FloodproBE Project WP 3: Reliability of Urban Flood Defences. D3.2: Rapid and cost-effective dike condition assessment methods: geophysics and remote sensing

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WP 3: Reliability of Urban Flood Defences

D3.2: Rapid and cost-effective dike condition assessment methods: geophysics and remote sensing

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Disclaimer

Summary

The recent and dramatic floods of the last years in Europe (Windstorm Xynthia, February 2010) and United-States (Hurricane Katrina, August 2005) have shown the vulnerability of flood defence systems composed of man-made structures (as levees, walls, etc.) and natural structures (as dunes, etc.). The first key point for avoiding these dramatic damages and the high cost of a failure and its consequences lies in the knowledge of the safety level of the protection system. Identifying weak points of the system is the most important but the most difficult issue.

Most of the levees are old structures, built several centuries ago, then rebuilt, modified, heightened several times, with some materials that do not necessarily match the original conception of the structure. Other factors introduce weaknesses in a levee: (i) trees, roots, burrows or nests could modify the structure of the levee and reduce its mechanical properties; (ii) particular geological formations and their evolution could also threaten the dike, as it occurred in the city of Orléans, France, where levees have collapsed in karstic areas. In urban context, the levees present many other singularities, such as embedded networks, canalisations, human constructions like houses and walls. Due to all these factors, levees have to be considered as heterogeneous structures. Considering the stretch of hundreds of kilometres and the heterogeneity of the structures, rapid, cost-effective and reliable techniques for assessing and surveying the defence system must be carried out.

This report refers to the question of assessing embankment levees safety. The first part briefly presents a synthesis of the global approach related to diagnosis.

The second part focuses on the contribution of geophysical methods; guidelines are issued from the conclusions of an International Workshop on Geophysics held in Paris in March 2011. This chapter contains guidelines on application to urban areas for managers to implement and integrate geophysical investigation results into the asset support system. If focuses on technical, practical and economical features such as geophysical method applicability, reliability, rapidity, limitations (particularly in urban areas) and cost-effectiveness. Approaches based on method combination and comprising overall investigation followed by detailed investigation phases are confirmed. *Slingram* (electromagnetic induction) profiling and Electrical Resistivity Tomography are among the most preferred methods. However, all other methods can play important and specific roles, depending on the stakeholder requirements and the asset features and setting. Temporal approaches have proved powerful tools for weak zone detection and monitoring and should be more widely used in the near future.

The third part is dedicated to remote sensing and more specifically to the helicopter borne LiDAR (Light Detection and Ranging) technology, which provides extremely accurate topographic data at a highly efficient rate. In support of a real case study (“Val d’Orléans” Pilot Site), a methodology is developed for performing an helicopter borne survey and for using remote sensing LiDAR data and high-resolution aerial imagery – acquired in “dry conditions” (e.g. not in a flood context) - to contribute efficiently to a rural or urban flood defense structure diagnostic or assessment.

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The recent and dramatic floods of the last years in Europe (Windstorm Xynthia in France, February 2010, floods in South of France, 2002 and 2003, historical floods in Central Europe, Summer 2005), United-States (Hurricane Katrina, August 2005) and Asia (Thailand, 2011) have shown the vulnerability of flood defence systems composed of man-made structures (as levees, walls, etc.) and natural structures (as dunes, etc.). The first key point for avoiding these dramatic damages and the high cost of a failure and its consequences lies in the knowledge of the safety level of the protection system. Identifying weak points of the system is the most important but the most difficult issue.

Most of the levees are old structures, built several centuries ago, then rebuilt or repaired (after a breach), modified, heightened several times, with some materials that do not necessarily match the original conception of the structure. The levee foundations are also heterogeneous and in general were not properly treated to improve their water-tightness or other fundamental properties. Other factors introduce weaknesses in a levee: (i) trees, roots, burrows or termite nests could modify the structure of the levee and reduce its mechanical properties; (ii) particular geological formations and their evolution could also threaten the dike, as it occurred in the city of Orléans, France, where levees have collapsed in karstic areas. In urban context, the levees present many other singularities, such as embedded networks, pipes, human constructions like houses and walls. Due to all these factors, levees have to be considered as heterogeneous structures. Considering the stretch of hundreds of kilometres and the heterogeneity of the levees, both good assessment methods, based on sturdy fundamental knowledge of the failure mechanisms and the strength of the levee components, and rapid, cost-effective and reliable techniques for data acquisition and surveying the defence system are necessary.

FloodProBE work package 3 relates to the question of assessing earthen levees safety, more specifically in urban area. Task 3.1 actions deal with fundamental knowledge about the failure mechanisms or resistance of the dike. Task 3.2 actions deal with rapid, cost-effective investigation techniques. Task 3.3 deals with the question of the assessment methodology itself.

An assessment[1] is a process that has the objective to evaluate the performance of a levee system relating to one of its main functions: to protect against a given natural event and to be stable/safe. A complete assessment should include a diagnosis of the actual or possible causes of failure, in order to remediate or prevent them.

The assessment process can be described, in a very simple way, as the use of one or more methods of treating and combining data in order to obtain an evaluation of the performance of the levee system, according to its main function (protect against flood) and/or its reliability (against the possible failure modes). This can be done in different ways, as there are different assessment methods used in different countries, all based on a combination of data processing, using expert judgment, index based methods, empirical models, physical and/or mathematical models.

[1] ASSESSMENT relates to the global process of evaluating the safety level of the levee; DIAGNOSIS comes in complement when we want to specifically analyze the causes (mechanisms, failure modes) of a problem or of a risk.

Assessment make use of a lot of data. Some are already available at the start of an assessment process, while other ones are needed but unavailable; so specific data gathering has to be made during the assessment process. These data gathering can be done during specific inspections and investigations. And all data has its place in the information system of the levee manager.

Task 1 of work package 3 deals with improving fundamental knowledge of:

- Mechanisms leading to failure of an earthen work (internal erosion, 3.1.1)
- Structural weaknesses and associated failure modes (structure transitions, 3.1.2),
- Performance of the levee (resistance to external erosion brought by vegetation, 3.1.3)

which are essential for understanding the possible failure modes of the levee.

Task 2 of work package 3 deals with rapid and cost-effective investigation techniques:

- Geophysics, to complement classical geotechnical investigations and tests,
- LiDAR to get a high quantity of topographic information as well as high resolution pictures and videos.

which are essential data to be used during an assessment process.

Task 3 of the work package 3 details the general assessment framework developed during the project, as well as presents different examples of assessment methods and the way they can be improved using the developed framework.

This report is on task 2 and refers to the question of getting data to be used in assessing earthen levees safety. The first part briefly presents a synthesis of the global approach related to diagnosis. The second part focuses on the contribution of geophysical methods; guidelines are issued from the conclusions of an International Workshop on Geophysics held in Paris in March 2011. The third part is dedicated to remote sensing and more specifically to the helicopter borne LiDAR (Light Detection and Ranging) technology, which provides extremely accurate topographic and imagery data at a highly efficient rate and that was tested on “Val d’Orléans” Pilot Site in the framework of FloodProBE, with the financial support of two structures managing organisations (DREAL Centre and SNCF) and of an industrial partner (Fugro-Geoid).

Statement: the terms “levee” and “dike” are considered as synonyms. We also employ the term “embankment” when the structure is made of earth.

1 Introduction to levee assessment

1.1 Levee break or damage mechanisms

In rural or suburban areas, flood protection dikes are generally built as embankments (and are most commonly referred to as “levees”). Such design has always been widely accepted by hydraulic work designers as it helps highlight the watertight (clay or silt) or semi-permeable (silty sand) ground deposits frequently observed in alluvial valleys. It specifically complies with the technical and financial optimum for levees by minimizing earthmoving constraints (cut and fill construction).

Embankment flood dikes are subjected to four main damages or break mechanisms (Mériaux & Royet, 2007) that are more or less associated with the action of water these structures are supposed to retain or contain:

- Internal erosion;
- Overflow: when the levee top is exceeded by the river water level (overflowing) or waves (overtopping);
- Sliding slope;
- Slope external erosion on the watercourse side from the action of flow or waves.

These mechanisms are not independent: they may be sequenced and/or maintain each other until they induce the levee break (total or partial breach with release of a flood wave). For example: current-driven erosion results in the slope getting steeper on the watercourse side of a waterway levee, with the said slope sliding upon the fall in the water level (mechanical “break” in so-called rapid draw-down conditions) and, at the next flood, the embankment – with a narrower profile, thereby supporting an increased hydraulic gradient – is subjected to internal erosion that will lead to a breach.

Of all such four mechanisms, internal erosion stands out as hardly identifiable as, by essence, it is produced at the heart of the structure and its foundation and develops at a more or less slow pace:

- From the one part, through visual observation which, by nature, only helps identify indications displayed outside the structure;
- From the other part, through geophysical or geotechnical methods since the event may be extremely local and internal erosion is only proven when the dragging of ground particles from the work or the foundation thereof has taken place and led to the formation of under-dense areas, voids or ducts.

Thus, internal erosion will rather be identified by reviewing its initiating events or indirect effects, including the specific construction or behavioral features of the structure or foundation thereof from which such internal erosion may arise: permeable areas, ground/rigid structure interfaces, internal flow development, etc.

1.2 A general methodology for levee assessment

The management of levees involves many stakeholders and consists of surveying, maintaining and making safety assessments (Mériaux & Royet, 2001). The initial assessment, including diagnosis of the (potential) problems, should identify the weaknesses of the structure (zoning) and provide the level of safety. Thus, a general assessment methodology (Figure 1.1) has been proposed by Fauchard & Mériaux (2007), including a particular interest for data originating from geophysics.

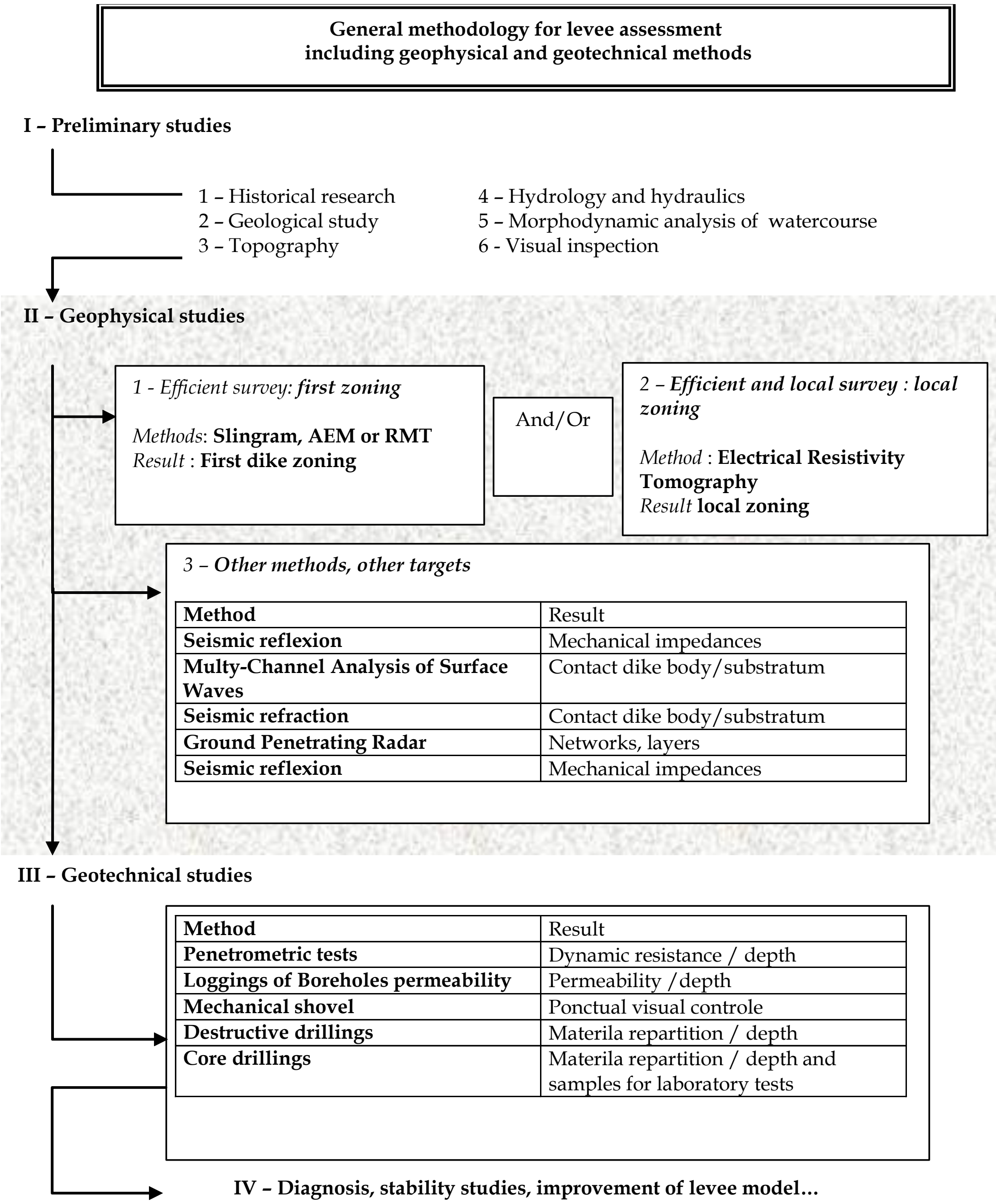


Figure 1.1 General methodology proposed in 2007 by the French National Project CriTerre (Fauchard & Mériaux, 2007)

It applies to the levees running alongside rivers, where the dikes are not in a permanent hydraulic loading. The assessment is performed in dry condition. This methodology is based on several tests carried out in the framework of the French National Project "CriTerre" and the ERINOH (Internal Erosion in Hydraulic Earthworks) project. This methodology can be applied to sea defences, with slight differences on in-situ inspections and hydraulic matters. A similar proposal is also included in the GMS methodology (Beneš et al., 2005)**.**

This assessment (Figure 1.1) begins with preliminary studies, before performing geophysical surveys. It goes on with geotechnical testing, before ending with the evaluation of the safety level.

1.3 Preliminary studies

The preliminary studies consist in gathering all available information concerning the levee, the near environment and its history, and producing the basic needed studies (Lino & al., 2000).

a) **The historical research** (Figure 1.2) can establish the way the levee was built, the locations of old repaired breaches, material distribution, etc. The study of historical archives gives clues wherefrom the materials were extracted so as to build and repair the dike.

