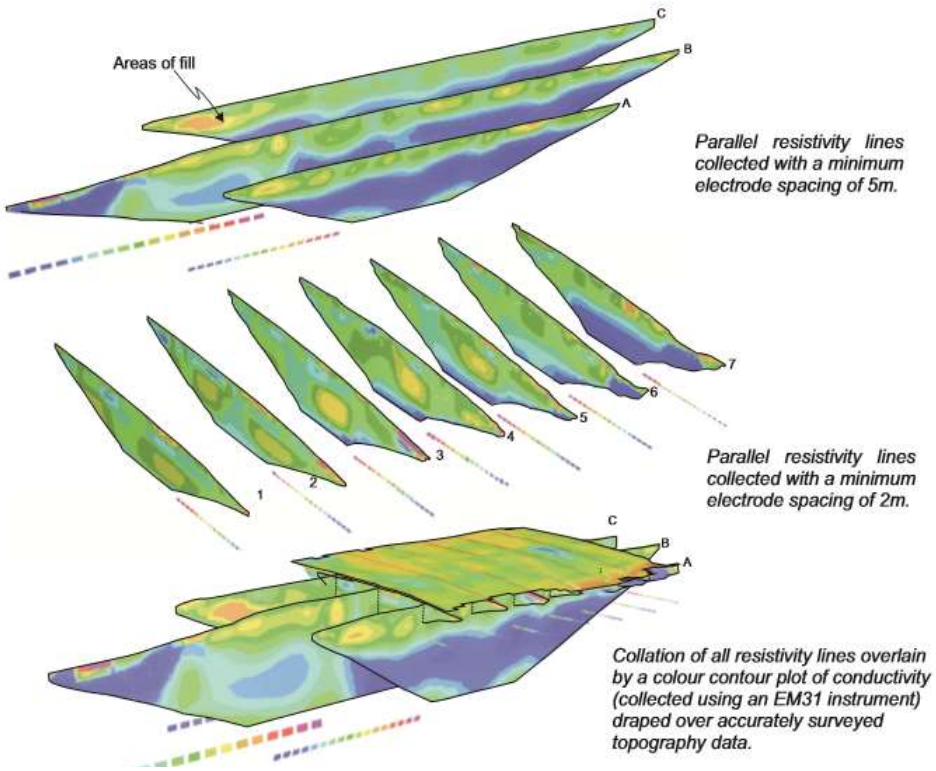


Figure 8- Collation of 2D mappings into pseudo-3D contour plot (RSK Geophysics, 2016)

more effective at mapping potential seepage flow paths.

2.3 Self Potential Method

The self-potential (SP) (or spontaneous potential) method is a passive[1] technique that measures the naturally occurring potentials in the ground. This has particular relevance in groundwater geophysics as water flowing through the pore space of soil generates an electric current, the size of which is proportional to the intensity of the flow. For this reason, SP is only suitable for sites under hydraulic load- i.e. impounding dams, and dikes/levees *only during flood conditions* i.e. transient seepage (Royet *et al.*, 2013). Measurements taken in dry conditions are useful only in comparison to flood conditions but can help provide valuable information about the

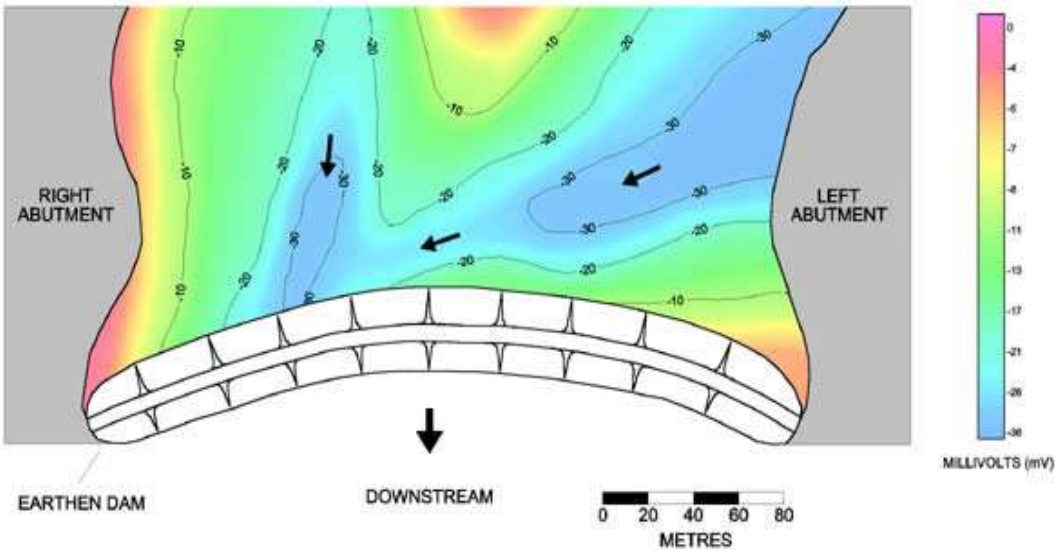


Figure 9- Colour contour plot produced by SP method for a reservoir (Frontier Geosciences, 2016)

extent of seepage.

This hints at self-potentials main advantage: it provides an estimation of the seepage intensity and not just the preferential flow path. It is extensively used in groundwater mapping for this reason, especially for instances where a seepage related issue has been identified but needs further analysis/conformation (Ikard *et al.*, 2014). SP is straightforward though reasonably slow to implement requiring only two non-polarising electrodes- usually one stationary electrode located at a base station, and another roving electrode with potentials being measured between the two. However, it is very susceptible to noise from interfering sources of potential such as telluric[2] currents, industrial currents, and electric railway systems (Kirsch and Ernstson, 2006). This limits the scope of SP's use. It can also be less effective in salt water applications, restricting its applicability for coastal defence monitoring. Data can be processed

[1] Passive technique simply measures environmental property whereas active techniques send out signals and measure how they are altered by the environment.
[2] Natural electric current in the Earth's current.

qualitatively very easily to produce contour maps of electric potential distributions such as that in Figure 9, or quantitatively via 2D inversion processing (more complex) to garner information about the origin of the source of potential (Royet *et al.*, 2013).