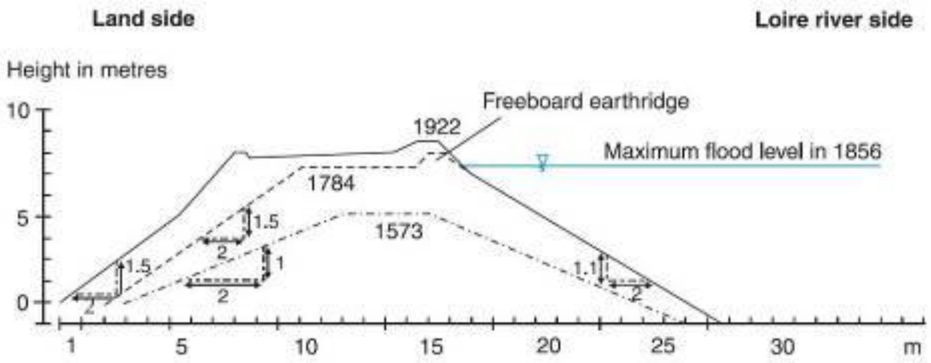


Figure 1.2 Example of historical data of the dikes of the Authion river (France, Loire) (Dion, 1961)

b) The **geological study** (map and in-situ observations) of the near area gives information about materials potentially used for building the levee and on the underlying substratum. Karstic areas or solutable foundation must be identified as they can threaten the levee.

c) The **topography** of the dike contains valuable information. From the longitudinal profile of the crest, we can assess the risk of overtopping during a flood by comparing it with the highest past flood. A map of the transverse profile is also required for stability studies and risks of internal erosion, as well as for an accurate location of any structure (walls, crest water gates, crossing networks…) that can modify the interaction between water and levee in case of flood. Finally, the topography is useful for levee management and maintenance. It provides 3D coordinates for visual inspection, geophysical and geotechnical studies. The topographic map has usually a scale of 1:500 to 1:1000. With conventional methods, longitudinal profiles are performed on the crest with a point every 20 to 25 m and transverse profiles are realized every 50 to 200 m, depending on the context. This is a critical issue in the dike study, and it could be time and cost consuming for dike of long extent. In that case, **LiDAR** systems are an interesting alternative surveying technique and provide accurate 3D points along the dike with a high point density (see chapter 3).

d) A **hydrological survey** involves determining the nature of floods with different recurrence intervals (flow rates, duration and frequency). It is based on watercourse flow rate measurements taken at stream-gauging stations, together with information on historical floods. Significant changes in land use in catchment areas (dense urbanisation, extensive reforestation programmes, etc.) or large-scale upstream developments (flood-control dams) are liable to modify flood-water regimes (especially during medium-intensity floods) and may necessitate the updating of previous hydrological surveys.

Hydraulic studies are used to convert the results from hydrological studies into flow lines for ten-year, thirty-year and hundred-year (or more) floods. They require knowledge of the detailed topography of the stream bed (costly) and the implementation of a hydraulic model. In most cases, a steady-state, mono-dimensional model is sufficient. Historical flood flow lines may provide enough information, dispensing with the need for the hydrological and hydraulic surveys mentioned above, provided that:

- Historical flooding has not led to dike failure;
- Stream bed modifications (longitudinal profile, new embankments, changes in floodplain land use) do not lead to any significant change in flow lines at equivalent flow rates;
- The hydrology of the catchment area has not changed significantly.

Comparisons of the flow lines for different flood recurrence intervals against the longitudinal profile of the levee (taking into account a necessary freeboard) make it possible to define the **maximum protection flood** – that is, the most extreme event against which the dike is expected to protect the valley.

The survey should be completed with an analysis of scenarios of exceptional flood peaks and associated phases of retreating water (spill over, filling and draining times of the flood spreading plain, operation of spillways, evacuation works, flap gates, sluices, etc.).

e) The **morphodynamic study consists in** understanding the sedimentology, the hydrology and the morphometric characteristics of the waterway. Geomorphic processes of rivers may impact the safety of levees by various means (Degoutte, 2006):

- Bank scour by flowing water that can destabilize levees if near the riverbed;
- Horizontal channel changes that may alter the currents during floods or bring the low flow channel closer to the levee;
- Evolution of the river profile by generalized incision - that can destabilize levees by rotational sliding, decrease the frequency of overflows, change the location of the first overflow, alter operation of weirs in levees;

– Evolution of the river profile by generalized aggradation – that can also change the conditions of overflow.

These processes are influenced by sediment transport of alluvial materials, but we will not forget the importance of woody vegetation, both for its role in the resistance of the banks, and for the transport and accumulation of wood. The transported wood can attack the river banks, slopes of the levee or protection of these slopes. Wood deposited during floods can cause localized areas of overflow on levees.

The morphodynamic study must take into account the temporal evolution of the watercourse channel such as translation of meanders, sideways progression of the river arms or deposits, regressive or progressive erosion of the river bed, aggradation, etc.

f) The **visual inspection** is performed after the historical research and the topographic work. This phase confirms, completes or invalidates any information previously collected. It is recommended to perform this inspection by three inspectors: one on the crest, and two at the levee toes on riverside and landside. Any anomaly should be reported on the topographic map and specific data sheets.

1.4 Geophysical studies

The geophysical exploration (see chapter 2) consists in mapping the levee body (nature and distribution of the material – the levee substratum is considered as a part of the levee body). Both the geometry (stretch and height) of the levee and the materials influence the choice of the methodology as well as the interpretation of the measurements.

Considering a typical study where the levee is a long structure of several kilometres, a classical approach starts with carrying out a rapid and cost-effective survey. It provides information on the homogeneity of the entire dike body. Then, heterogeneous areas that may weaken the dike body during a flood event are located.

Depending on the geophysical method, a physical parameter is measured according to different profile paths: along the crest (longitudinal profile), across the dike (transverse profile), at the toes of the dike (longitudinal profiles at the river side and the land side). The results of a geophysical survey must be **correlated** with the previous studies. This first survey helps focusing on interesting areas, which can be measured with appropriate geophysical or/and geotechnical methods (Figure 1.1).

1.5 Geotechnical testing

Geotechnical testing is generally carried out after the first investigations (prior knowledge of historical building and materials, localisation of heterogeneous areas). The final interpretation of geophysical measurements is only relevant when coupled with geotechnical testing. People interpreting the measurements have to decide to extrapolate - or not – the local tests to the rest of the levee.

Geotechnical testing locally provide physical parameters of the levee body that are required for a good diagnosis. A detailed methodology is given in (Lino et al., 2000)

Penetrometric tests are generally the first geotechnical method used to provide information about the soil density (derived from the measured dynamic resistance (in MPa) with regard to depth) and the layer thickness in the dike body. It consists in hammering a conical tip in soil with some characteristics depending on the penetrometric device. The depth of penetration can easily reach 10 m.

Permeability testing (e.g. the Lefranc test) consists in drilling a borehole, injecting and/or pumping water in an open-ended cavity, called a lantern, at the bottom of the borehole. It measures the variations of hydraulic head and its flow rate and gives the hydraulic conductivity ($m.s^{-1}$) around the lantern. Some devices evaluate both the soil density and the permeability.

Shear tests with phicometer provide the shear strength and the friction angle of soil. It consists in a probe – metal expansion shells - fitted with horizontal annular teeth inserted into the borehole. The shells move only laterally so that the teeth dig the soil. The method needs a good drilling quality with no lining –not the case in highly heterogeneous soils – and is not suited for soft soils.

A local investigation can be carried out with a mechanical shovel, digging a pit in the dike body or at its toe. It provides the distribution of materials.

Mechanical drilling basically provides the advance speed in borehole, and the location of interface layers. In case of destructive drilling, materials are breaking up and transported to the surface (cuttings) using a circulating fluid or a helicoidal cutting tool (auger). If percussion or roto-percussion conducts drilling (for cohesive and rocky soils), the analysis of cuttings can be difficult, but more information is provided by registered parameters like advance speed, tool pressure, circulation fluid pressure... The auger is applied mostly for loose and poorly cohesive soils and allows taking some material samples for lab-test analysis (water content, Atterberg limits, etc). In case of core drilling - non-destructive testing – soil samples are extracted directly from borehole without modifying physical properties of soils. Then the samples can be packed and sent for lab testing. Core drilling is local, more expensive and time consuming than destructive drilling, but provides very useful information for assessing dike properties.

All these methods require a free access to vehicle in the measuring location (crest and/or toe of the dike).

1.6 Numerical modelling

Numerical modelling is now widely used in geotechnical design. Improvements in the computational ability of modern computers and the development of more user-friendly specialist software programmes mean that a whole range of structural loading hypotheses can be tested rapidly on a given structure. Though useful, such tools nonetheless have two major limitations:

- Any model is an intellectual simplification of the real situation, which is based on the more or less complete representation of a few physical phenomena and their interactions (including boundary conditions);
- The quality of modelling results depends directly on the quality and representative character of the data used to set the model's parameters.

On the first point, we can consider that, being relatively simple structures, levee analysis does not require highly sophisticated models and that many tools used widely in engineering could be considered suitable for use. On the second point however, modelling proves to be limited in that levees are heterogeneous and certain model parameters are difficult to obtain in a representative and reliable fashion (mechanical properties in particular).

So, dike modelling should be carried out by:

- Referring whenever possible to the results of previous studies before embarking on any new calculations;
- Prioritising simple models, the parameters and boundary conditions of which can be relatively easily fixed;
- For levee diagnosis, systematically checking the sensitivity of results by varying the data within ranges determined by the results of exploratory surveys or by other studies;
- Using models to compare a variety of upgrading solutions and/or optimise their dimensions.

The purpose of **internal hydraulic modelling** carried out in a steady state with a parametric study of permeability values is to obtain the internal piezometric head to be taken into consideration in mechanical modelling in addition to the hydraulic gradients used to evaluate the risk of piping (see FloodProBe D3.1). This is particularly relevant in case of sand layers in connection with the river bed.

Geomechanical modelling is carried out using simple two-dimensional models based on circular or plane failure mechanisms, as part of studies into the overall stability of the dike. It is best to opt for a parametric approach, given that one of the major advantages of mechanical modelling is to assess the improvements afforded by upgrading and to compare different solutions.

1.7 Synthesis of the assessment

When carrying out diagnosis, it is good practice to include an assessment of the infrastructures and human activities that would be affected in the event of levee failure or malfunction.

A brief assessment of the consequences of levee failure should be made so as to classify segments being studied in order of priority and to gear diagnostic and upgrading methods to the vulnerability of the protected area as necessary.

Vulnerability is evaluated according to the following criteria:

- Land use (urban, periurban, industrial, agricultural, etc.);
- Size of the protected population;
- Infrastructures and networks under threat (roads, railways, channels, buried networks, etc.)

and is graded according to different levels:

(1) – Low to medium vulnerability;

(2) – High vulnerability;

(3) – Very high vulnerability.

Risk results from a combination of hazard probability (unforeseeable turns of events) and vulnerability (importance of human interests liable to suffer the prejudicial consequences of such events). This risk is evaluated for a given flood level, which is usually associated with a reference recurrence interval or historic event.

Failure probability is evaluated on the basis of conclusions drawn from diagnosis, which seeks to classify each segment of dike according to a category of failure probability:

(1) – reliable dike in terms of the reference event (flooding)

(2) – dike with a low degree of failure probability;

(3) – dike with a high degree of failure probability.

The global failure probability of a particular segment is the failure probability corresponding to the failure mechanism or degradation (overtopping, scouring, internal erosion, etc.) most likely to occur.

Evaluation of the risk associated with a particular segment is a combination of that section's *failure probability* and the *vulnerability* of the protected area. It is possible to give a score that could be, for example, the multiplication of the probability and vulnerability scores.

A suitably-scaled (1:10,000) cartographic approach is recommended for conclusions about risk analysis. It should show:

- Division into homogeneous segments;
- Grading by segment of the probability of malfunction and failure;
- Vulnerability by zone of protected areas;
- The category of risk associated with each segment.

2 Rapid geophysical investigation for condition assessment of embankment dikes in urban areas

2.1 About this geophysics guidance

2.1.1 Problem statement

Geophysical investigation has become a popular phase within overall methodologies for assessing embankment dike condition, as it allows investigating larger volumes as compared to conventional exploration techniques for assessing geotechnical properties. Nonetheless, geophysics experts' views on geophysical method selection and applicability appear to not always converge. Debates seem to circle and to feed on technical, regional and cultural preferences rather than on more fundamental and practical issues. This in turn prevents end users, such as flood defence managers, to more widely and confidently make use of geophysics, as concluded from the FP6-FLOODsite research programme. Furthermore, it is definitely desirable to work towards European harmonisation of guidance.

2.1.2 The FloodProBE 'Geophysics' Task

A specific task within the FP7-FloodProBE programme was entitled "Rapid, non intrusive geophysical methods for assessing dikes". It originated from the above problem statement. This task comprised:

- Organizing and holding an international workshop on the above mentioned issues
- Carrying out geophysical studies and cross-testing on some of the pilot sites provides by FloodProBE partners

Task outputs included reports on the Geophysics Workshop and on the Pilot studies (see references: Palma Lopes et al., 2012; Boukalová et al., 2010; Boukalová et al., 2012; Fauchard et al., 2012). This chapter represents the main task deliverable as a guidance on application to urban areas for managers to implement and integrate geophysical investigation results into the asset support system.

The **FloodProBE International Geophysics Workshop** (FIGW) was held from March 21st to 23rd, 2011, in Paris, France. It brought together a panel of about twenty attendees including geophysics experts and stakeholders from European and worldwide countries. It provided these experts with space for discussion with the aim of gaining wider international agreement on the applicability and reliability of geophysical methods for the cost-effective investigation of urban flood defence embankment systems. The experts complied with the proposed goals and produced agreed conclusions. A report on the FIGW has been produced and is available for download (see Palma Lopes et al., 2012).

These conclusions together with state-of-the-art, results from recent key research initiatives (e.g. CRITERRE, DEISTRUKT, IMPACT, FLOODsite, GEMSTONE, ERINOH and USACE initiatives e.g. Sabatier, 2010) questionnaires and surveys circulated among the invited experts are the foundation for the present guidance.

In support to the FIGW outputs, known geophysical approaches were validated and method complementarity was also tested on FloodProBE pilot sites (Boukalová et al., 2010; Boukalová et al., 2012; Fauchard et al., 2012).

2.1.3 Scope and objectives of chapter 2

This chapter addresses the geophysical investigations that schematically stand in phase II of the overall dike assessment methodology presented in Chapter 1 and Figure 1.1. It also shows the importance of the interactions with the other phases included in this overall assessment plan.

The scope of the present 'Geophysics' guidance (Chapter 2) includes the applicability, reliability and cost-effectiveness of geophysical methods for assessing the condition of embankment dikes and levees in urban areas.

It is important to note here that "urban area" is a context that is critical to geophysics applicability. The present guidance addresses embankment hydraulic structures that protect urban areas. But these structures themselves can actually stand in a variety of situations (from nearly rural to completely inserted in urban environment, see Figure 2.3). Therefore, the impact on method applicability is also very variable and deserves special attention.

The main objectives are the following:

- To give asset managers more insight into the applicability and reliability of geophysical methods for assessing embankment flood defence systems in urban areas, before using it in practice;
- To show asset managers how geophysical investigation is brought to practice and how geophysical results can cost-effectively contribute to an embankment dike condition assessment which in turn contributes to its stability assessment.

2.1.4 How to use this chapter

The core of chapter 2 stands in sections 2.2 to 2.5, each having a specific role and approach:

Section 2.2 addresses issues and concepts from a **'geophysics' angle**. Depending on their geophysical background and experience, readers may read it as a whole or just browse it to find answers to a variety of questions (from very general to very specific) such as:

- What is (near surface) Geophysics?
- What is specific to applying geophysics to embankment dike investigation?
- What is specific to geophysics in urban areas?
- What are the most recommended geophysical investigation approaches?
- Which geophysical methods are applicable to the dike I manage and the requirements I have?
- Which geophysical methods are disturbed (outcast) by the urban environment of the dike I manage?
- Which geophysical methods are rapid, cost-effective enough for what I need?

Section 2.3 addresses the geophysical investigation process from a **'stakeholder' point of view**. It is built as a step-by-step approach mimicking the successive steps that make up a dike investigation process. The section mainly aims at showing how the geophysical methods are brought to practice and how geophysical investigations are implemented (from the method selection to the data interpretation). It also shows the needed interactions between all condition assessment phases (Figure 1.1) and the corresponding actors (dike manager, geophysics sub-contractor, and geotechnical engineer). Again, depending on their background and experience, asset managers may read the section as a tutorial or simply use it as a reminder check list.

Section 2.4 and **section 2.5** present **real case studies** in order to show how the previously described approach is implemented. The aim is to provide 'non-expert' readers with an example of real geophysical results and interpretation, and to link to the investigation process steps unfolded in section 2.3. The case studies were carried out on the Hull and the Orléans pilot sites within the FloodProBE project.