2.4 Ground Penetrating Radar

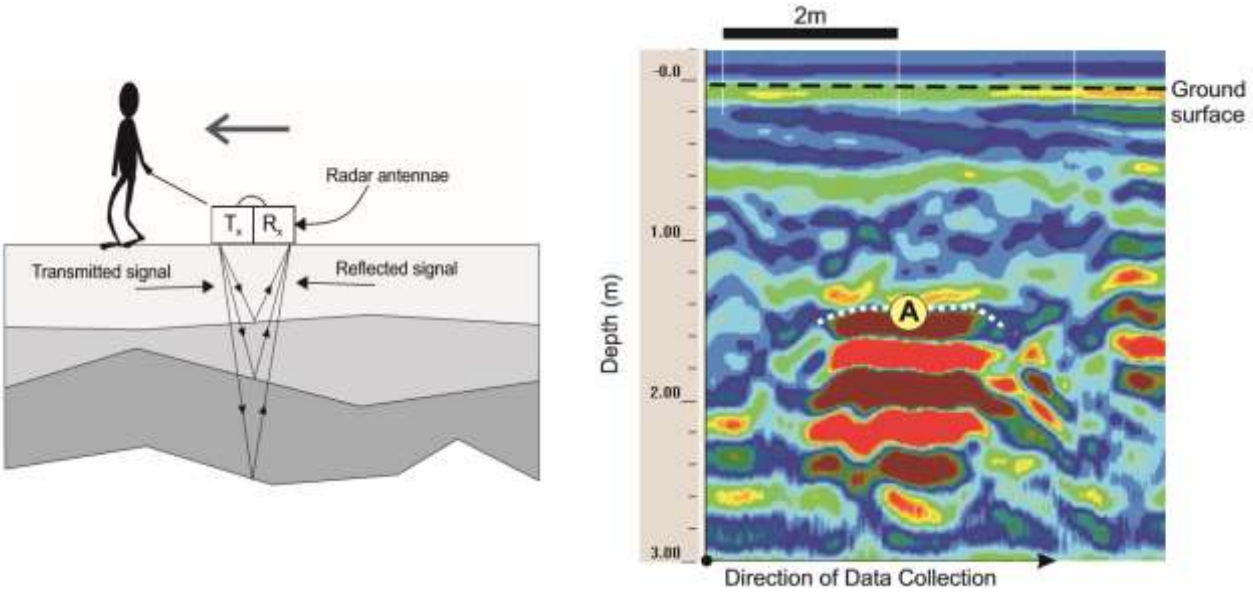


Figure 10- Field Implementation pictorial and example of processed data from a GPR study. (A) highlights the top surface of a hidden underground storage tank (RSK Geophysics, 2016)

Ground penetrating radar (GPR) profiling is a technique that has come into regular use for various geophysical studies in recent years due to its simple and fast data acquisition coupled with a good level of detail/resolution (Antoine *et al.*, 2015). A representation of field implementation and data after processing can be seen in Figure 10. GPR is sensitive to changes in dielectric permittivity[3] which again can be used to ascertain soil properties as well as material changes, internal structures and voids (Karastathis *et al.*, 2002). Studies can be straightforward to carry out with a variety of devices operated by one surveyor, some handheld some towed along the ground. Although resolution is quite high, processing/interpretation is very difficult, partially due to the sheer volume of data produced. The depth of investigation is generally no more than a few metres, restricting GPR's value for use on higher assets such as reservoir impounding dams (Royet *et al.*, 2013)

The main limiting factor for GPR profiling is that it is not applicable for low resistivity materials- clayey soils for example, which are present in many embankments and flood assets (Rubin, Y., Hubbard, 2005). Highly conductive substances attenuate the signal, severely reducing the already quite low depth of investigation (Antoine *et al.*, 2015). A list of soil types and their corresponding resistivity are shown in table 3,

[3] a diagnostic physical property of a material characterising how it interacts with an electric field.

highlighting GPR's suitability in green for each. Furthermore, data can be disrupted by the presence of ground structures and dense vegetation.

Type of Soil	Mean Value of Resistivity in Ωm
Swampy soil, bogs	1 - 30
Silt alluvium	20 - 100
Humus, leaf mould	10 - 150
Peat, turf	5 - 100
Soft clay	50
Marl and compacted clay	100 - 200
Jurassic marl	30 - 40
Clayey sand	50 - 500
Siliceous sand	200 - 300
Stoney ground	1,500 - 3,000
Grass-covered-stoney sub-soil	300 - 500
Chalky soil	100 - 300
Limestone	1,000 - 5,000
Fissured limestone	500 - 1,000
Schist, shale	50 - 300
Mica schist	800
Granite and sandstone	1,500 - 10,000
Modified granite and sandstone	100 - 600
Fertile soil, compacted damp fill	50
Arid soil, gravel, uncompacted non-uniform fill	500
Stoney soil, bare, dry sand, fissured rocks	3,000

Table 3-GPR only suitable for materials of >100Ωm resistivity (Engineering Toolbox.com, no date)

2.5 Seismic Methods

Though there are various types of seismic geophysical survey that can be carried out separately or together, all involve the transmission of seismic waves through the site under observation. Detection here is focussed on the mechanical properties of material, such as shear strength and internal structures and voids (Royet *et al.*, 2013). It is reasonably easy to implement in the field, often using a transmission device as simple as a hammer,

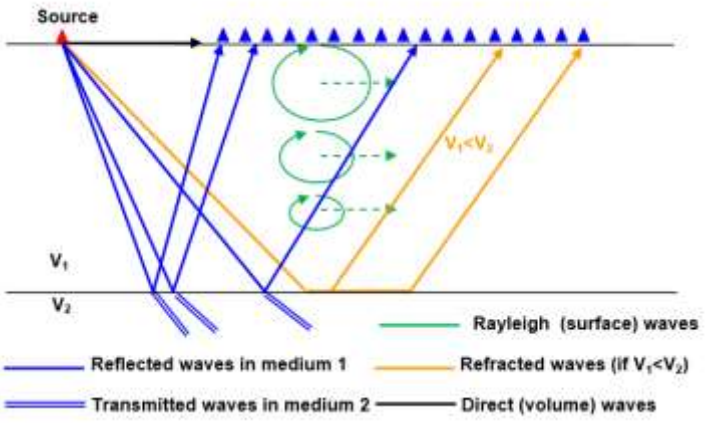


Figure 11- Diagram highlighting the different seismic waves and there travel path in the sub-surface (Royet *et al.*, 2013)

and an array of geophone receivers. This is a very slow process however, which is one of the main limitations (Lum and Sheffer, 2005). Multi-channel analysis of surface waves (MASW) has a higher output rate than seismic refraction but its data interpretation requires a high level of expertise, so this trade-off must be considered. The distinction between these techniques is discussed in appendix a with Figure 11 highlighting the different waves that can be analysed. Seismic techniques are regularly used for deeper subsurface investigations (Eaton, Milkereit and Salisbury, 2003), meaning measurements can easily be taken down to the foundations of any asset here (if no other limiting factor is present). An added benefit of MASW is its ability to utilize vibrations caused by external noise such as traffic in an urban environment as the source of seismic waves.

2.6 Temperature Methods

Temperature measurements are a well-established form of monitoring that make use of the seasonal variations that act on a waterbody (Lum and Sheffer, 2005). The two major techniques of data gathering for water impounding assets involve either attaching discrete thermistors to the face of the dam, or inserting rows of temperature sensors into the body of the dam via small boreholes as shown in Figure 12. The latter method, known as temperature sounding, is particularly useful because it can reliably detect seepage using water temperature as a tracer (Royet *et al.*, 2013). The boreholes needed are small enough that they can be created using hand-tools, and the sensors can be left in for long-term monitoring. Indeed, repeated measurements can allow for determination of seepage velocities rather than just seepage identification, similar to, though not as precise as self-potential. Neither method can be carried out on a dry asset however one advantage of temperature sounding is that water temperature anomalies remain detectable for a good period of time after a flood event (about 10 times as long as the event) (Royet *et al.*, 2013). This makes the technique more applicable to dikes and levees than SP (though still

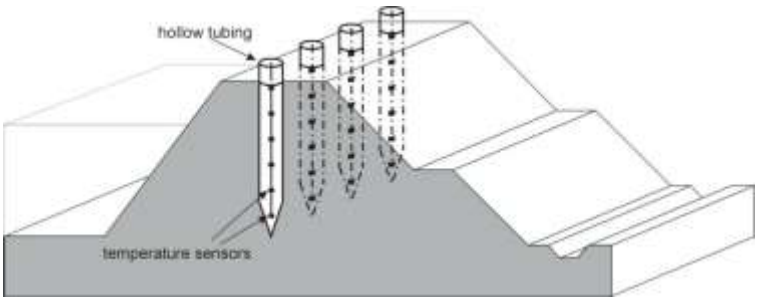


Figure 12- Schematic sketch of the ground temperature sounding technique (Royet *et al.*, 2013)

not the preferred method in general).