Section 2.6 presents a general conclusion on the guidance and prospects for the geophysical approaches applied to embankment dikes in urban areas.

Section 2.7 is an appendix containing **technical sheets** introducing each of the main geophysical methods discussed in this guidance. References to well known textbooks are also given for readers wishing to see more detailed information on a specific method (including methods for which no technical sheet is provided here).

2.1.5 Legitimacy

The information and recommendations contained in this chapter have been validated by all contributors to the FIGW (invited experts and other contributors), many of whom represent National practices build on recommendations from key research initiatives from around Europe and abroad.

The present 'geophysics' guidance (Chapter 2) is consistent with other guidance and program results such as:

- CRITERRE research project (Fauchard and Mériaux, 2007) recommendations;
- DEISTRUKT project (RIMAX) recommendations (Weller et al., 2008 ; Niederleithinger et al., 2012);
- The outcomes from the following research initiatives (Boukalová and Beneš, 2008): GEMSTONE (E!3658 GEMSTONE: GEophysical Methods for STudying OperatioN of Embankments, EUREKA Program, http://www.vodnizdroje.cz/gemen.htm), IMPACT (IMPACT: Investigation of Extreme Flood Processes & Uncertainty, FP5 project, http://www.samui.co.uk/impact-project/; Beneš et al., 2005) and FLOODsite (FLOODsite: Integrated Flood Risk Analysis and Management Methodologies, FP6 integrated project, http://www.floodsite.net/html/project_overview.htm);
- ERINOH research project (Coll., 2012) guidance book (due for publication end of 2012);
- The International Levee Handbook initiative (ILH, Coll., to bee released 2013).

It needs to be emphasized that the legitimacy of the present guidance is only relevant within the scope of the FloodProBE project and at the time of publication. Indeed, it is expected that research efforts will be focusing on enhancing relevant methodologies and technologies in the near future.

2.2 Geophysical methods applied to embankment dike investigation

2.2.1 A brief introduction to near-surface geophysics

This section is dedicated to introducing some basic principles of near-surface geophysics (practical information, not theoretic) and also a quality questioning that is common to most geophysical fields of application (including dike investigation).

2.2.1.1 Basic principles

Near-surface geophysics provides a variety of methods and technologies to investigate subsoil from the surface. Investigations are **non-intrusive**, as in medical auscultation and imaging techniques.

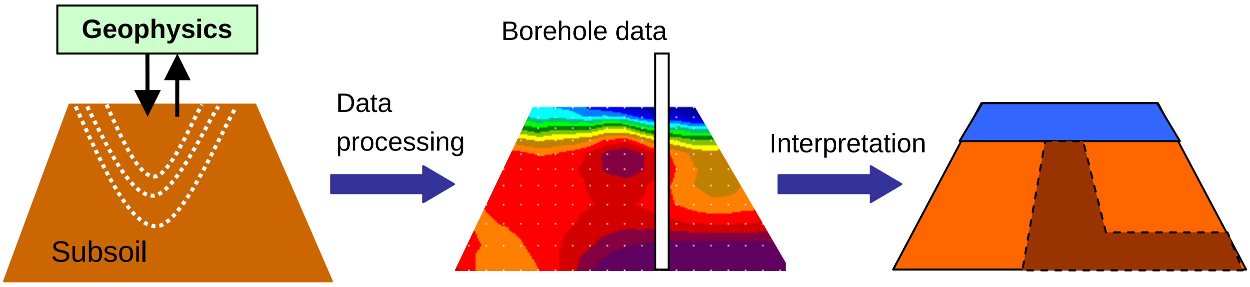
Geophysical investigation is based on the interaction between a physical field (e.g. electromagnetic field or mechanical wave propagation field) and the subsurface materials. These interactions are sensitive to material properties (nature and state parameters such as bulk density or moisture content). Therefore, geophysical investigations have shown great potential to inform on subsoil features such as: structure (layering), nature (geology), condition and spatial variations of soil properties. Development and use of temporal approaches for detecting and monitoring time changes has also become a dynamic field of activity.

Fields of application are numerous and have grown from former geophysical prospecting (mining, oil and water prospecting, geology identification) to the smaller scales of environmental, civil engineering and hazard mitigation applications.

A geophysical survey is designed on the basis of available site information and the aims and constraints of the investigation. This process implies the selection of one (or more) geophysical method(s) applicable to the case study. The implementation comprises data acquisition, data processing and interpretation (Figure 2.1).

There are several types of data acquisition techniques (e.g. profiling, sounding, mapping, imaging, monitoring), depending on the investigation goals, the selected method, the equipment used and the required depth of investigation and spatial resolution. For each geophysical method, a number of commercial devices are available (see examples Figure 2.2). Data processing ranges from very basic to very complex, also depending on the selected geophysical method and the purpose of the investigation. Expected geophysical results take the form of graphs, horizontal maps or vertical sections.

The geophysical interpretation requires modelling and result quality assessment (reliability or uncertainty level). The joint interpretation of data from various sources (e.g. combination of geophysical methods with borehole/CPT data, geologic data and/or historical data) usually yields higher reliability results.



(a) Data acquisition (b) Geophysical result (c) Subsoil model

Figure 2.1 General scheme of a geophysical investigation process: (a) geophysical data acquisition, (b) geophysical parameter graph, map or cross-section with additional borehole data and (c) subsoil structure model or geotechnical property distribution.

(a)

(b)

(c)

(d)

Figure 2.2 Geophysical acquisition device examples: (a) Dipole electromagnetic profiling with GEM2 equipment (© METCENAS, G IMPULS PRAHA s.r.o.), (b) *Slingram* electromagnetic profiling with EM31 device towed on non-metallic cart (© LRPC Saint-Brieuc), (c) GPR profiling with towed antenna (© LRPC Saint-Brieuc) and (d) Electrical Resistivity Tomography (© ERINOH, Ifsttar).

2.2.1.2 A common quality questioning

As for any experimental field, geophysical measurements are sensitive to various internal and external sources of noise. Moreover, geophysical methods are non-intrusive investigation tools (similarly to Non-Destructive Evaluation techniques) and thus they only allow for **indirect** sub-surface investigation. Furthermore, some interpretation processes (e.g. data inversion) are complex and face 'equivalence' problems (non-unique solutions). The combination of data noise with inversion error inevitably leads to some **model uncertainty**. This uncertainty can be reduced by calibrating and confirming the geophysical results by direct investigations acquired in one or more locations (e.g. geotechnical testing, geological data). Nevertheless, a potential **risk of error** remains. This fact has not always been well explained by geophysicists to geophysics end-users, which in turn has lead to some misunderstanding and disappointment.

This problem relates to the general issue of geophysics **quality**, which includes geophysics expertise, report quality and transparency. Stakeholder **understanding** and **confidence** in geophysics can be significantly improved when the geophysical results **reliability** is thoroughly assessed and clearly explained to the end-user. Moreover, the most rapid geophysical investigation may not yield the highest resolution and reliability. Therefore, this issue is also a matter of **risk/cost** compromise.

Recently, there have been national initiatives to improve geophysical result quality and enhance end-users' understanding and confidence level: e.g. Czech (certification by Ministry of Environment, Czech Republic), French (www.agapqualite.org/) and German certification procedures for geophysics sub-contractors. There are standardization efforts on progress as well, in Europe (e.g. CEN, 2011) and in the USA (e.g. ASTM International, 2011).

2.2.2 Geophysics applied to embankment dike investigation

Application of geophysical methods to the investigation of embankment manmade structures has grown for at least two decades (e.g. Jackson et al., 2002). Nowadays, geophysical techniques are frequently used for assessing and monitoring earth hydraulic structures (e.g. Fauchard and Mériaux, 2007; Llopis and Simms, 2007; Boukalová and Beneš, 2008; EDF experience in France), and there are numerous recent or on-going research works focusing on the improvement of these applications (e.g. Sjödahl et al., 2006).

Further details on state-of-the art literature and recent and on-going key research initiatives can be found in the FIGW report (Palma Lopes et al., 2012). A broad variety of case studies and research works can also be found within the scientific and technical material submitted and discussed by the geophysics experts attending the FIGW (Coll., 2011), as well as in Sabatier (2010). These sources of information show that there are now numerous geophysical methods successfully applied to embankment dike investigation.

The most commonly used geophysical methods for investigating and monitoring embankment dikes and levees are:

- ***Slingram*[2]** electromagnetic induction (EMI) profiling,
- **Radio Magnetotelluric** (RMT) profiling,
- **Airborne Electromagnetic** (AEM) induction profiling,
- **Lateral Resistivity profiling** (LRP, e.g. Schlumberger Resistivity profiling),
- **DC-Electrical Resistivity Tomography** (ERT),
- **Ground Penetrating Radar** (GPR),
- **Multichannel Analysis of Surface Waves** (MASW),
- **Seismic Refraction**,
- **Micro-Gravimetry**,
- Magnetics (e.g. **Magnetic profiling**),
- **Self-Potential** (SP) techniques,
- Thermometry based techniques (e.g. **Temperature Sounding method**).

Most of these methods were discussed in detail during the FIGW (Palma Lopes et al., 2012), except for RMT and AEM that were barely mentioned. A technical sheet can be found in appendix (section 2.7) for each of the geophysical methods that were mainly discussed. Further theoretical and practical information has been widely published (e.g. Telford et al., 1990).

When implementing geophysics, what is specific to investigating an embankment dike or levee? What are the additional constraints, particularly in urban areas?

- An embankment is a manmade earth structure generally lying on a natural formation (foundation); the embankment may have a non-homogeneous structure and include reinforcement/repair zones, thus presenting a complex picture to geophysics. Urban earth structures have a key role and safety challenges are huge: asset managers wish geophysical investigation results to be **accurately** and **reliably** meet a variety of detection and zoning needs (see Section 2.3.2.1 and Table 2.2).
- Traditional geotechnical investigation techniques are accurate but only provide local information whereas asset managers need quick and overall condition assessment; Geophysics offers volume investigation that allows for optimizing geotechnical testing number and location. However, geophysics results are less accurate and require calibration based on geotechnical testing data, and reliability assessment. Therefore **geophysical and geotechnical information** are both needed and improve each other mutually.

[2] '*Slingram*' techniques mentioned in this guidance are consistent with those defined as ground-based *Slingram* techniques in the CEN CWA 16373:2011 standard (CEN, 2011). These include single and multi-frequency based devices.

- An urban flood protection system is usually a very long linear structure (tens to hundreds of km long) protecting a dense urban area; assessing (or monitoring) a complete asset brings an obvious time/cost challenge: asset managers wish investigation approaches to be **cost-effective.** This should include balancing assessment budget among complementary investigation options such as geotechnical testing, rapid geophysical investigation, detailed geophysical investigation and repeated geophysical investigation.
- The **geometry** (topography) of a dike has an impact on most geophysical methods as the physical field/subsoil interaction is affected by the surface shape; this needs to be accounted for when implementing and interpreting geophysical investigations of dikes and recent research efforts have been put on this topic.
- Also to be accounted for: the load conditions at the time of the geophysical investigations, as the **presence of a large volume of water** (permanent, periodic or sporadic) next to the embankment may have a significant impact on the geophysical signals.
- On the positive side, seasons and varying load conditions lead to time changes of soil properties, which offers the opportunity to implement temporal investigation approaches for detecting and monitoring anomalous time changing zones within an embankment dike. These are potential weak spots for the future; therefore investigation approaches not only need to offer one-time surveys but also **temporal and monitoring** techniques, either for detecting weak spots or for implementing long term surveillance (see section 2.2.3.3).
- In **urban areas**, there is variable amount of anthropogenic structures/activities surrounding the dike (Figure 2.3) (e.g. metallic objects, electric power lines, building encroachment, traffic vibrations, etc.). These features can either disturb geophysical signals, or even simply prevent the use of some geophysical methods.

Figure 2.3 Examples of embankment levees protecting urban areas (Orléans, France). Some stretches are very lightly embedded (left side views) whereas others are very strongly embedded (right side views) in the urban environment. (© CETE Normandie Centre, DREAL Centre).

2.2.3 Recommended geophysical approaches for investigating embankment dikes

Geophysical investigations are the second phase of the general dike condition assessment methodology (Figure 1.1, phase II). Within this phase, a main geophysical investigation approach has been recommended: it consists of **two zoning stages** which interact with the other phases in the general dike assessment and most particularly with geotechnical investigations. This main approach is now widely used (e.g. Fauchard and Mériaux, 2007; Boukalová and Beneš, 2008; Weller et al., 2008; Coll., 2012). It was agreed among all experts during the FIGW (Palma Lopes et al., 2012) and there are a few preferred geophysical methods for implementing it. However, some noteworthy alternatives are presented. Most importantly, all presented approaches can be repeated over time, thus leading to temporal and monitoring approaches.

2.2.3.1 The main recommended zoning approach

The main approach based on two zoning stages is shown in the upper part of Figure 2.4 (see ‘First approach’). It was initially meant for implementation within a one-time assessment process. However, the whole scheme (first zoning + possible second zoning) can be repeated over time at different water saturation levels of the dike or levee for more focused weak zone characterization or for monitoring purposes (see section 2.2.3.3).

First zoning stage:

The first zoning stage consists of a **rapid (overall) investigation** of the dike over its full length. ***Slingram* profiling** is the most commonly used geophysical method for this stage. It is a very rapid method. Nevertheless, results only provide low resolution information (graph representing apparent conductivity versus longitudinal position along the dike, for one or a few depths of investigation; currently, it is also possible to get a basic idea of the vertical resistivity structure by carrying out *Slingram* profiling in various acquisition modes allowing for a range of investigation depths, see appendix: Section 2.7). Examples of *Slingram* results are presented in sections 2.4 and 2.5. From the results, number and locations of geotechnical testing points can be optimized and potentially weak zones may be identified.

Second zoning stage:

If potentially weak zones were previously detected in the first stage, then the second zoning stage consists of a **detailed investigation** of these zones. **ERT** is the most commonly used geophysical method for this stage, as it is highly sensitive to soil nature and state parameters and it can provide a high resolution image of the dike body and foundation (see ERT result examples in sections 2.4 and 2.5).

2.2.3.2 Noteworthy approach alternatives

There are important alternatives to the main recommended approach and the preferred geophysical methods mentioned in the previous section.

Again, these approaches can be implemented within a one-time assessment process or can be repeated at different water saturation levels of the dike or levee for further detection and monitoring purposes (see section 2.2.3.3).

Geophysical method selection and combination:

Although *Slingram* profiling and ERT are the preferred geophysical methods respectively for the first and second zoning stages, there are numerous other options. The most common options were discussed during the FIGW and are addressed in section 2.2.4 and in 'Step-by-step section 2.3). It is important to note that these options are not exclusive and that they are frequently used in combination, depending on the dike context, the investigation goals and the type of searched defects (e.g. *Slingram* and ERT can be complemented by Seismic Refraction or Micro-Gravimetry). Most importantly, there is no such thing as a standard investigation scheme (Niederleithinger et al., 2012) and the actual scheme is always site specific.

Zoning approach variant:

The variant presented here is implemented by some stakeholders (e.g. it is the common practice in Germany and is applied by EDF in France as well) and seems to relate to cultural and economical differences. In this approach, **ERT** is carried out right from the start of the zoning stage instead of *Slingram* profiling (see 'Second approach' Figure 2.4). ERT profiles are then implemented with a faster *roll along* technique based on sufficient personnel and equipment. Nonetheless, ERT remains much slower than *Slingram* profiling. But it yields much higher resolution results. Therefore this alternative is slower and more expensive, but less risky. This approach may yield sufficient information in one single survey of the embankment dike over its full length; otherwise, additional ERT profiles can be carried out on potentially weak zones, if higher resolution is needed, just like in the second zoning stage of the main recommended approach.

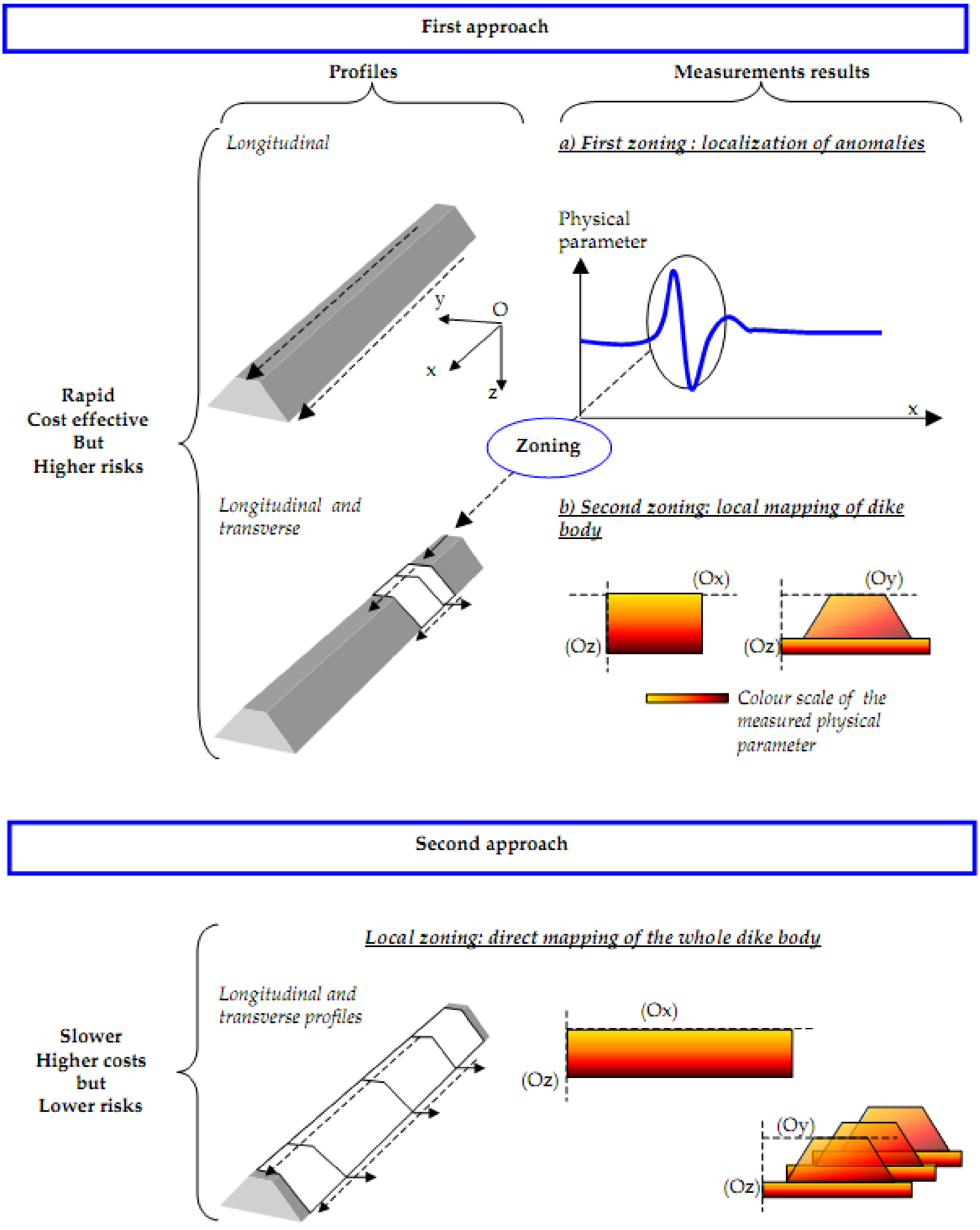


Figure 2.4 The main recommended geophysical investigation zoning approach ('First approach') and a significant alternative ('Second approach') (in Fargier et al., 2012).

2.2.3.3 Temporal approaches

The present section addresses the fact that any of the above-mentioned approaches can be repeated over time, which brings new possibilities and added value to the asset manager.

Taking advantage of temporal variations

The transition from dry season to wet season causes soil hydric properties within an embankment dike to change because of rainfall increase, water table and river level rise. These global property changes may not be problematic and may simply show a seasonal variation trend for the particular asset. In weak zones though, more significant property changes may be the sign of progressive disorders (e.g. water infiltration, seepage, internal erosion and piping).

In turn, soil property variations induce geophysical response variations. Therefore, one can take advantage of these seasonal differences to improve weak zone detection and monitoring by implementing temporal approaches based on repeated geophysical investigations (Figure 2.5) (Beneš et al., 2005; Boukalová and Beneš, 2008). Geophysical methods that are highly sensitive to hydric state properties like geoelectrical and electromagnetic methods are most recommended (e.g. *Slingram*, ERT, GPR, SP methods) although methods that are sensitive to density or mechanical properties may also be applicable in some cases (e.g. Micro-Gravimetry, MASW or Seismic Refraction). Such approaches have proved very effective and are now being gradually applied to dike assessment and surveillance. Ideally, one should always try and repeat geophysical investigations at different times when weak zones are suspected, as it provides additional or even essential information compared to the main zoning approach presented before (section 2.2.3.1).

Coastal and estuarine flood defences also face varied load conditions. These are ruled by tidal cycles in combination with climatic events. Therefore, temporal approaches still stand for these defences. For instance, one can conduct an initial geophysical investigation in neap tidal conditions and a subsequent investigation in spring tidal conditions (Boukalová et al., 2012). Moreover, sea water is much more conductive than fresh water and may lead to higher geoelectrical variations where infiltration or seepage occurs, which is an advantage when using, e.g., *Slingram* profiling or ERT for detecting weak zones.

Basic principles of geophysical temporal approaches applied to dike investigation

Temporal approaches consist of carrying out identical surveys at different times, meaning that the same stretch of dike is repeatedly investigated in the exact same way, although in different seasons or load conditions. Indeed, the sets of repeated measurements are conducted at different water saturation levels of the dike, ideally in dry season and then during or right after flooding (or in low tides and then in high tides, Figure 2.5). In order to enable high-value and cost-effective results, such approaches require rigorous measurement procedures, use of good precision devices, high-quality repeatability of the measurements including simultaneous GPS/geophysical data acquisition and appropriate data analysis techniques.

Depending on the number of repeated investigations and the data analysis method involved, there are a number of temporal approaches from basic to more complex ones. Objectives range from detecting weak zones that would not be brought to light by a one-time investigation (Boukalová and Beneš, 2008), to long term monitoring of stretches that are considered critical (Mériaux et al., 2012).

Although these temporal approaches based on repeated geophysical investigations have shown great potential, uptake is still low on a European scale. As agreed during the FIGW, integration of such approaches into dike stability assessment and maintenance procedures would certainly benefit asset managers. Currently, long term geophysical monitoring is more commonly applied to embankment dams (e.g. Sjödahl et al., 2010), whereas applications to embankment dikes or levees are still mainly experimental (Mériaux et al., 2012, including tentative use of permanent geophysical sensors).

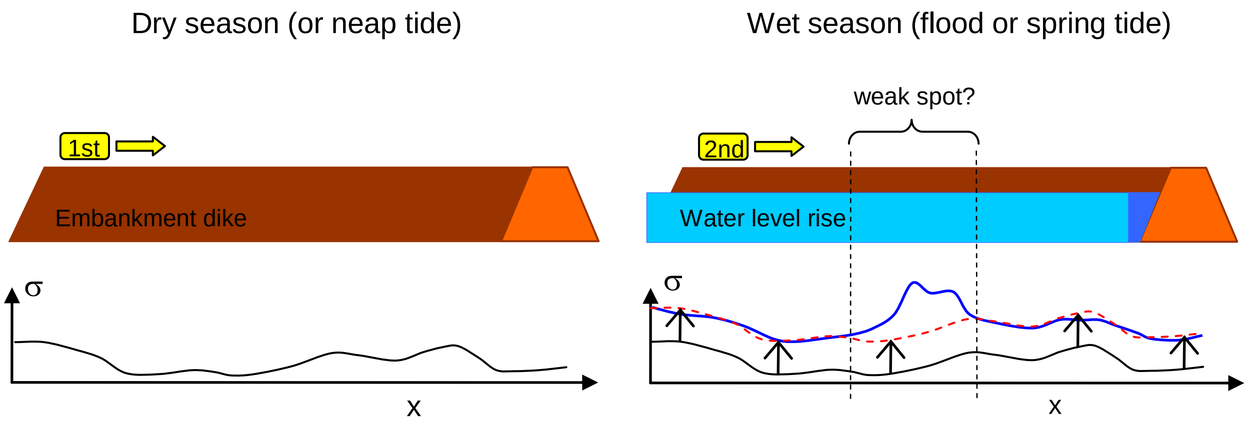


Figure 2.5 Principle of temporal approaches
Identical geophysical and GPS data acquisitions (yellow block and arrow) are conducted over the same dike profile in load conditions as different as possible to one another. Seasonal geophysical responses (σ) are shown by the black and the blue lines for the dry and wet seasons respectively. The general shift between both curves may indicate seasonal variations related to the total change in the dike water saturation level. When analysing the wet season curve, one has to suppress global seasonal variations (dashed red line), in order to highlight local residual anomalies that are considered potential weak spots.

Analysis, data processing and interpretation

Analysis of temporal variations is based on techniques that focus on bringing local anomalies into light. For instance, one can compare pairs of subsequent data sets, or compare each data set to the first data set that represents the initial dike condition in a dry state. It is essential to remove the effect of seasonal (climatic) changes from the measured data (Figure 2.5). This leads to calculating ‘residual’ geophysical responses that mainly show local changes that are beyond the ‘normal’ seasonal changes (e.g. Boukalová and Beneš, 2008). Significant variations showed by residual responses are considered potential weak spots. Cross-correlation of such residual geophysical responses measured at different times can serve as a guide for more consistent weak zone detection.

This general methodology is well suited for analyzing raw geophysical data, e.g. apparent conductivity profiles yielded by *Slingram* profiling, or apparent resistivity sets yielded by ERT measurements on the investigated dike. It is also applied to other geophysical methods, such as Self-Potential (SP) and Micro-Gravimetry.

To some extent, this methodology can also be applied to more elaborate geophysical results, e.g. to resistivity distribution models which are the output of ERT data inversion. However, in this case, 'time-lapse inversion' approaches may prove more appropriate. In such approaches, geophysical data sets obtained at different times are inverted jointly rather than separately, which provides zones of significant temporal variations that are more relevant and less disturbed by inversion uncertainty.

In order to yield a correct interpretation, all temporal and spatial aspects need to be considered. For example, temperature has an effect on soil resistivity that may be opposed to that of soil moisture content: in wet season, the soil moisture increases which decreases resistivity, whereas temperature decreases which increases resistivity. Another example is the potential effect of the water volume next to the embankment flood protection in high waters conditions (river or sea level rise) on some geophysical methods: depending on geometrical and soil nature considerations, a decrease in apparent resistivity values might be due to that conductive volume rather than to moisture content changes within the dike body. This is particularly the case when interpreting ERT results (Fargier et al., 2012). Finally, soil remoistening rate depends on soil permeability and maximum soil water saturation level is delayed with respect to maximum river (or sea) level.

2.2.3.4 Outcomes of the geophysical investigation approaches

The primary outcome of the first zoning stage is the **overall segmentation** of the dike or levee into horizontal zones that lie in three categories: quasi-homogeneous segments that show nearly constant geophysical response, anomalies that are limited zones showing significant spatial variations compared to the surrounding areas, and zones of transition between homogeneous segments or between a homogeneous segment and an anomaly (transition zones are usually considered as potential weak spots).

When a second zoning stage is carried out, the outcome is a **more detailed segmentation** of the potential weak zones, including the location of vertical contacts (transition between materials along the dike), horizontal contacts (bedrock, foundation, embankment layers) and the imaging of structural singularities that may be the place of internal weaknesses (e.g. cavity, cracking, material transition, internal erosion) although confirmation by additional observations is highly recommended.

When a geophysical temporal approach is implemented (repeated investigations, monitoring), the outcome is a consistent **identification of changing weak spots** that are highly sensitive to load conditions potentially unstable.

After being interpreted jointly with all available information (e.g. historical data, geological setting, geotechnical testing, hydrologic information) the geophysical investigation results significantly contribute to the description of dike models in terms of the dike inner structure, segment nature and condition including clear evidence of weak spots. In turn, these (geological, mechanical, and hydrological) models are integrated in the asset safety assessment process.

2.2.4 Practical features of the main geophysical methods applied to embankment dike investigation: Usefulness, applicability and cost-effectiveness

This section addresses geophysical method features that are important for asset managers to evaluate their usefulness and cost-effectiveness.

The geophysical methods considered here are those introduced in section 2.2.2. They are the most popular methods for investigating embankment dikes or levees and they were discussed during the FIGW to gain wider agreement on their applicability, limitations and cost-effectiveness. The conclusions drawn from this workshop and from state-of-the-art are presented in Table 2.1 from a geophysical point of view, but in a way that aims at being understandable by non-specialists. Although geophysical methods are usually combined and used within integrated approaches when investigating dikes (section 2.2.3), they are considered individually in this section, regardless of which method is preferred. This enables comparison of method usefulness to some extent.

Note: Airborne Electromagnetic (AEM) profiling was not included in Table 2.1 as no documented dike investigation survey using AEM was found within Europe, and this method was only poorly discussed during the FIGW. A more detailed note can be found in section 2.3.5.

Description of Table 2.1 contents

The following columns are presented in this table:

1. **Geophysical methods:** Addressed geophysical methods are the most popular methods for dike investigation and were discussed in detail during the FIGW.
2. **Mainly used in which investigation stage: Overall or Detailed?** The 'Overall' (first zoning) and the 'Detailed' (second zoning) investigation stages are described in the previous section. Each method is then assigned to one of the stages or sometimes to both.
3. **Sensitive to which geophysical and geomechanical soil properties?** This column details the specific properties linked to each geophysical method, knowing that geophysical properties (e.g. electrical conductivity) depend on soil properties (e.g. moisture and clay contents).
4. **Which features within dike and foundation can be detected?** In the field of embankment dike investigation, each method can play a specific detection role that relates to its physical principles and how it interacts with subsurface. The information in this column relates to geophysical method applicability. Applicability is also addressed in Table 2.2 from a stakeholder point of view.
5. **Type of dike model or dike information produced:** After being interpreted jointly with geotechnical data (e.g. borehole data), geophysical investigations produce information or models that are as close as possible to the asset manager needs, depending on the geophysical methods used.
6. **Additional advantages:** Some geophysical methods provide additional acquisition or detection benefits.

7. **Conditions / Limitations:** It is obvious that each geophysical method works under certain conditions and has clear limitations. Although not detailed here, one of the most common conditions is the need for validation and calibration of geophysical interpretation results, based on independent observations (geological setting, borehole data, sampling and testing). The geophysical result reliability highly depends on such calibrations.

8. **Applicable in urban areas?** As previously mentioned, this guidance addresses geophysical investigation of embankment dikes protecting urban areas. Such dikes and levees stand in environments that range from quasi-rural to fully urban, leading to variable impact on the applicability of each geophysical method.

9. **Acquisition speed:** This relates to the length of dike that can be surveyed per day, and gives an idea on how rapid (or slow) is a given geophysical method. For further details, please refer to the "*Cost*" paragraph below.