Temperature measurements are most effective when the natural gradient in the water temperature (discussed in appendix a) is maximised, so studies are best carried

out at the height of summer or winter. Anomalies that are close to the surface are difficult to detect (Kappelmeyer GTC, no date). This method is often favoured by engineers/surveyors, probably due to its likeness in implementation to a more traditional geotechnical study. Discrete data can be interpolated to produce a tomography of the site, with measurement depths reaching to 35-40 below the surface (Royet *et al.*, 2013). Sounding is unaffected by the presence of metal, or interfering potential sources that can often disrupt the geo-electric techniques. It can be employed in almost all materials (so long as there is a temperature contrast between it and the water) and it is unperturbed by vibrations that could be present, especially in urban environments. (Royet *et al.*, 2013)

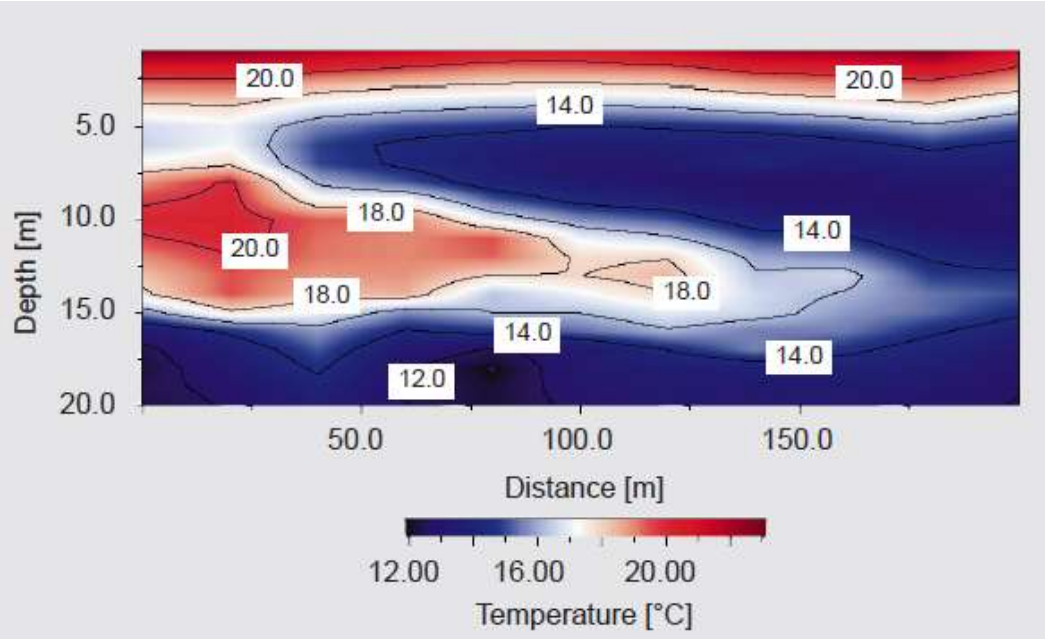


Figure 13- Contour Plot data using (Kappelmeyer GTC, no date) *sounding method*

Temperature sounding is quite time-consuming and comparatively expensive for the level of detail it can garner from a site, but its reliability and resilience to external interference lends itself as a useful technique for particular situations (Royet *et al.*, 2013). Advancements in this field have led to higher sensitivities in detection using fibre optic temperature measurement devices. Figure 13 is an example of the contour plots that can be created from data processing, and demonstrates an area of leakage being detected as high temperature anomalies under a slurry trench wall.

2.7 Micro-Gravimetry

Micro-gravimetry uses highly sensitive instrumentation to take measurements of variations in gravitational acceleration due to the presence of high or low-density material. This has particular application for detecting voids and cavities in asset bodies, which would register as "negative gravity anomalies" being features of low

density (RSK Geophysics, 2016). It can also be used more generally for material zoning through changes in soil density. Data collection for this process is extremely time consuming and delicate as the apparatus used is extremely sensitive, requiring rigorous methodology (Royet *et al.*, 2013). Data cannot be gathered continuously so there is risk of missing anomalies, and is severely susceptible to limiting factors in the environment. These factors result in micro-gravimetry being one of the most expensive geophysical techniques. It is not considered in the comparative summary due to its lack of viability as a competitive method of FCERM assessment.

2.8 Magnetic Profiling

Magnetic Profiling is a fast and cheap method of investigation, though with a very narrow range of detection capabilities. It is a passive technique, analysing small disturbances in the earth's magnetic field in a similar fashion to micro-gravimetry's analysis of gravitational disturbances. It can be employed quickly and easily in the field using one-person devices, making it useful as an overall study technique. Magnetic profiling has not been included in the comparative summary due to its limited outputs- it is only a competitively useful technique for detecting the presence of buried metallic objects, for example outlet pipes. This is still a desirable trait for mapping sites of unknown composition however, making magnetic profiling a useful complimentary technique.

2.9 Other Methods

Other geophysical techniques have previously been considered and researched for use in reservoir/dike monitoring, such as radio-magnetotellurics, the very-low-frequency method and seismic reflection. They have largely been discarded by geophysicists for this type of investigation due to their numerous limitations and out-dated technology and so are not considered here (Mériaux, Lino and Royet, 2000).

4. Comparative Summary of Analysis

The following tables summarise the information discussed in sections 1 and 2, and indicate the suitability of each major geophysical technique for different sites and stakeholder requirements. They help to highlight the more broadly applicable techniques and can be used as a quick-reference guide when making decisions concerning the most effective type of investigation for a specific asset.

	Asset Type		Site			Detection Requirement				
Geophysical Method	**Dikes, Levees** (Transient Seepage)	**Impounding Dams** (Steady State Seepage)	**Rural**	**Coastal**	**Urban**	**Internal Composition/ Zoning**	**Identifying Seepage Paths**	**Seepage Flow Intensity**	**Larger voids due to animal burrowing, erosion cavities**	**Damage from environment desiccation, root growth etc.**
Electromagnetic Profiling	EM-31, handheld 1 person, very fast data collection	EM-34, 2 person operated, fast data collection			Usually too many metallic disturbances	Only as a 1D mapping				Could be detected but not identified solely from EM
Electrical Resistivity Tomography	Not time effective to be done across km				Great care must be taken to account for metallic objects					
Ground Penetrating Radar Profiling	Soil dependent. Ground must be reasonably free of vegetation etc.	D.o.I. too low for monitoring down to foundations. Soil dependent		Soil dependent. Saltwater attenuates signal.					May not resolve smaller animal burrows	
Seismic Methods	Not time effective to be done across km				Traffic & other vibrational disturbances must be removed					
Self-Potential Methods	Only during flood conditions			Salt water can disrupt data.	Device very sensitive to electrical perturbations					
Temperature Measurements	Only during/after flood conditions							With repeated measurements		

Table 4- Matrix of geophysical techniques in terms of suitability and application: Green = Suitable, Yellow = Can be suitable but with limitations, Red = Not suitable

Geophysical Method	Type of Detection	Field Implementation	Depth of Investigation (DoI)	Data Processing and Resolution	Limiting Factors	Acquisition speed	Cost of Investigation
Electromagnetic Profiling	Overall dam assessment, soil properties through soil electrical conductivity.	Easiest data gathering method	Variable, smaller equipment around 3m, larger down to 40-50m	Low Resolution but straightforward to process.	Not detailed enough for use as the sole monitoring technique	Fast	Low
Electrical Resistivity Tomography	Detailed assessment, soil properties and geological structure, seepage and void detection	Can be problematic. Applicable in the largest variety of circumstances.	Site and configuration dependent but quite large.	High resolution, needs corroboration for other data.	Must account for metallic objects and other artefacts in data.	Slow	High
Self-Potential Methods	Detects soil conditions and seepage paths as well as seepage intensity	Land or Waterborne. Simple implementation	Waterborne. DoI large enough for most reservoirs.	Medium Resolution. Interpretation must account for any other SP sources.	Very susceptible to interference. Not applicable for salt water/ "dry" sites	Slow	Medium
Ground Penetrating Radar Profiling	Fairly detailed. soil properties, material changes, internal structures and voids.	Straightforward can be towed manual or by vehicle.	Small, generally no more than a few meters.	Good resolution but very complex interpretation.	Not applicable for low resistivity materials- clayey for example.	Fast	Low
Seismic Methods	Detailed. Mechanical Properties of soil/material, structures/voids	Reasonably easy to implement	Large enough to reach foundations.	Requires high level of expertise in processing/ analysis. Low-Medium resolution	Time consuming. Soil characteristics may inhibit DoI	Slow	Very High
Temperature Measurements	Anomalies in the seasonal temperature gradient can indicate seepage.	Straightforward installation but can be expensive.	Intrusive- any depth to which sensors can be positioned	Interpolation of discrete values. Resolution dependent on probe spacing	Sounding method is intrusive. Needs distinct temp. gradient contrast between water and medium	Medium	High

Table 5- Summary of analysis of geophysical techniques

4.1 Example of Geophysical Selection Method.

Applying the knowledge gained and collated in these analysis summaries to a real-life site will help to demonstrate their value, and highlight a typical overall methodology

Dam A was built in the late 1930's and comprises a 120m long earth-fill embankment, straight on plan, with a maximum height of about 24m. There is no pre-existing GI information regarding the dam's internal composition. The drawings indicate that the dam has a central puddle clay core, with adjacent zones of "selected material" (presumed to be finer material) and outer shoulders of "earth embanking". The core extends below the embankment foundation level to rock to a depth of about 15m across the centre of the valley. The drawings indicate several steep vertical faces in the base of the cut-off trench on the valley sides, most notably at the draw-off culvert and at the interface with the spillway channel.

The upstream face slopes at 1(V):3(H), steepening above top water level to 1(v):1.5(H). It is protected against erosion from waves by hand set stone pitching. A reinforced concrete wave wall ~0.75m high above the crest was added along the upstream edge in the mid 1990's.

The crest is ~3m wide and grassed. The downstream face, which is also grassed, incorporates two 3m wide berms at quarter and three quarters height (approx.), giving an overall slope of 1(V):2.5(H), with the slope between the berms being 1(V):2(H) approx.

The drawings indicate tile drains extending beneath the outer part of the downstream shoulder to a French drain along the downstream toe. This discharges via a ditch to the stilling basin at the downstream end of the spillway and outlet channel from the draw-off culvert.

A reinforced outlet culvert passes through the left-hand side of the embankment at foundation level.

A concrete overflow spillway is situated at the left-hand end of the embankment.

The issue

During a period of wet weather water ingress through honeycombed construction joints in the invert of the reinforced concrete draw-off culvert towards its downstream end suggested that leakage might be occurring, particularly when the depth of spill was greater than 100mm. As this occurrence coincided with a prolonged period of wetter weather, it was not possible to establish from the drainage flow records whether the response was related to reservoir level or rainfall. Following the very wet weather the flow into the culvert ceased. Drainage flows at

the downstream toe were judged as being greater than might be expected given the size of the dam wall, but it was not possible from the records to establish if there had been a gradual increase over time, or a more recent change.

Geophysics

It is first necessary to note that the presence of large amounts of reinforced concrete in the areas of interest may well affect the accuracy/reliability of a geophysical study looking for seepage. From the information provided we can first identify the 3 broad factors that influence the decision-making process that are discussed in table 4. Dam A is an **Impounding dam** in a **rural area**, and the requirement of the study is to detect **seepage flow paths and intensities**, if they exist. The following proposal is made using analysis tables 4 and 5 as a guide along with knowledge of the general steps that must be taken in a geophysical study:

To investigate the cause of the increased drainage flow, an initial visual investigation of the site is essential. An area of seepage on the grassed downstream face could be marked by an increase in vegetation growth (reeds etc.) or suffosion- finer material from the interior of the earth-fill brought to the surface by seepage flow. Suffosion can easily be mistaken for animal activity. If any such anomalies are detected the geophysical study can be localised, and a suggested first method would be ERT. If none are found, an overall EM profiling of the dam is worthwhile before using more detailed methods. Following the ERT survey, applying the self-potential method could provide further useful information about the seepage path and intensity.

High seepage through the embankment will either be coming from the draw-off culvert or via a separate path. If the former is the case, the geophysical data may be too impeded to provide conclusive results. SP in particular is not likely to be effective near the culvert. The study may however serve to direct further, more intrusive investigation. On the other hand, seepage may well be coming from an unrelated area of the dam (i.e. the latter case) and the further this is from the reinforced concrete, the more accurate and detailed information the geophysical methods will provide.

Taking repeated temperature measurements via sensors on the face of the embankment or intrusively using borehole sounding may be a valuable next step if the previous methods have not been conclusive. This would be unaffected by the reinforce concrete though is more expensive and time-consuming.

At this stage, one would evaluate all the collected data together to decide whether the results are conclusive to an acceptable degree or if further investigation is needed. This would be done either by using other geophysical methods, repeating

measurements with the same techniques, or employing more intrusive geotechnical studies.

5. Conclusions and Proposed Research

This study is based on insights from research papers mainly focussed on field work using the various techniques. as well as discussion with experts in geophysics. It has led to a number of important considerations for the use of geophysical methods generally:

1. All methods need to be used in combination with all available site data, and geotechnical/geodetic survey methods to verify findings and provide the most reliable and accurate information. Repeating a geophysical method measurement can provide critical info about properties such as seepage intensity.
2. The person in charge of data processing should always be part of the field study i.e. should be gathering the data themselves as exact methodologies vary depend on the circumstances, and having the full "picture" is essential for accurate analysis.
3. This person needs to have both an engineering and geophysics background, with strong knowledge of both dams/failure processes and the geophysical techniques, theoretically and practically.

5.1 Proposed Investigation Outline

As demonstrated in this report, it is evident that much research has already been carried out applying geophysical techniques to reservoir and dike monitoring, and that each technique has different merits, limitations and can be used to suit different needs. From the summary tables in section 4 it is clear however that certain techniques are more widely applicable and effective. Combining these with the study methodology discussed in section 2, the following is a suggested outline for carrying out geophysical investigations:

1) Preliminary: Desktop Study and Visual Inspection

It is imperative to first visually inspect the dam and look for any anomalies, areas of seepage, appearance of downstream sediment, cracks, increased vegetation etc. Gather all historic data for the site available to provide the most thorough analysis and inform decision making.

2) Overall: Electromagnetic Profiling

Overall survey of the site- quick and cost effective to use EM. Identifies anomalies to be investigated further by ERT. This significantly reduces costs and survey time as

ERT does not need to be implemented across the whole site, and as it can detect similar properties, EM profiling is very suitable for confirming the tomography data.