10. **Minimum recommended data processing and interpretation time (in engineer days) for the amount of profile surveyed per day:** The information in this column represents the recommended interpretation effort based on the conclusions from the FIGW, state-of-the-art documentation and published recommendations. It is expressed in minimum number of days of engineer work needed for thoroughly process and interpret the amount of geophysical data acquired within one full day of field work (related to the amount of surveyed profile denoted in the previous column).

11. **Estimated cost per km of profile:** Geophysics cost range is estimated based on practice discussed during the FIGW and on published recommendations. Estimated cost ranges are only relative to one another and are represented by classes. In order to cover the broad range of costs, a logarithmic scale was chosen. There is about one order of magnitude in cost between classes A and D, and again between classes D and G. For further details, please refer to the "*Cost*" paragraph below.

Cost-effectiveness analysis:

One of the main objectives of this guidance is to provide stakeholders with some insight into the cost-effectiveness of geophysical methods and approaches applied to embankment dike investigation. Therefore, some focus on cost-effectiveness concepts is needed.

Cost-effectiveness analysis (e.g. http://en.wikipedia.org/wiki/Cost-effectiveness_analysis) is a form of economic analysis that compares the relative costs and outcomes (effects) of two or more courses of action. It is distinct from cost-benefit analysis, which assigns a monetary value to the measure of effect. Cost-effectiveness analysis is often used in the field of health services, where it may be inappropriate to monetize health effect. An analogy can be drawn between health interventions and dike condition assessment to some extent, since 'preventive' and 'therapeutic' measures can be taken in both fields of human activity.

Cost:

In average, the cost of the geophysics phase represents about 15 to 30% of the total dike condition assessment cost (Palma Lopes et al., 2012). Geophysics cost depends on various expenditure, from survey design through to validation and reporting. For comparison purposes between geophysical methods, we make a simplification by assuming that cost differences mainly arise from data acquisition (method rapidity) and data processing and interpretation (method complexity). Since embankment dikes and levees are line structures, the cost of data acquisition, processing and interpretation per dike unit length (e.g. cost per km of investigated dike) appears to be a relevant information for comparison purposes. Therefore the investigation cost for each geophysical method in Table 2.1 represents the cost per km including data acquisition, data processing and interpretation. In order to cover the broad range of estimated costs, a logarithmic scale was chosen represented by classes A (lowest cost/km) to G (highest cost/km). There is about one order of magnitude in cost between classes A and D, and again between classes D and G. These huge differences in cost simply show that some methods (more rapid acquisition, less processing effort) can be implemented over several kilometres, whereas other methods (slower acquisition, more processing effort) can only be considered for stretches not longer than hundreds of meters.

Although cost differences may be very significant from one country to another, estimated cost ranges presented here are relative and we assume they are meaningful for a cost-effectiveness comparison. In Table 2.1 acquisition speed, data processing, interpretation effort and estimated cost are presented in columns 9 to 11.

One also needs to ascertain that the geophysical acquisition design matches the investigation requirements in terms of depth of investigation, spatial resolution and data quality. Improving these features has a negative impact on cost but a positive impact on relevance and reliability. The spatial sampling assumed for each method is given in the note bellow.

Similarly, conducting more parallel profiles (on dike crest, slopes or at toes) leads to more comprehensive (possibly 3D) information but also generates higher costs. There is therefore an important trade-off that the asset manager needs to decide upon, leading to variable level of risk of error. A single profile on the dike crest centreline is assumed in Table 2.1.

The number of staff needed for a given acquisition design and the amount of expertise needed for processing and interpreting the data also have an obvious impact on cost. The costs that we present here are estimated on the basis of published recommendations (http://www.agapqualite.org/images/stories/pdf/recomandfiche.pdf).

Effectiveness:

In health services, effectiveness is measured in terms of health gain (e.g. increased life expectancy). Proceeding with the previous analogy, one would need to estimate the increase in dike service life enabled by the geophysical investigations conducted on that dike.

Alternatively, we present a much simpler approach here in which we mainly give the **added-value** associated to each geophysical method. By added-value, we mean any useful and reliable information that potentially contributes to the asset support system in order to improve the asset condition assessment and to optimize its maintenance and surveillance plans. In Table 2.1, added-value spreads over columns 2 to 6. The more the information is reliable and close to the stakeholder's needs (columns 4 an 5) and the higher is the added-value. It should be noted that not all the geophysical methods answer the same questions or answer questions in the same way, so not all the methods are comparable. Indeed, those that are not comparable turn out to be complementary (e.g. ERT and Seismic Refraction, among numerous possibilities). When combining geophysical methods into more integrated approaches (section 2.2.3), one can derive the resulting cost and added-value from the individual method details in Table 2.1.

Finally, to benefit from such added-value, one first needs to check the method applicability. Therefore columns 7 and 8 show some conditions and possible drawbacks, particularly in urban areas. In any case, it is recommended that a trial is run on a test zone in order to validate the geophysical method selection.

Note: Information in Table 2.1 is based on the following assumptions. The height of the investigated dike is approximately 5m. For all geophysical methods, a single acquisition profile on the crest centreline is carried out (although additional profiles on dike slopes and/or at toes may be recommended). The assumed spatial samplings for the geophysical surveys are as follows. Station spacing is 10m for Lateral Resistivity profiling; Electrode spacing equals 2m for ERT; MASW source station separation is 10m; Seismic Refraction panel length is limited to 60m and a hammer is used as seismic signal source (no explosive used on dikes); Micro-gravimetry stations are located every 2m on the profile; Non-polarizing electrode spacing is 2m for on land Self-Potential imaging; Probe spacing is 10m for the Temperature sounding method; The other methods are considered continuous.

Table 2.1 Practical features of the main geophysical methods applied to dike investigation

Geophysical methods	Mainly used in which investigation stage: Overall or Detailed?	Sensitive to which geophysical and geomechanical soil properties?	Which features within dike and foundation can be detected?	Type of dike model or dike information produced:	Additional advantages
Slingram profiling	Overall	Soil electrical conductivity: Soil nature, moisture content, clay content	Material transitions along dike, conductive anomalies, buried metallic objects	Longitudinal dike segmentation into 'homogeneous' blocks, roughly material type	Acquisition for several depths of investigation is possible; Suitable for monitoring (requires GPS and accurate procedure) Metal pipe detection
Radio Magnetotellurics profiling	Overall	Soil electrical resistivity: Soil nature, compaction level, moisture content	Material transitions along dike	Longitudinal dike segmentation into 'homogeneous' blocks Roughly: material type (needs calibration)	Applicable to dikes made of resistive or conductive materials
Lateral Resistivity profiling	Overall (mostly) or Detailed (conditionally)	Soil electrical resistivity: Soil nature, moisture content, clay content, temperature	Material transitions along dike	Longitudinal dike segmentation into 'homogeneous' blocks, roughly material type	Applicable to all types of dikes and soils; Investigation depth usually adaptable; Continuous Resistivity Profiling (CRP) is faster (spike wheels or 'capacitive' device)
Electrical Resistivity Tomography	Detailed or Overall (slow)	Soil electrical resistivity: Soil nature, moisture content, clay content, temperature	Structure; Depth of layers and foundation; Water table; Soil: type, condition (moisture, compaction, clay content) and transitions; Signs of internal erosion and seepage	Lateral and vertical segmentation of dike and foundation into identified blocks (material type and condition, anomalies)	Quantitative; Applicable to all types of dikes and soils; Investigation depth is very adaptable; Suitable for monitoring time changes
Ground Penetrating Radar profiling	Overall or Detailed	Contrasts in material dielectric permittivity: Material type, moisture and density	Structures and material transitions: Voids; Networks; Built-in elements; Layers; Water table; Damaged zones; Metallic features	Dike segmentation: Layer depths (needs calibration) Location of material transitions	Detection of metallic pipes and structures
Multichannel Analysis of Surface Waves	Overall	Mechanical properties; Direct link to shear strength of material	Voids (e.g. karstic cavities) Zones of deconsolidated soil	Dike segmentation into zones of homogeneous mechanical condition, including mechanically weak zone location	Potentially quantitative method, with intermediate spatial resolution; Use of towed land streamers enables faster acquisition
Seismic Refraction	Detailed	Soil mechanical condition; Layer thickness and hardness; Direct link to shear strength of material	Layer thicknesses; Depth of foundation.	Horizontally layered model of identified materials (needs calibration); Depth to foundation all along dike	Quantitative
Micro-Gravimetry	Detailed	Earth gravimetric field, bulk density variations; Absence of mass	Cavities in dike body; Karsts in foundation; Washed zones; Relative changes in soil density; Variations in substratum depth	Relative density variation profiles; Location of zones of probable voids	Directly linked to density variations Potentially: weak zone monitoring (when density changes are significant)
Magnetic profiling	Overall (Detailed: Potentially, requires further testing and research)	Induced and/or remanent magnetization; Lithology of soils and rocks	Buried iron manmade structures (and ammunition); Potentially: repaired zones, disturbed soil	Accurate location of ferromagnetic elements; Image of soil magnetization within dike body and foundation	Provides crucial information for assisting interpretation of methods disturbed by buried metal targets
Self-Potential methods	Overall (waterborne profiling) Detailed (on land imaging; see conditions)	Electrical properties Seepage intensity	Water seepage (estimation of depth and velocity) Signs of internal erosion Leakage location	Seepage flow distribution in dike body and foundation	Applicable to dike (dam) of any dimensions
Temperature sounding method	Detailed or Overall (slow)	Soil thermal conductivity Temperature contrasts	Water seepage, cracks, signs of internal erosion	Thermal model of dike body and foundation, showing seepage anomalies	Use of temperature of seepage water as a tracer; Applicable to all types of dikes/materials and up to 30-40m depth

Table 2.1 (Cont'd)

Geophysical methods	Conditions / Limitations	Applicable in urban areas?	Acquisition speed	Minimum recommended data processing and interpretation time (in engineer days) for the amount of profile surveyed per day	Estimated cost per km of profile (see 'Description of table contents' for details)
Slingram profiling	Qualitative; Low resolution Needs calibration Disturbance by metallic objects; Effects of dike geometry	Possibly, have to run a test to confirm; Signal disturbed in dense urban areas (metal, networks, power lines); May require traffic disruption or work at night	5 to 10 km/day	0.5	A
Radio Magnetotellurics profiling	Needs steady signal reception; Low resolution; Field diffraction on dike geometry (incidence on dike); Disturbance by metallic structures	Rarely, but have to run a test; Signal disturbed in dense urban areas (field diffraction)	5 to 10 km/day	0.5	A
Lateral Resistivity profiling	Qualitative; Disturbed by metallic structures; Soft soil: use ground stakes or spike wheels; Paved surfaces: use 'capacitive' device (faster, noisier)	Yes, depending on noise level On sealed or paved surfaces: use 'capacitive' (but noisier and lesser resolution)	2 to 4km/day	0.5	C (point measurements) B (continuous profiling)
Electrical Resistivity Tomography	Artifacts due to 3D effects; Interpretation needs expertise and calibration; Temperature effects; Disturbed by metallic structures	Yes, conditionally; Paved surfaces: drill holes (slower, traffic disruption) or use 'capacitive' device (faster, but noisier, lesser resolution and depth)	0.6 to 1.2 km/day	2.5	E
Ground Penetrating Radar profiling	Limited investigation in conducitve materials e.g. clayey soils Signal scattering in heterogeneous conditions Disturbed by presence of metal	Yes (see limitations)	5 km/day	2.5	B
Multichannel Analysis of Surface Waves	False anomalies; Affected by vibrations; Slow acquistion when not towed; Topography effects: Not significant (conditions to be confirmed)	Depending on traffic and vibrations (test signal to noise ratio, measure overnight)	2 to 3 km/day	5	D
Seismic Refraction	Slow acquistion; 1D model; Requires wave speed in materials to inscrease with depth; Resolution for dike body is weak; Limited to 20m depth	Depending on traffic and vibrations (test signal to noise ratio, measure overnight); May require drilling of road paving and traffic disruption	0.2 to 0.4 km/day	2	F
Micro-Gravimetry	Information is not continuous, may miss target unless station offset sufficiently small; Procedure is delicate (drifting of device and gravity field corrections)	Yes, potentially; Built environment: strong limitations (requires difficult and significant correction of mass distribution)	0.1 to 0.2 km/day (2m spacing between stations)	2	G
Magnetic profiling	Requires recording of temporal variation or gradiometry if presence of aerial metallic structures, power lines, industrial activity	Yes (may depend on surronding infrastructure, see limitations)	10 to 20 km/day	1	A
Self-Potential methods	Only in load conditions; Signal strength limited if presence of sea or brackish water; Not applicable if presence of reinforced concrete	Possibly, depending on disturbance by other sources of SP signal	2 km/day (waterborne profiling) 0.5 km/day (on land imaging)	0.5 (waterborne profiling) 1 (on land imaging)	C (waterborne profiling) E (on land imaging)
Temperature sounding method	Embankment in load conditions for a certain time; In winter or Summer conditions; Short range 'Intrusive': Needs holes (passive) or initial installation (active)	Yes	0.5 km/day (depending on sounding spacing, a few days for a complete estimation)	1	E

2.3 Step-by-step guidance to selecting and implementing geophysical approaches

This section addresses the geophysical investigation process from a ‘**stakeholder**’ point of view when an embankment dike condition assessment is about to be planned. It aims at showing how geophysical investigations are brought to practice by unfolding the successive steps that need to be covered in order to select and implement a geophysical approach that is best adapted to a specific case. The present section is also meant to show the needed interactions between all condition assessment phases (Figure 1.1) and the corresponding actors (dike manager, geophysics sub-contractor, and geotechnical engineer).

Next section is a reminder of these phases emphasizing on the **interactions with the geophysical investigations**. Then the following sections address the geophysical process in detail.

Preliminary question: Knowing there are numerous geophysical methods that are applied to embankment dike investigation, what is the process that leads to/limits the selection of a ‘geophysical approach’ (i.e. a combination of applicable methods)?

Figure 2.6 is a diagram representing the selection process, starting from all available geophysical methods and adding information, requirements and constraints to end up with a limited number of applicable geophysical methods.