3) Detailed: Electrical Resistivity Tomography

ERT is the most well-tested, widely applicable method of detailed investigation. Set up of equipment can be problematic but the procedures are clearly defined. Field work and analysis/processing should be carried out by the same team to allow accurate interpretation of the data. Much work has been carried out using EM and ERT as complimentary methods (Sentenac *et al.*, 2013; Delage *et al.*, 2016; Michalis, Sentenac and Macbrayne, 2016) and as discussed, ERT needs corroboration with other data to help rectify the ambiguities in inversion processing.

4) If necessary; Other geophysical technique

The summary tables provided can be used to help select the most appropriate other techniques to use at this stage if the EM and ERT surveys have not proved conclusive enough for the stakeholder. Self-potential has the valuable ability to infer seepage flow intensity, and not just identify preferential flow paths. Research often employs both ERT and SP (Slob, Snieder and Revil, 2010; Ikard *et al.*, 2014), but due to cost/time aspects ERT is preferred. Generally, SP is carried out when there are findings from the desktop study, visual inspection, ERT data and/or other methods that seepage is anticipated to occur in the dam. It is important to have a trace of seepage activity to use SP. Temperature sounding can often be used in place of SP if there are too many sources of electrical noise. Seismic methods are suitable for zoning and mechanical property detection, and GPR is a cheap overall method worth using if its various site limiting factors discussed are not prevalent. The main conclusion here is that the more methods applied to a site, the wider and more accurate picture can be created of the sub-surface.

5) Geotechnical Investigations

Most studies agree that geotechnical investigations are necessary to validate the conclusions garnered from geophysical studies. The scope and size of this is very much dependent on the site and stakeholder requirements, but the different methods available and their application are well documented (Mériaux, Lino and Royet, 2000; Fauchard and Mériaux, 2007; Dam Safety Bureau, 2008). The main aspects of geotechnical studies are discussed in appendix b.

This methodology conforms with similar outlines produced specifically for dikes and levees (Mériaux, Lino and Royet, 2000; Fargier *et al.*, 2012; Lopes and Fauchard, 2013;

Royet *et al.*, 2013) but has accounted for a wider array of FCERM assets, discussed in section 1.

5.2 Theory to Implementation

The fact that many geophysical survey methods are well-researched and long established as a cost-effective alternative to traditional monitoring techniques begs the question- Why have these practices not yet been adopted commercially on a significant scale?

3 brief conclusions from this work:

1.) Field methodologies can be delicate and complex
2.) Data processing requires in-depth knowledge of both dam engineering and geophysics.
3.) There is no set or clearly most effective methodology for carrying out investigations.

To address these issues, rather than researching applications and experimenting with new techniques, work should be focussed on producing clear implementation information for engineers and surveyors, perhaps in the form of a field manual or guidance document. This guideline could follow the sequence of methods proposed here and use this work as a basis, but more research should be carried out by collating information from experts. A questionnaire sent out to leading practitioners would serve to better understand limitations and practicalities of each technique.

A seminar or series of lectures on the use and data analysis of geophysical methods aimed at dam engineers and surveyors would help to bridge the gap in understanding between the two fields and improve confidence in applying geophysical assessment to reservoirs. Currently engineering consultancies will employ external geophysical surveyors when required, most of which do not provide them with any conclusive analysis of the results from a geophysical study. Encouraging geophysics firms to learn more about dams and their failure modes would give them the tools to interpret the data in a way that is more pertinent to the overall goals of the project. Any seminar or training should be specifically crafted to present theory and practices in a digestible manner, and provide clear steps for field work and analysis.

6. Appendices

A. Underlying Theory of Geophysical Methods

The following is a summary of the theoretical principles behind the major geophysical techniques being considered. A more detailed explanation can be found in (Telford, Geldart and Sheriff, 1991; Rubin, Y., Hubbard, 2005; Kirsch and Ernstson, 2006)

Electromagnetic Profiling

In an EM profiling device, an electromagnetic field is generated by an alternating current in a coil. This induces what's known as Eddy currents in the conducting material under observation. The size of these currents is directly related to the conductivity of the material and they in turn generate a secondary magnetic field, which is detected in the receive coil as an induced voltage.

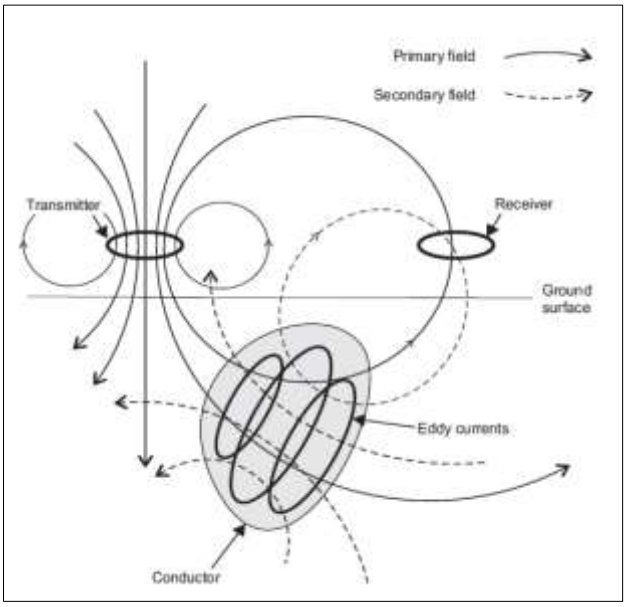


Figure A.1- EM field theory (RSK Geophysics, 2016)

Electrical Resistivity Tomography

An ERT survey utilises an array of electrodes connected in sequence to map a site in terms of apparent ground resistance. A pair of electrodes inject current into the ground and a second pair measure the resulting electrical potential distributions as can be seen in Figure A.2. This potential, together with the current value and a constant based on the array geometry, yields an apparent resistivity reading of the

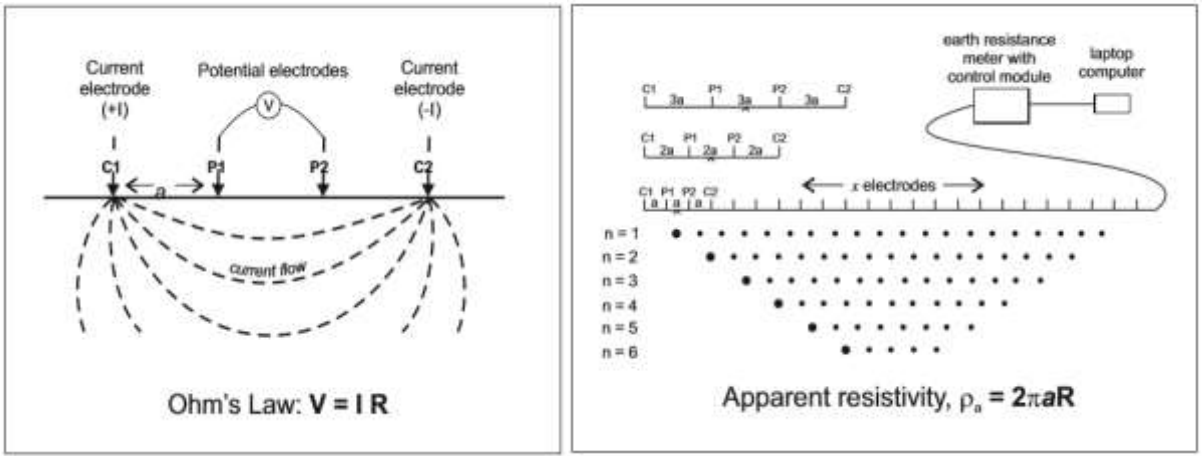


Figure A.2- ERT operation principles (RSK Geophysics, 2016)

underlying geological layering. Measurements are taken for different 4-electrode combinations- increasing the spacing between them increases the depth of measurement but decreases resolution.

Various spacing configurations are used in practice (Wenner, Schlumberger arrays etc.) and have different advantages, so it is often useful to implement more than one.

Material resistivity is the inverse of conductivity, so EM profiling and ERT are both sensitive to the same properties of soil. Values of resistivity are well known, and can be seen in Figure A.3 for a range of materials. Values such as these can be compared

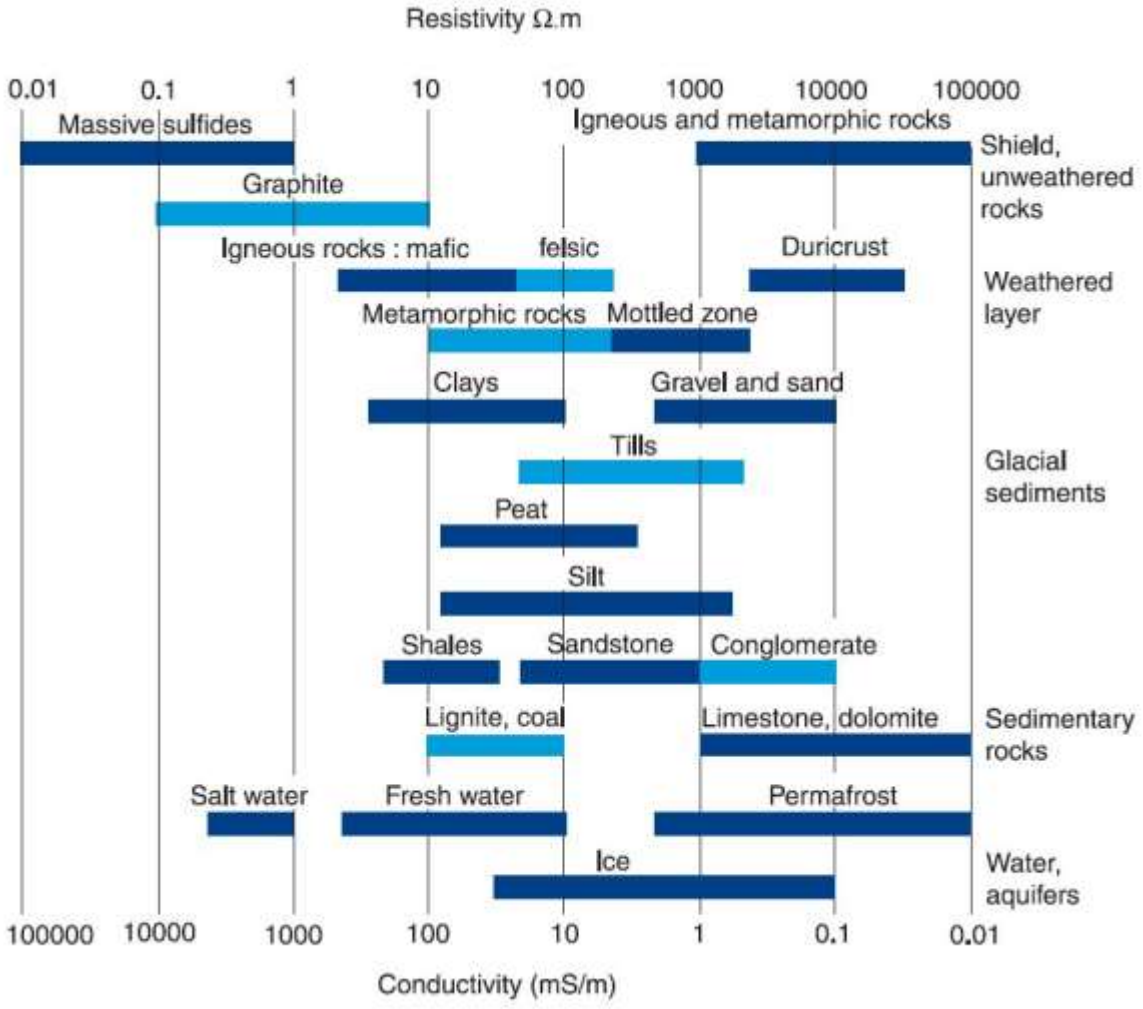


Figure A.3- Resistivity (and its inverse, conductivity) of the main earth materials (J. Palacky, 1988)

to field data and allow for material identification of unknown sites.

Self-Potential Method

SP measures naturally occurring potentials in the ground using a pair of non-polarising electrodes and a high impedance voltmeter. These potentials can originate from various electrochemical, electrophysical and bioelectrical processes in the ground (Kirsch and Ernstson, 2006) but the main process relevant to hydrological studies is the streaming potential generated by water flowing through the pores of soil and porous rock. Theoretically this method is very basic to implement, as the potentials in between the mobile and stationary electrode are simply detected as small voltages.

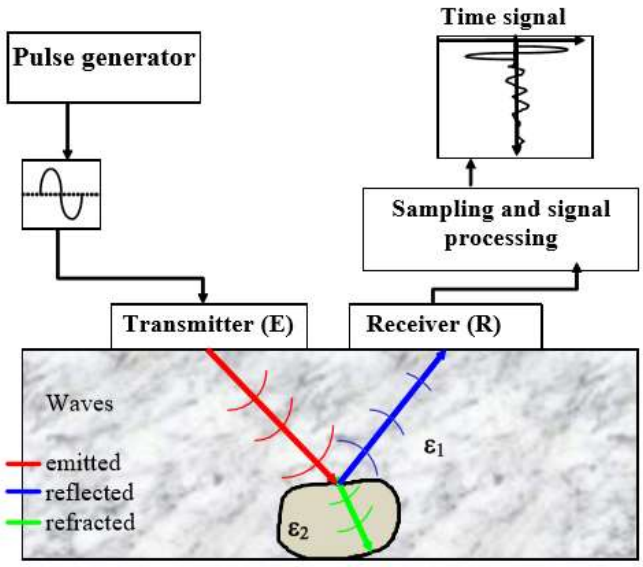


Figure A.4- Flow diagram of GPR operation principles (Royet *et al.*, 2013)

Ground Penetrating Radar

In GPR profiling, electromagnetic waves are transmitted into soil as seen in Figure . When these waves reach a boundary between 2 materials of different dielectric permittivity, they are partially reflected and refracted. The amplitude and travel time of the reflected wave is related to the dielectric permittivity ε_2 of the new material the wave interacted with. Defined permittivity values are well established for the typical materials present in FCERM assets and so can be correlated with field data.

Seismic Methods

As discussed, the two main types of seismic method commonly applied in dam and dike monitoring are seismic refraction and multi-channel analysis of surface waves (seismic reflection is another common technique for other applications but is not considered particularly viable in this specific field). A similar concept to GPR but transmitting seismic waves of low frequency acoustic energy, the waves reflect/refract off material boundaries and travel times are measured. If the length of the path travelled by the wave is known, the seismic velocity can be calculated which is related to the mechanical properties of the material. MASW deals specifically with the surface Rayleigh waves, the dominant influence of which is shear wave velocity distributions (FrontierGeosciences)

Temperature Methods

The natural temperature gradients that occur in waterbodies are well understood, and result from the contrast in temperature radiating from the earth's core and its seasonal atmospheric variations. If anomalies are present that do not correspond to this natural gradient it can indicate an area of higher seepage flow (and material of higher permeability) than the surrounding area. (Lum and Sheffer, 2005).