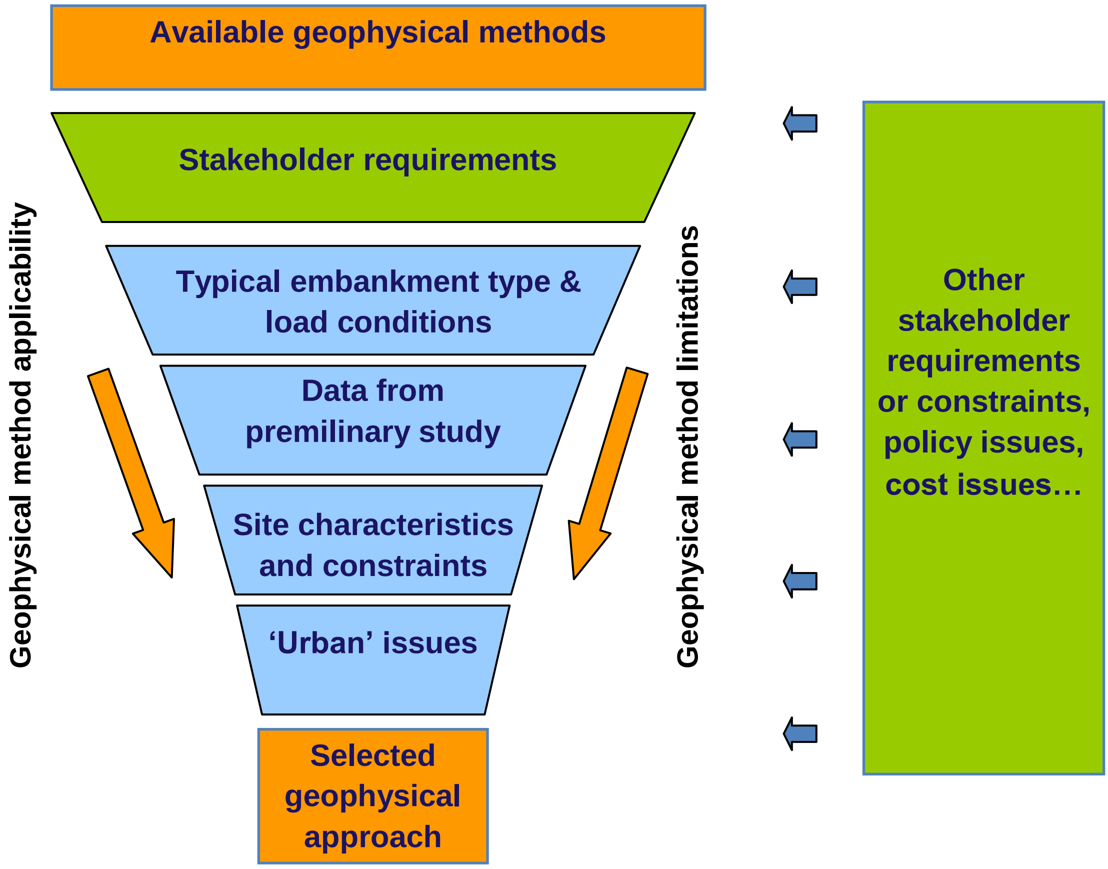


Figure 2.6 Overall concept for selecting a geophysical approach (© M.W. Morris and FIGW participants).

2.3.1 Overall assessment methodology: interactions with geophysical investigations

The recommended assessment methodology is a multidisciplinary approach that requires contributions from various fields of expertise. It includes several milestones that imply strategic decisions based on technical, economical and risk criteria. For taking such decisions, an asset manager needs to rely on a group of experts covering all these fields (geology, hydrology, geophysics, geotechnical engineering, and soil mechanics).

As detailed in Chapter 1, the overall dike assessment methodology comprises a series of phases (Figure 1.1) as follows.

Preliminary studies

This phase is dedicated to carrying out studies and gathering all available information on the dike or levee to be assessed. It is of **primary importance** that the dike manager collects all the following information to be provided to the geophysics expert (see section 1.3 for details) before the design and implementation of the geophysical investigations:

- All asset historical data including the building, heightening and repair phases, construction materials and dike body and foundation structure, reported failures, all previous condition assessment and monitoring data;
- The geological setting (map and in-situ observations);
- The dike context (urban area) and known infrastructure (buried networks, power lines, etc.);
- The dike maps and topography that provide **common spatial references** for visual inspection, geophysical and geotechnical studies;
- Data from the hydrological, hydraulic and morphodynamic studies;
- Visual inspection data and observations.

The conclusions from the preliminary studies and data compilation may indicate suspected weak zones (including their locations, lengths and suspected disorders), which would then provide primary objectives for the subsequent geophysical and geotechnical investigations.

Geophysical investigations

The geophysical investigation phase is designed on the basis of the data from the preliminary studies and the stakeholder requirements.

Implementing the geophysical investigations requires the selection of a combination of applicable geophysical methods by the geophysics expert. This guidance provides some knowledge for the dike manager to be able to assess and discuss the method selection process, knowing there are many geophysical methods that can be applied to embankment dike investigation.

The geophysical results contribute to optimizing the number and locations of the subsequent geotechnical investigations (see Figure 2.7).

The same principle applies when geophysical investigations are repeated over time for detecting or monitoring time changes (section 2.2.3.3): Interactions are essential between geophysics and newly available information or new geotechnical testing (if any). But more importantly, an updated GIS based system is needed for storing all forms of data and observations over time, and for enabling data processing and comparisons that will support decisions by the asset manager.

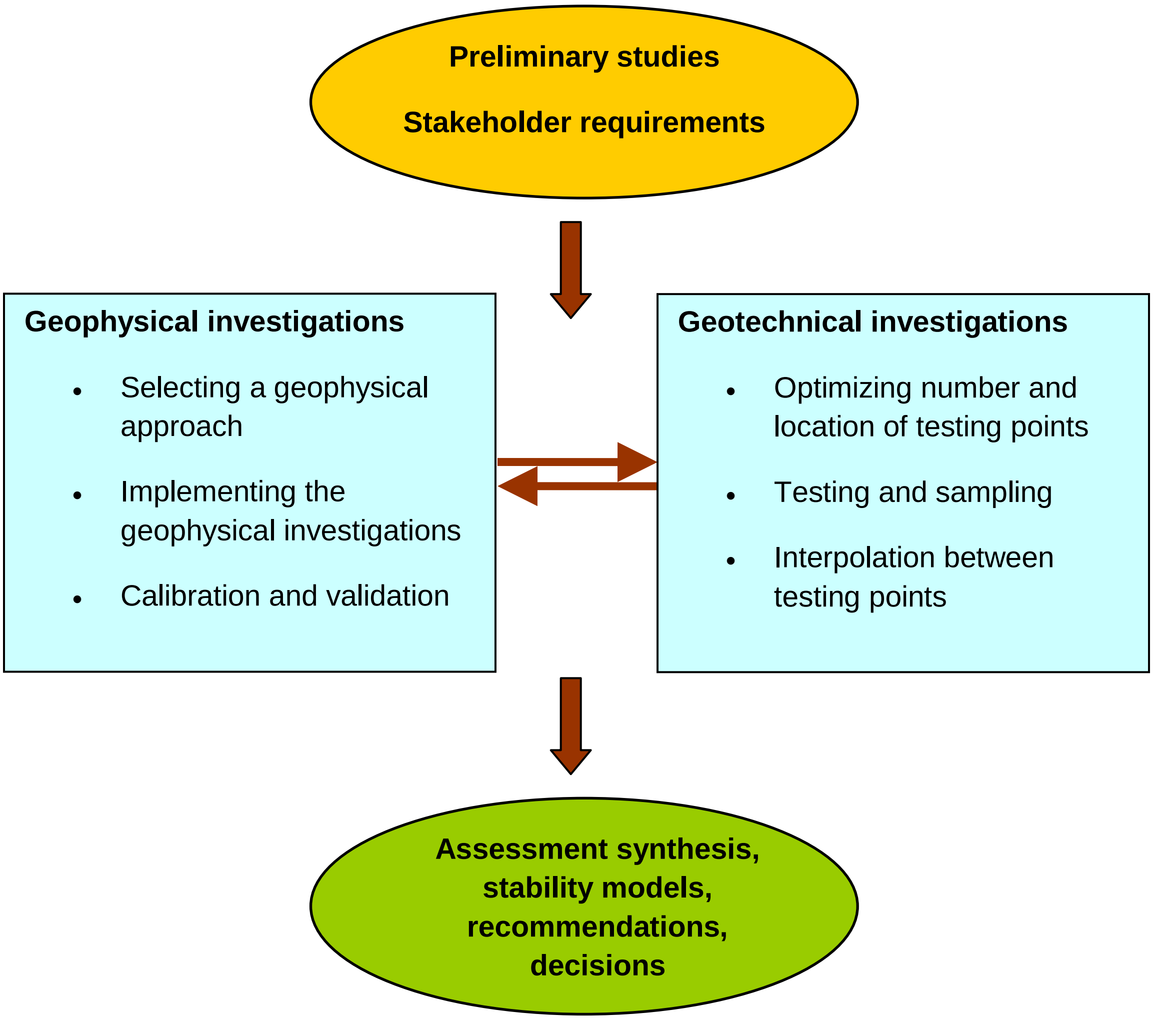


Figure 2.7 Condition assessment methodology: this diagram presents a close-up and an alternative to Figure 1.1 in the sense that geophysical and geotechnical investigations are conducted in a fully interactive process (with mutual expectations and benefits).

Geotechnical investigations

Geotechnical investigations yield accurate data although in very localized positions. Geophysical investigations provide a means for **interpolating** the dike body characterization in between geotechnical testing points. Nevertheless, geophysical results and models need to be **calibrated** and/or **confirmed** by direct and independent investigations such as borehole data. Therefore, geophysical and geotechnical investigations are mutually beneficial and it is desirable to implement these investigation phases within an **interactive process** (Figure 2.7).

Numerical modelling
Although numerical modelling (e.g. internal hydraulic modelling, geomechanical modelling) is now widely used in geotechnical studies, geophysical results do not seem to be often linked to these calculations.

However, the interpretation of geophysical maps together with local geotechnical or borehole data usually produce a segmented dike model (dike divided into quasi-homogeneous blocks) which could be used as an input to dike numerical modelling.

Condition assessment synthesis
This phase consists in producing models (dike segmentation) and information (dike reliability) from the joint interpretation of all previous data and results, including validated geophysical investigation results.

As for any other type of "observations", geophysical investigation results can be added to the asset support system within a GIS and have great potential in bringing added value to the dike safety assessment.

2.3.2 Stakeholder requirements
From the preliminary studies (and potential indicators of malfunction or progressive disorders) asset managers may have a clear view on what they need to be assessed. It is important that they list the objectives of the dike investigation for the geophysics expert to understand what is wanted.

The following sections present possible requirements and comments that stakeholders may have. It was compiled from the **FIGW conclusions** discussed among invited stakeholders and geophysics experts. Although this list may not be complete, it aims at helping asset managers to pick up their own requirements in the list and to express them in terms understandable by geophysics experts. They are divided into two categories: requirements specific to the objectives of the geophysical investigations and requirements the geophysics subcontractor have to meet along the investigation study.

2.3.2.1 Stakeholder requirements on the investigation objectives

What is wanted from a geophysical investigation?

- Material zoning:
    - Dike body: Determine 'homogeneous' blocks of different material (sandy clay, sand…) in terms of lateral/longitudinal zones and vertical layering.
    - Foundation: Determine depth, layering, e.g. presence and thickness of clay or sand layer overlying gravel.
- Weak zone detection: anomaly detection and determination of weakness nature:

    - Mapping of contact surfaces between new material at breach repairs and previous/potential places of weakness (understanding of historical repairs).
    - Detect meandering buried channels in foundation, cracks in dike body.
    - Seepage areas; Potential erosion/piping.
    - Manmade structures; pipes and metallic objects.
    - Detect voids and dissolution (karstic) cavities, animal burrows.
    - Tree roots: Need for detection and locating.
    - Detection / monitoring of time changes: If possible, initial investigation (1st zoning) in dry season; Repeat (ideally) during flood or high water; Assess seepage flow velocities, material transport when loaded by water; Stakeholders are interested in monitoring alert systems that include geophysical information.
    - Repeat investigations if/when required by regulation or dike authority policy/procedures, e.g. to check for illegal structures or modifications.
  - Other information (e.g. geotechnical/geological) to design remedial measures (e.g. depth to bedrock and subsurface information):
    - Determine geotechnical properties of material within detailed investigation (porosity, consolidation, permeability).
    - Foundation: Depth and condition.

Which geophysical methods are applicable to those investigation requirements?

Table 2.2 matches stakeholder investigation requirements with geophysical method applicability. It was compiled from the FIGW conclusions. It is also based on results from key research initiatives (CRITERRE, DEISTRUKT, ERINOH, IMPACT, FLOODSite, GEMSTONE) and sate-of-the-art.

Note: Although tree root detection and locating is of great importance for improving embankment dike condition asssessment, it is not addressed in Table 2.2 as it was not discussed in detail during the FIGW. From a geophysical point of view, it is generally considered as a very challenging task. Research is under progress.

Table 2.2 Geophysical method applicability with respect to stakeholder requirements. (Green: Recommended method or even preferred method; Yellow: Conditionally applicable method; Red: Not applicable method or not recommended method from a cost-effective viewpoint (see Table 2.1)).

			Geophysical methods										
			Slingram profiling	Radio Magnetotellurics	Lateral Resistivity profiling	Electrical Resistivity Tomography	Ground Penetrating Radar	Multichannel Analysis of Surface Waves	Seismic Refraction	Micro-Gravimetry	Magnetic profiling	Self-Potential methods	Temperature Sounding method
Detection requirements	Zoning and structure delineation	Horizontal segmentation of dike into 'homogeneous' blocks	Green	Green	Green	Green	Yellow	Green	Red	Red	Yellow	Red	Red
		Vertical structure: layers, depth to foundation, water table	Yellow	Red	Red	Green	Yellow	Yellow	Green	Red	Red	Red	Red
	Weak spot and anomaly detection	Structural anomalies (e.g. breach repairs, transitions)	Green	Green	Green	Green	Green	Green	Red	Yellow	Yellow	Red	Red
		Contact surfaces between layers of contrasting material or condition (compaction, permeability etc.)	Red	Red	Red	Green	Yellow	Yellow	Yellow	Red	Red	Red	Red
		Cracks	Red	Red	Red	Yellow	Yellow	Red	Red	Red	Red	Yellow	Yellow
		Voids, animal burrows (in dike body); Subsidence, cavities (karsts in foundation)	Red	Red	Red	Yellow	Yellow	Green	Red	Green	Red	Red	Red
		Buried channels (in foundation)	Yellow	Red	Red	Yellow	Red	Yellow	Red	Red	Red	Red	Red
		Seepage areas; Potential erosion and piping	Yellow	Red	Red	Green	Red	Yellow	Red	Yellow	Red	Green	Green
		Embedded manmade structures	Green	Green	Green	Green	Green	Yellow	Red	Red	Yellow	Red	Red
		Buried metallic structures	Green	Yellow	Yellow	Green	Green	Red	Red	Red	Green: if ferro-magnetic	Red	Red
	Material property and condition identification	Soil type, moisture content, clay content estimation	Yellow	Yellow	Yellow	Green	Red	Red	Red	Red	Yellow	Red	Red
		Soil geotechnical property estimation (porosity, consolidation, bulk density, permeability)	Red	Red	Red	Yellow	Red	Green	Yellow	Yellow	Red	Yellow	Yellow
		Monitoring of time changes (dry season/flood conditions)	Yellow	Yellow	Yellow	Green	Yellow	Yellow	Red	Yellow	Red	Green	Green
		Seepage flow detection (and potentially: velocity estimation)	Red	Red	Red	Red	Red	Red	Red	Red	Red	Green	Green

What length / depth / speed is needed?

- Length:
  - Overall and rapid investigation needs to be carried out over large lengths: From a few km to hundreds of km.
  - Local, slower and detailed defect investigation to be carried out over parts of previously assessed length: In total, it can be over hundreds of m to a few km (up to 10% - 20% of total dike length) .
- Depth:
  - Dikes and levees can be up to 10m to 12m in height; In order to investigate dike body in detail, measurements may need to be carried from the crest, the slopes and at the toes whenever possible. Although longitudinal profiling is the most effective way to investigate (distance-wise), additional transverse profiling is recommended.
  - Typically one will need to investigate an additional dike height into foundation material (this will also cover old breaches); Note: This investigation may be carried out on the land and (during dry season) water side of the dike to limit the required depth of penetration of geophysical signal.
  - In cases where foundation material is potentially problematic (e.g. karstic areas, deep buried channels) one needs to investigate to probable depth of problems, and complementary measurements at toe of dike and/or on land side are highly recommended.
- Speed: Rapid (high output rate) investigation is generally desired. Further requirements and comments:
  - Investigations may be required during limited periods of flooding, to provide for additional information when searching and characterizing weak zones (section 2.2.3.3).
  - There may be restrictions on disturbance to urban environment (e.g. traffic disruption).
  - *Comment*: The speed requirement is site and management specific; The real issue is cost and related risk (cost/risk trade-off).