During summer, areas of high permeability or water flow will be detected as positive temperature anomalies, due to ground temperature being lower than the waterbody temperature (Lopes and Fauchard, 2013). The opposite will be the case in winter. Real data shown in Figure captures how this natural gradient fluctuates with the seasons.

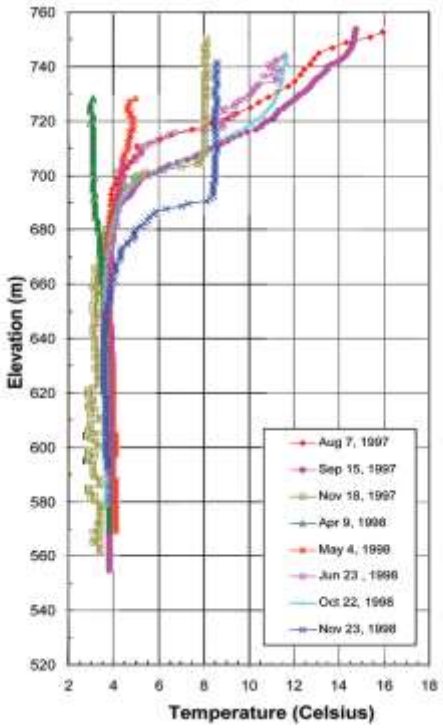


Figure A.5- vertical temperature profiles, measured in the reservoir impounded by a dam in British Columbia (Lum and Sheffer, 2005)

B. Geotechnical Investigations

Geotechnical methods of investigation are well-established techniques that provide localised physical characteristics of sub-subsurface material in a site. The main techniques often employed include cone penetration tests, borehole permeability testing, shear tests and material sampling. Explicit methodologies of these practices can be found in "Méthodologie de diagnostic des digues" (Mériaux, Lino and Royet, 2000), but the main aspects to note are:

- They are intrusive surveying methods, usually requiring boreholes or some form of site excavation which can be expensive and hazardous on structures such as dams
- Surveying of this form is carried out at discrete points on the site and it must be determined whether or not the data gathered should be extrapolated across the whole site.
- As with geophysical methods, geotechnical techniques are usually carried out after a preliminary study

Geotechnical techniques are necessary in partnership with geophysical surveying, providing validation and added knowledge of the site that aid processing of raw geophysical data.

C. Inverse Processing

Inverse processing is different to conventional data processing in that it does not simply involve taking raw data, manipulating it, and output a result. As shown inFigure , one must first estimate a model for what is likely to be occurring in the site, calculate data corresponding to what the survey technique would produce if it was measuring across said model, and then compare this to the actual field data. (D.W. Oldenburg and F.H.M. Jones, 2007) If the two data sets do not correlate well, the estimated model must then be modified and the process repeated. The estimated model should be created from knowledge of the site and failure processes, and all other available survey data.

The issue with this form of processing comes from the concept of non-uniqueness. Two models can correspond to essentially the same data, so there is an uncertainty that stems from the choice of estimated model, highlighted in Figure C.2. This is one of the major hindrances in geophysical monitoring, and the reason it is so essential to carry out multiple forms of survey and have significant experience.

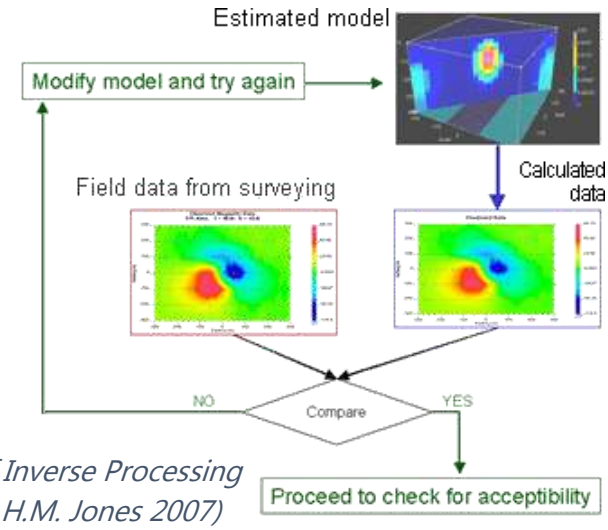


Figure C.1- Flow Map of Inverse Processing (D.W. Oldenburg and F.H.M. Jones 2007)

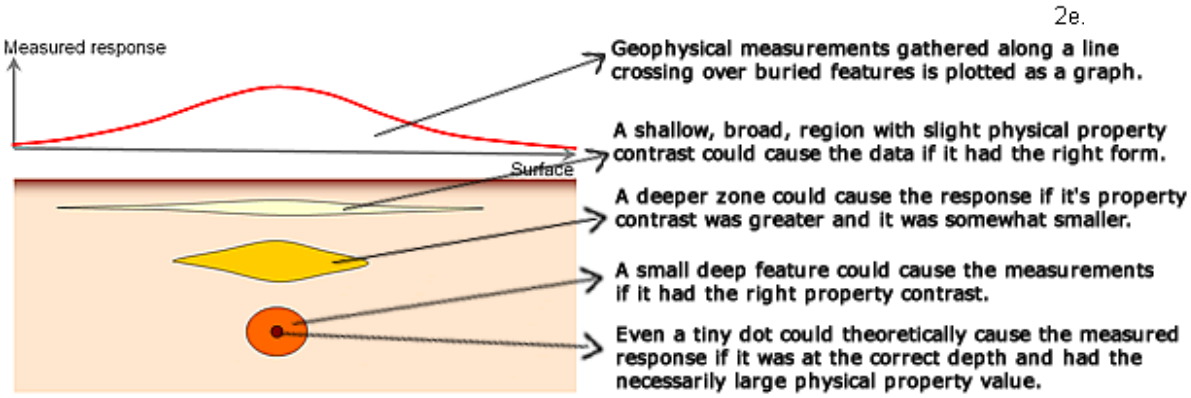


Figure C.2- An example of non-uniqueness (D.W. Oldenburg and F.H.M. Jones 2007)

D. A Note on the Advancement of Remote Sensing Techniques

Remote sensing is the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites (National Ocean Service, 2009). Remote sensing has become increasingly prevalent in geological and structure monitoring due to its potential for cost-effective surveying over very large areas. An airborne variant of electromagnetic profiling has been applied to kilometres of levees in the US, and the data gathered correlated well with land assessments (Dunbar *et al.*, 2003). Satellite based imaging has found significant use in subsidence and deformation monitoring. LIDAR, or Light Detection and Ranging, is one such technique that provides geo-referenced distance measurements to the earth's surface via laser (Mériaux, Lino and Royet, 2000). This can map surface tomography and bathymetry to a high level of detail. INSAR (Interferometric synthetic aperture radar) is another remote sensing technique that shows potential for widescale use. It uses multiple radars to generate elevation data by phase difference, of similar output data to LIDAR. INSAR does not yet have high enough resolution to be competitive, but the technology is quickly advancing. (Tomás *et al.*, 2014)

References

Almog, E., Kelham, P. and King, R. (2009) *Modes of dam failure and monitoring and measuring techniques*.

Antoine, R. *et al.* (2015) 'Detection of leakage areas in an earth embankment from GPR measurements and permeability logging', *International Journal of Geophysics*, 2015. doi: 10.1155/2015/610172.