Are specific failure modes envisaged? Any related investigation requirements?

- Subsidence/mechanical weakness of foundation material that might cause settlement and subsequent overtopping
- Seepage; *Comment* on g*eophysics applicability:* Very few geophysical methods can directly detect seepage, e.g. SP or ERT monitoring in some cases and only if dike is water loaded; Better detected by temporal/monitoring approaches (see section 2.2.3.3).

  - Internal erosion; *Comment* on g*eophysics applicability:* Geophysical methods cannot directly detect internal erosion process until/unless it covers significant volume and evolves along with linked processes, e.g. progressing water saturation front, settlement, seepage, piping; Better detected by temporal/monitoring approaches (see section 2.2.3.3).

What are the accuracy, resolution and reliability requirements?

Note: These are general requirements that also related to the quality of the geophysical study (see section 2.3.2.2)

  - Measurement uncertainty needs to be assessed, e.g. by checking equipment calibration and accuracy and measurement repeatability on site
  - Geophysical result calibration and validation is essential, which can be done by comparing results to all available information and direct observations, e.g. geological setting, geotechnical testing (borehole data, sampling) etc.
  - Resolution and reliability of results also need to be assessed; E.g. in a soil resistivity distribution (model drawn from ERT measurements), assess the resolution, and assess the reliability of each part of the model or anomalies detected.
  - Based on all previous items, **confidence level** in interpretation (and risk of error) has to be clearly stated.

Having listed these requirements on the investigation goals, what leads to the final selection of a geophysical method/approach?

It is important to note that Table 2.2 only indicates which methods are **potentially applicable** to such-and-such investigation goal. Indeed, the final selection of a geophysical method (or method combination) also depends on the characteristics and the setting of the dike to be investigated. Therefore asset managers need to run further steps in order to infer which methods are **actually applicable** to their specific case study:

- To fully describe the features of the embankment defence system they manage, including urban constraints (see section 2.3.3);
- To check whether these features alter the applicability of the originally selected methods, by referring back to the information in Table 2.1 (and geophysical method sheets in Appendix 2.7).

2.3.2.2 Recommended requirements on the geophysical study

This section presents requirements that the stakeholder may address to the geophysics subcontractor in order to improve the overall **quality** of the geophysics study.

- General requirements and recommendations:
  - Quality depends on experience of geophysics company and staff, therefore only geophysics experts / certified subcontractors should be selected.

  - The cheapest campaign is not always the best option, and public procurement processes can 'get in the way'; It is highly recommended to include a quality component in the tender assessment.
  - Stakeholder to provide space for good communication and interactions between stakeholder, geotechnical engineer and geophysics engineer at all stages, including a joint analysis of all available data – this is essential for the reliability and usefulness of the geophysical study.
- Requirements on the geophysical survey implementation:
  - The geophysical survey design (method selection and implementation plan) should always be presented to the stakeholder and based on all available information (from preliminary study / data collection).
  - If applicable, a combination of methods always leads to more reliable results than a single geophysical method; costs are higher, but added value is higher too.
  - Whenever possible, the asset manager should require that a **'test zone'** is implemented for validation of method selection, equipment calibration, repeatability assessment; Some (moderate) additional budget to be planned though.
  - Accuracy and reliability of results have to be assessed and presented to stakeholders.
- Requirements when being presented with the geophysical results and report:
  - Calibration/verification on the basis of independent data (borehole data, geotechnical testing) should always be presented to stakeholder; Conditions: to be added to budget if necessary, and good communication between actors to be enabled (stakeholder, geophysics engineer, geotechnical engineer).
  - Interpretation: Experienced interpretation is highly recommended; Stakeholder to allow reasonable time for thorough interpretation and reporting; Make sure that interpretation is relevant and kept close to context and is not 'forced' beyond validity by geophysicist and/or stakeholder requirements; Consider cross-interpretation of raw data by independent geophysicist/expert.
  - Geophysics report has to include: Clear explanations on method principles and method selection; Clear spatial referencing of all measurements and detected anomalies; Transparency on data quality and processing, estimated model reliability and risk of error in the geophysical interpretation.

2.3.3 Dike information needed by geophysics expert

This section is an aid for the stakeholder to compile all the data describing the embankment structure and its setting and that the geophysics expert will need for: i) Finalizing the selection of a geophysical approach, ii) Designing the geophysical acquisition campaign and iii) Interpreting the geophysical data. Most required information is available from the preliminary study and data collection (see Chapter 1, and Phase I Figure 1.1).

Table 2.3 lists the information and data related to the detailed description of the embankment protection system and the stretch(es) to be investigated. It can be seen as a data sheet template for the asset manager to collect all required information and present it to the geophysics expert.

Table 2.3 Asset data sheet compiling the information needed by the geophysics expert.

Required information	Examples, options, comments
General asset information	
Geographical setting	River levee / estuary or coastal defence…
Type of flood defence	Levee; Permanent head dike; Offline flood storage
Type of load cycles Is the asset in wet or dry condition? Is the asset in flooding conditions?	Permanent head / tidal load / seasonal load To be specified (site/season specific) To be specified (site/season specific)
Geological setting	Karstic formations / alluvial foundation…
Asset additional functions	Networks / walkway / cycling / road …
Asset historic data	Raised sections / former breaches / repaired areas…
Information on stretch(es) to be investigated	
Geometry: Dimensions, course linearity (bends), cross-section variability along dike	Total Length to investigate, cross-section dimensions (Height, Width, slope ratios, longitudinal variability) Sharp bend at position X
Construction materials, structure	clayey sand, gravel, layered structure (if known)…
Other available information?	e.g. list of available historic data, geological data, borehole data, etc.
How 'urban' is the dike context? ➔ Known or suspected disturbance sources, anthropogenic 'structures', urban constraints (types, locations and distances to dike)	
Networks	Embedded along dike, depth, between X1 and X2
Conduits, pipes (metallic, plastic, concrete)	Through dike or longitudinal
Urban encroachment (houses, buildings, walls)	Number, positions
Traffic, vibrations	(see additional functions) Traffic rate at day time/night time; vibrations: type of source and distance to dike
Crash-barriers, fences, railway, …	
Sheet piling	Known positions, depth and height
Power lines	Aerial: transported voltage & frequency, distance to dike Buried : position, depth, insulating conditions

2.3.4 Getting ready for the geophysics implementation

At this stage, the stakeholder have defined their requirements, data from preliminary studies and information on dike features and setting (including 'urban' constraints) have been compiled. Moreover, a non-geophysics expert should now be able to have their own opinion on the geophysical methods that are actually applicable to their case study (on the basis of the data provided in the previous sections).

Before actually implementing geophysics, an asset manager first needs to undertake obvious tasks such as preparing the terms of reference for the geophysical study and selecting a geophysical subcontractor. The agreement needs to clearly identify the selected geophysical approach and require collaboration at all stages between parties (particularly when new data become available such as rapid geophysical investigation results or geotechnical testing results).

2.3.5 Overall rapid investigation

This section addresses the **first zoning** investigations (section 2.2.3) to be carried out over the full length of an embankment dike or levee.

The following recommendations and comments were agreed among all participants at the FIGW (Palma Lopes et al., 2012) and apply to a 'generic' case study. We emphasize that there is no such thing as a standard investigation scheme (Niederleithinger et al., 2012) and the actual investigation scheme always depends on the specific site features and manager requirements. More geophysical options and details can be found in sections 2.2.3 and 2.2.4. In particular, attention is drawn again to the fact that this overall investigation phase can be **repeated** over time in different seasons and load conditions to bring valuable information on weak zone characterization and monitoring (section 2.2.3.3).

Recommended geophysical methods for rapid overall investigation

Further details on method applicability, limitations and cost-effectiveness can be found in section 2.2.4.

<u>Summary (most preferred methods)</u>:

- ***Slingram* profiling**: Most rapid method for initial investigation of dike body from crest; Low resolution; Low cost.
- Traditional **Lateral Resistivity profiling (LRP)**: Rapid method (depending on spacing and available staff and equipment, and type of device/electrical contact). Low to intermediate resolution method; Cost: About twice the cost of *Slingram* profiling when continuous LRP is implemented (using mobile devices based on, e.g., capacitively coupled electrodes or spike wheel electrodes); For non-continuous LRP (using traditional stake electrodes for point measurements), cost can be significantly higher.
- <u>Important note</u>: In some countries, some stakeholders require that **ERT** is carried out directly in the overall investigation stage instead of *Slingram* profiling, as mentioned in section 2.2.3.2; Even though more staff and equipment may be deployed on site, ERT remains much slower than *Slingram* profiling and costs are much higher. Resolution is considerably higher (as ERT is an imaging technique), although it depends on the selected electrode spacing.

Comments and alternative options:

What is high / low?

- Cost? *Slingram* profiling cost is low; LRP cost is comparable (about twice as much as *Slingram*); ERT cost is significantly higher.
- Output rate? *Slingram* profiling output rate is high: 5 to 10km per day; LRP output rate is a bit lower (depending on spacing and type of coupling/contact); ERT output rate is much lower: Hundreds of m to a few km depending on electrode spacing, acquisition speed and number of staff (higher output rates mean lesser resolution).
- Quality? *Slingram* profiling quality is good for surface layer but not for deeper layers; LRP has potential for more information (e.g. if more than one spacing is carried out, but then slower and less cheap); ERT gives complete 'picture' (although imaged model needs calibration and expertise).
- Cost/risk issues: Decision between *Slingram* profiling and ERT based on cost and accepted risk. In UK, for example, a tiered risk assessment process is expected and in low risk areas, probably *Slingram* profiling is acceptable; in urban areas where risk/consequences are higher, then it might be easier to persuade clients such as Environment Agency to spend ERT prices. Performing LRP (traditional lateral resistivity profiling) with several electrode spacing is an interesting alternative to carrying out full ERT surveys: information detail, rapidity and cost are intermediate between *Slingram* profiling and ERT (depending on number of spacing carried out and available staff); Thus it appears to be an adaptable zoning option; furthermore, it is an obvious method for guiding further detailed ERT surveys.

Reachable depth of investigation and resolution?

- Depending on equipment and implemented acquisition technique
- *Slingram* profiling investigation depth is limited to between 3 to 10m; For foundation investigation implement additional measurement from dike toe.
- *Slingram* profiling has limited vertical resolution when operated in a single mode of acquisition. However, one can survey the same profile by means of various modes to allow for a range of investigation depths; E.g. by carrying out successive profiles for both vertical and horizontal coil (magnetic dipole) directions, or for various inter-coil distances, or for various operating frequencies: It is then possible to get a basic idea of the vertical resistivity structure.
- LRP investigation depth is variable and adaptable: from 0 to at least 20m.
- ERT depth of investigation: From 0 to 20m, sensitivity to soil property decreasing exponentially with depth.
- *Slingram* and LRP techniques: Spatial resolution is low (graph of apparent conductivity versus distance).

- ERT: Spatial resolution is high (imaging of vertical section); Recommended acquisition coverage: 3 longitudinal profiles respectively on crest, mid-slope and toe.

Reliability level?

- LRP, *Slingram* profiling: Good reliability level; Usually good repeatability with rigorous implementation procedure (unless significant disturbance from urban environment); Field equipments are robust.

- ERT: Same as above, except: Reliability level depends on data quality and inversion process, output model is high resolution but model uncertainty can occur; Need for experimented interpretation and calibration based on direct observations.

- Interpretation concerns (including 1D, 2D, 3D): Simplest interpretation is 1D for *Slingram* and LRP methods, and interpretation in terms of material is limited and qualitative; 2D inversion and interpretation is also possible for LRP when carried out with several electrode spacing; 2D inversion and interpretation should be possible in the near future for *Slingram* profiling as well, in the case where multiple modes of acquisition (investigation depths) are used (e.g. multifrequency apparatuses or apparatuses with a variable distance between coils); Interpretation is usually 2D for ERT; Average resistivity variations are picked up/detected.

- <u>WARNING</u>: for all methods, classical 1D or 2D inversion of profiles carried out along the dike may yield serious artefacts and lead to some misinterpretation as the problem involves 3D features (research in this field is well under progress).

Can the applicability be extended to:

- Different soil types? Yes, *Slingram*, LRP and ERT methods are suitable to detect material changes in dike body such as clay/sandy clay transitions, changes of resistivity/conductivity caused by changing conditions along the dike and variations in foundation; ERT yields information on material, resolves depth to interfaces as well as inhomogeneities along the levee.

- <u>Urban area conditions/constraints</u>:

  - *Slingram* profiling useful to pick up information about orthogonal structures, e.g. can be used to detect presence of metal pipes. ERT gives much more detailed picture, but can be significantly affected by presence of buried metallic structures (transverse or longitudinal pipes, sheet piling). LRP gives intermediate information, also affected by buried metal objects.

  - *Slingram* profiling sensitive to interference from presence of power lines and other items longitudinal to dike line: disturbance may invalidate results. In this case LRP (e.g. Schlumberger Resistivity profiling, about twice the cost of *Slingram*) or ERT (more expensive than LRP) are alternatives. Up to 4km per day can be achieved with LRP. Another option: Seismics (Refraction or MASW, depending on detection requirements), although sensitive to traffic noise.

- In case of a road surface: Grounded electrode contact LRP and ERT require drilling of road paving and possibly traffic disruption; Alternative options: Continuous Resistivity profiling (CRP) techniques based on towed arrays of mobile electrodes; Among available technologies: Capacitively coupled electrodes (wheels or weights, e.g. Ohm-Mapper®) provide an means for a faster profiling on road surface, although data is noisier than with grounded stakes, depth of investigation and resolution are lower than with complete ERT.

- NOTE on buried metallic structures: Depending their on shape, orientation, depth, and complexity of urban area, **buried metallic objects** can be detected by carrying out profiling or mapping with one of the following methods: ***Slingram*** detects pipes perpendicular to the profile; **GPR** detects metallic interfaces within the investigated volume; **Magnetic** measurements are very cost-effective for detecting even small and deep manmade iron structures, although not in a dense urban or industrial environment with iron or steel structures around (posts, barriers, fences, gates, tracks…). Then GPR is probably better adapted for metal structure detection.

Alternative options?

- **GPR**: Rapid and cost-effective method; Limited to case where resistivity of (top) dike material is larger than about 100 Ohm.m; Limited investigation depth in many cases (not applicable for investigating foundation unless dike is not very high); Signal may suffer from too many layer echoes when dry over wet soil (limiting interpretation); Good for detecting buried manmade objects in dike body.

- **MASW**: High resolution method that links directly to mechanical properties (shear strength of material) and allows detection of voids and deconsolidated soil; Quantitative interpretation (understanding of dike geometry effect is under progress); Use of towed land streamers enables faster acquisition making the method more cost-effective.

- Note on **RMT**: In principle, Radio Magnetotelluric profiling (RMT) has potential as a rapid method to be used in the overall dike investigation phase. The output rate is similar to that of *Slingram* profiling. It was barely mentioned during the FIGW, mainly because it is not widely used, and most importantly because the CRITERRE (French) and the DEISTRUKT (German) initiatives concluded that it has significant limitations when applied to embankment dike investigation, whether in rural or in urban areas (see Table 2.1).

- Note on **AEM profiling** methods: Airborne electromagnetic (AEM) induction profiling was only poorly discussed during the FIGW as no documented dike investigation survey using AEM was found within Europe. Helicopter-borne EM (HEM) was experimented in the USA (Dunbar et al., 2007), as part of an integrated condition assessment of 270 miles of rural levees and their foundations. It was concluded that the approach was economical and reliable. Investigated depths ranged from shallow subsurface up to 30m. Airborne (HEM) and grounded (*Slingram*) profiling data proved consistent, although HEM spatial resolution is quite poorer. Qualitative interpretation may be sufficient for capturing information on dike and foundation composition, including buried channels. The obvious advantage of HEM profiling is the operating speed (up to 130 km/h), but survey cost is comparable to that of LiDAR surveying. In urban areas (Auken et al., 2006), the coupling of the transmitter to metallic features (fences, crash barriers, buried cables, etc.) is still a severe problem.