Berga, L. (2006) *Dams and Reservoirs, Societies and Environment in the 21st Century: Proceedings of the International Symposium on Dams in the Societies of the 21st Century, ICOLD-SPANCOLD, 18 June 2006, Barcelona, Spain*. Taylor & Francis (Balkema-proceedings and monographs in engineering, water, and earth sciences). Available at: https://books.google.co.uk/books?id=_68IPAAACAAJ.

British Geological Survey (2010) 'Capacitive Resistivity Imaging'.

D.W. Oldenburg and F.H.M. Jones (2007) *Inversion Concepts: The Inversion Process*, *University of British Columbia, Inversion for Applied Geophysics*. Available at: https://www.eoas.ubc.ca/ubcgif/iag/tutorials/invn-concepts/how.htm.

Dam Safety Bureau (2008) *Geotechnical Investigation and Analyses for Dams*, *NEW MEXICO OFFICE OF THE STATE ENGINEER*.

Delage, P. *et al.* (2016) 'Advances in the monitoring of geo-structure subjected to climate loading', *E3S Web of Conferences*, 9, p. 4001. doi: 10.1051/e3sconf/20160904001.

Dunbar, J. B. *et al.* (2003) 'Condition assessment of U.S. International Boundary and Water Commission, Lower Rio Grande Valley Levees, South Texas', *US Army Corps of Engineers, Engineer Research and Development Center.*, 1.

Eaton, D. W., Milkereit, B. and Salisbury, M. (2003) 'Seismic methods for deep mineral exploration: Mature technologies adapted to new targets', *The Leading Edge*. Society of Exploration Geophysicists, 22(6), p. 580. doi: 10.1190/1.1587683.

Engineering Toolbox.com (no date) *Soil Resistivity Values for Different Types of Soil*. Available at: http://www.electricalengineeringtoolbox.com/2015/12/soil-resistivity-values-for-different.html.

Fannin, R. J. and Slangen, P. (2014) 'On the distinct phenomena of suffusion and suffosion', *Géotechnique Letters*, 4(4), pp. 289–294. doi: 10.1680/geolett.14.00051.

Fargier, Y. *et al.* (2012) 'Methodology Applied to the Diagnosis and Monitoring of Dikes and Dams', *Novel Approaches and Their Applications in Risk Assessment*, 3, pp. 263–280. doi: 10.5772/16318.

Fauchard, C. and Mériaux, P. (2007) *Geophysical and Geotechnical Methods for Diagnosing Flood Protection Dikes: Guide for Implementation and Interpretation*. Quae. Available at: https://books.google.co.uk/books?id=R6OC9eH-BZwC.

Frontier Geosciences (2016) *Surveying Methods*. Available at: http://www.frontiergeo.com/surveying-methods/.

Ikard, S. J. *et al.* (2014) 'Characterization of focused seepage through an earthfill dam using geoelectrical methods', *Ground Water*, 52(6), pp. 952–965. doi: 10.1111/gwat.12151.

J. Palacky, G. (1988) *3. Resistivity Characteristics of Geologic Targets*. doi: 10.1190/1.9781560802631.ch3.

Johnston, T. A. *et al.* (1990) 'An Engineering guide to the safety of embankment dams in the United Kingdom', *Building Research Establishment report*, p. 155.

Jones, G., Zielinski, M. and Sentenac, P. (2012) 'Mapping desiccation fissures using 3-D electrical resistivity tomography', *Journal of Applied Geophysics*, 84, pp. 39–51. doi: http://dx.doi.org/10.1016/j.jappgeo.2012.06.002.

Kappelmeyer GTC (no date) *Sensitive inspection and monitoring of embankment dams- Temperature Sounding Method*.

Karastathis, V. K. *et al.* (2002) 'Geophysical methods contributing to the testing of concrete dams. Application at the Marathon Dam', *Journal of Applied Geophysics*, 50(3), pp. 247–260. doi: 10.1016/S0926-9851(02)00145-3.

Kirsch, R. and Ernstson, K. (2006) *Groundwater Geophysics*, *Groundwater Geophysics, A Tool for Hydrogeology*. doi: 10.1007/3-540-29387-6.

Lopes, S. P. and Fauchard, C. (2013) *The FloodProBE International Geophysics Workshop*.

Lum, K. and Sheffer, M. (2005) 'Dam Safety: Review of Geophysical Methods to Detect Seepage and Internal Erosion in Embankment DamsNo Title', *Hydroworld*. Available at: http://www.hydroworld.com/articles/hr/print/volume-29/issue-2/articles/dam-safety-review.html.

McDowell, P. *et al.* (2002) 'Geophysics in engineering investigations', *Geological Society, London, Engineering Geology Special Publications*, 19(1), p. NP-NP. doi: 10.1144/GSL.ENG.1999.019.01.14.

Mériaux, P., Lino, M. and Royet, P. (2000) *Méthodologie de diagnostic des digues: appliquée aux levées de la Loire moyenne*. Quae. Available at: https://books.google.co.uk/books?id=C5tJfZDgNcgC.

Michalis, P., Sentenac, P. and Macbrayne, D. (2016) 'Geophysical Assessment of Dam Infrastructure: the Mugdock Reservoir Dam Case Study', (April), pp. 1–6.

Mitchell, C, Brown, A & Morris, A. (In P. (no date) 'Overflow erosion of levees and dams – current practice and research needs', *Dams and Reservoirs - ICE*.

Morris W. et al, M. W. . A. (2008) 'Failure modes and mechanisms for flood defence

structures', *Flood Risk Management- Research and Practice*.

National Ocean Service (2009) *What is remote sensing?* Available at: https://oceanservice.noaa.gov/facts/remotesensing.html.

Royet, P. *et al.* (2013) 'FloodproBE Project report WP 3: Reliability of Urban Flood Defences. D3.2: Rapid and cost-effective dike condition assessment methods: geophysics and remote sensing'.

RSK Geophysics (2016) 'A Reference for Geophysical Techniques and Applications', (Third Edition).

Rubin, Y., Hubbard, S. S. (2005) *Hydrogeophysics*, *Vasa*. Available at: http://medcontent.metapress.com/index/A65RM03P4874243N.pdf.

Sentenac, P. *et al.* (2013) 'An approach for the geophysical assessment of fissuring of estuary and river flood embankments: Validation against two case studies in England and Scotland', *Environmental Earth Sciences*, 69(6), pp. 1939–1949. doi: 10.1007/s12665-012-2026-z.

Sentenac G; Zielinski, M.; Tarantino, A, P. ; J. (2013) 'An approach for the geophysical assessment of fissuring of estuary and river flood embankments: validation against two case studies in England and Scotland', *Environ Earth Sci*. doi: 10.1007/s12665-012-2026-z).

Slob, E., Snieder, R. and Revil, A. (2010) 'Retrieving electric resistivity data from self-potential measurements by cross-correlation', *Geophysical Research Letters*, 37(4). doi: 10.1029/2009gl042247.

Subsurface Surveys & Associates (1988) 'Geophysical Methods & Applications', pp. 1–10. Available at: www.subsurfacesurveys.com.

Telford, W. M., Geldart, L. P. and Sheriff, R. E. (1991) *Applied Geophysics*. 2nd edn.

Tomás, R. *et al.* (2014) 'Radar interferometry techniques for the study of ground subsidence phenomena: A review of practical issues through cases in Spain', *Environmental Earth Sciences*, 71(1), pp. 163–181. doi: 10.1007/s12665-013-2422-z.