- **Self-Potential (SP)** techniques: waterborne continuous profiling is applicable during flood conditions (when boat can tow electrodes along); Method is able to pick up when seepage flow occurs; But can be difficult to implement if current velocity is high; Needs bathymetry at the same time.
- **Thermometry** based techniques: Applicable during flood conditions to detect seepage; moderately slow acquisition.

2.3.6 Detailed local investigation of suspected weak zones

This section addresses the **second zoning** investigations (section 2.2.3) of suspected weak zones identified from the 1st zoning.

The following recommendations and comments were agreed among all participants at the FIGW (Palma Lopes et al., 2012) and apply to a 'generic' case study. We emphasize that there is no such thing as a standard investigation scheme (Niederleithinger et al., 2012) and the actual investigation scheme always depends on the specific site features and manager requirements. More geophysical options and details can be found in sections 2.2.3 and 2.2.4. In particular, attention is drawn again to the fact that this detailed investigation phase can be **repeated** over time if needed to bring high resolution information on weak zone characterization and monitoring (section 2.2.3.3).

Recommended geophysical methods for detailed local investigation

Further details on method applicability, limitations and cost-effectiveness can be found in section 2.2.4.

Summary:

- **ERT**: most preferred method for detailed investigation; Slow method; Resolution is high to very high (imaging technique); Cost is intermediate to high.

Details and comments on ERT and alternative options:

? *What is high / low?*

- Cost? (variable costs) ERT cost is medium to high. However if many profiles are required then price can fall significantly, perhaps by up to 80% per unit length; In Germany, where ERT is extensively used (crest and toe either side).
- Output rate? ERT output rate is low to moderately low when applied to detailed investigations (depending on electrode spacing, acquisition speed, deployed staff and cables on site): 100m to 1000m for reasonably fine resolution.

- Quality? ERT data quality is good; ERT gives complete 'picture', but imaged model requires calibration and expertise.

Reachable depth of investigation and resolution?

- Depth of investigation: From 0 to 20m or more (very adaptable); spatial resolution (sensitivity) decreasing exponentially with depth.
- Resolution/implementation: Use on crest or toe (or both); Additional perpendicular profiles recommended to get 2D or 3D effects; Recommended electrode configurations: There are many options (selection is time-consuming and requires qualification): *Wenner* (alfa) and *Schlumberger* are among preferred electrode configurations for detailed dike investigation; Dipole-Dipole configurations not recommended, particularly when temporal / monitoring approaches are implemented.

Reliability level?

- ERT data has good repeatability; Field equipments are robust.
- ERT result reliability depends on data quality and inversion process; Need for experimented interpretation; Interpretation is mostly 2D; Possibility of 3D although acquisition is much slower; Inversion model is not unique (best constrained by additional information such as direct observations, see below).
- Need for transverse profiles every 100 to 200m to confirm whether the material property/nature variations are only 2D or merely 3D.
- WARNING: 2D inversion of profiles carried out along the dike may yield serious artifacts and thus lead to some misinterpretation as the problem involves 3D features.
- Need for borehole/geotechnical testing information periodically along the dike to provide calibration and validation of models.

Can the applicability be extended to:

- Different soil types?
  - Yes, applicable to all soil types (including dike body and foundation).
  - Useful for fresh / brackish water delineation.
- Urban area conditions/constraints:
  - Limited use when sheet piles or metal pipes run along the dike or levee (distorted ERT data). Then look at other preferences. Presence of transverse metallic objects may strongly impact data and inversion, better interpreted if object position is known and used to constrain inversion.
  - NOTE on buried metallic structures: Depending their on shape, orientation, depth, and complexity of urban area, **buried metallic objects** can be detected by carrying out profiling or mapping with one of the following methods: ***Slingram*** detects pipes perpendicular to the profile; **GPR** detects

metallic interfaces within the investigated volume; **Magnetic** measurements are very cost-effective for detecting even small and deep manmade iron structures, although not in a dense urban or industrial environment with iron or steel structures around (posts, barriers, fences, gates, tracks…). Then GPR is probably better adapted for metal structure detection.

- In case of a road surface on crest: ERT based on grounded electrode contact requires drilling of road paving and possibly traffic disruption; ERT can be tested on slopes and toes where accessible, otherwise alternative options are GPR and Seismics; Important note: Resistivity profiling techniques based on mobile arrays of capacitively coupled electrodes allow faster acquisition. However, they do not provide sufficient investigation depth and spatial resolution for detailed investigation.

Alternative options? To be used for linking to specific material property:

- **GPR**: 2nd preference for detailed investigation; Rapid and cost-effective; To be used where resistivity exceeds 100-200 Ohm.m: Sand and gravel and saturated layers and where water is fresh; Other limitations: Limited depth of investigation, not applicable to clayey material, too much information in signal in some cases and potential problems with air reflections at surface, signal screening if presence of longitudinal metal structure within investigated volume; Interference from FM to microwaves; Applicable to investigation of masonry riverside and top wall.

- **Seismic Refraction**: 3rd preference for detailed investigation; Slow method; Limitations: Sensitive to traffic noise, 50Hz power signals can distort signal (but can be filtered out); Implementation: Use both P and S waves (include surface waves) for composition of dike and base clay layer; Time-consuming acquisition but method yields mechanical properties that can be related directly to geotechnical data (shear strength/CPT usually show good correlation).

- **Micro-gravimetry**: may be used for detailed investigation, although applicability is very specific to locating cavities in dike body and karsts in foundation, and to detecting washed zones after a long-term seepage; Slow and delicate data acquisition and processing.

- **Self-Potential (SP) continuous waterborne profiling**: Applicable during flood conditions (when boat can tow electrodes along); Method is able to pick up when seepage flow is occurring; But can be difficult to implement if current velocity is high; Needs bathymetry at the same time.

- **Self Potential (SP) imaging techniques** (on ground: crest, slope and toe): Recent developments applicable to permanent head dikes or during flood conditions; Able to image seepage paths (if occurring).

- **Thermometry based techniques**: Applicable on permanent head dikes or during flood conditions to detect seepage; Moderately slow acquisition.

2.3.7 Interpretation and reporting of the geophysical results

The geophysical result interpretation process comprises several stages such as geophysical signal processing, geophysical data processing (including inversion), calibration and validation based on direct observations (e.g. borehole data), interpretation and suggestion of a dike model compatible with all available information (including from the preliminary studies). In case geophysical investigations are repeated over time in different seasons and load conditions, specific data processing and interpretation is needed for yielding more accurate weak zone location and features.

All these need to be thoroughly conducted and reported and good collaboration needs to be ensured with the geotechnical engineer and the asset manager.

At this stage, the geophysics expert has worked jointly with other involved experts and produced results and a report that presents the asset manager with interpreted models along with some reliability assessment (recommendations to the stakeholder are included sometimes, although this may be clearly out of the geophysicist mission alone). These outputs should then be added in the asset support system to contribute to the dike safety assessment.

As from this stage, all decisions remain with the asset manager in compliance with regulations and budget constraints.

2.4 A real case study on the Orléans pilot site

All the following measurements were carried out by Regional Environmental Centre of Czech Republic and National Environmental Centre of France.

2.4.1 Orléans pilot

The studied dike is located along the Loire river upstream the city of Orléans (France) and near the city of Saint-Denis-En-Val. We have investigated a length of 3200 m long. The dike is typically a rural case study (Figure 2.9): there is only a known gas network that transversally crosses the dike and a road pavement on the crest. Though this dike is located in rural context, it indirectly protects the urban South area of Orléans. The diagnosis is a major issue for the authorities and stakeholders who are in charge of this dike.

2.4.2 Preliminary studies

The geological context is shown on Figure 2.8. The dike (1/50000 geological map edited by Bureau de Recherche Géologique et Minière, cartes d'Orléans XXII-19 et de Ferté Saint Aubain XXII-20) is located on alluvial materials of the Loire mainly composed of sand, gravels and roundstones, and chalky limestone and marl limestone of the Beauce formation (Aquitanian). The limit between these two formations is irregular and karstic phenomena such as dolines, avens and underground cavities could occur and threaten the dike safety.

Figure 2.8 Geological map of Orléans and the surrounding countryside

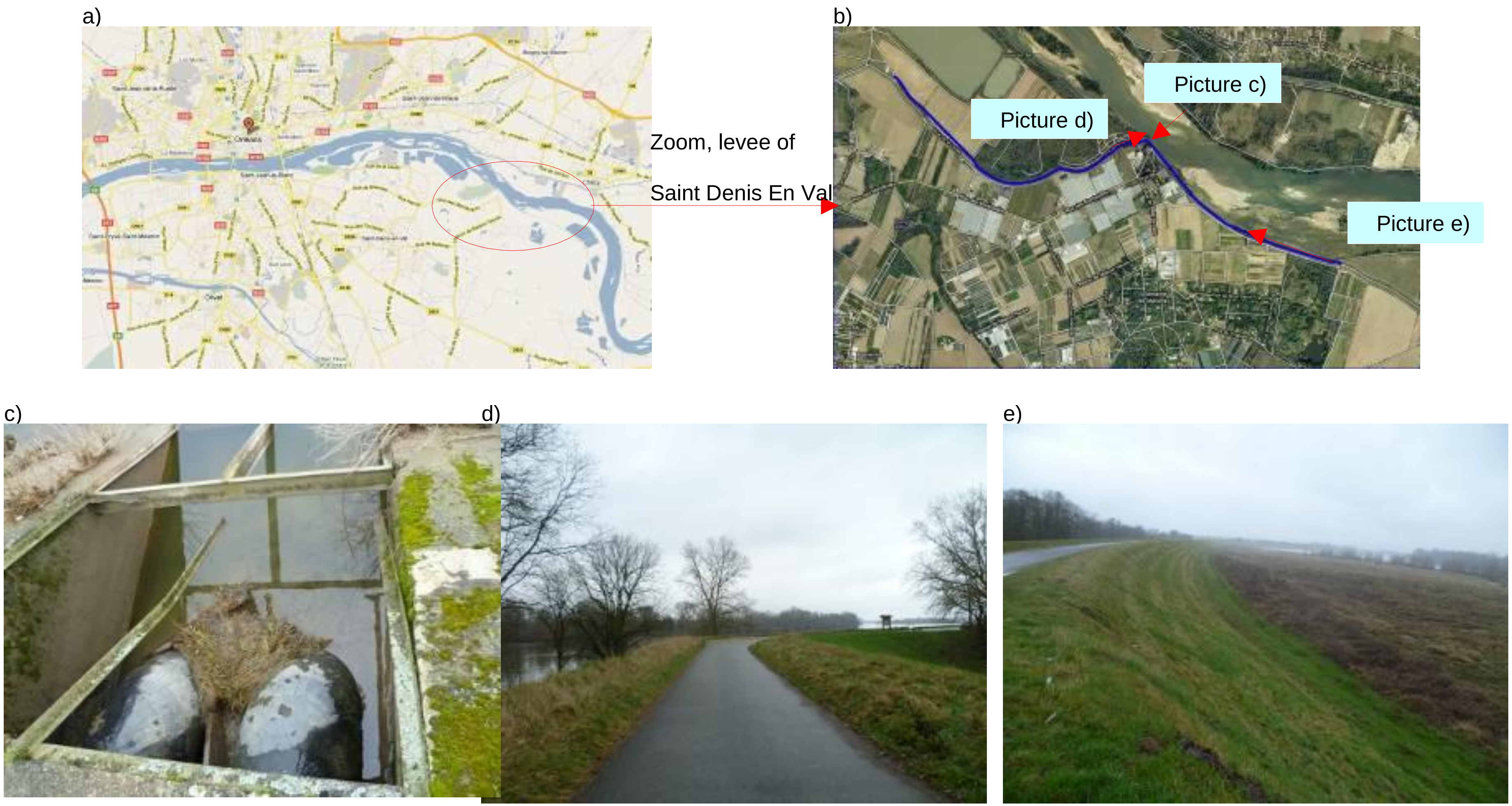


Figure 2.9 a) Map of Orléans and its region, b) aerial photo of studied dike in Saint-Denis-En-Val, c) gas network, d) road structure and e) view of the dike and the Loire bed

Previous studies reported important data such borehole logging and estimated locations of old breaches. The boreholes survey led to a first interpretation of dike model and a detailed description of the materials that compound the dike body and its substratum (Figure **2.11** Dike model from geotechnical testing

The historic research gathered major data about the occurrence and approximate location of old breaches (Figure 2.10, Breach of " Melleray" in 1755 and Breach "De l'Isle" in 1866).

Figure 2.10 Stretch studied with location of old breaches

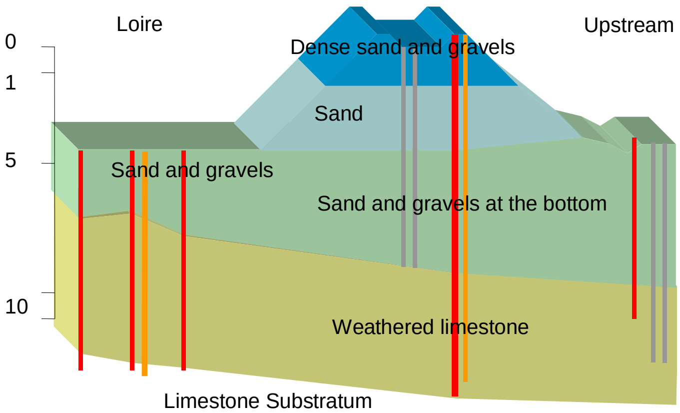


Figure 2.11 Dike model from geotechnical testing

2.4.3 Geophysical investigations

2.4.3.1 First zoning with rapid, cost-effective methods: RMT, GEM2, EM31 and GPR

We applied the general methodology described in the section 1.2 of this report. Rapid and cost-effective electromagnetic methods were carried out to quickly delineate the homogeneous parts of the dike. The radio magnetotelluric (RMT) method at 162 kHz and

693 kHz, and two *Slingram* methods (GEM2 in the context of the GMS methodology by IMPACT project and EM31) were applied. The results are presented Figure 2.12 andFigure 2.13.

The dike is subdivided in three parts with a highly resistive zone 1 between 0 and 1100m. A second zone 2 shows resistivity variations related to a change of materials content in dike body (known old breach of "De L'Isle", see Figure 2.10). The approximate depth of investigation is 5 m. The response is less significant in RMT profiles (Figure 2.12). In these measurements, the depth of investigation depends on the apparent resistivity and frequency. It varies between 10-20 m at 693 kHz and 20 to 50 m at 162 kHz, so that the measured apparent resistivity is more sensitive to the deeper materials (limestone). The gas network is well identified with both methods by a sinusoidal variation of the apparent conductivity (Figure 2.13, *Slingram* profile at 1380 m).The measurements with electromagnetic methods show that the dike body is fortunately composed of high resistive materials: the ground penetrating radar (GPR) can easily be performed. The GPR measurements are reported on Figure 2.14 and were undertaken on crest with a 200 MHz bowtie antenna. The entire profile is not very explicit, but one can find the previous zoning made with the electromagnetic methods. The most interesting results from GRP survey are the zoomed-in profiles of the two old breaches: their locations were estimated according to the historic research but they were not accurately defined. The GPR data on the breach of "Melleray" clearly show the repaired part of the dike: the start and stop are given with a quasi-metric precision.

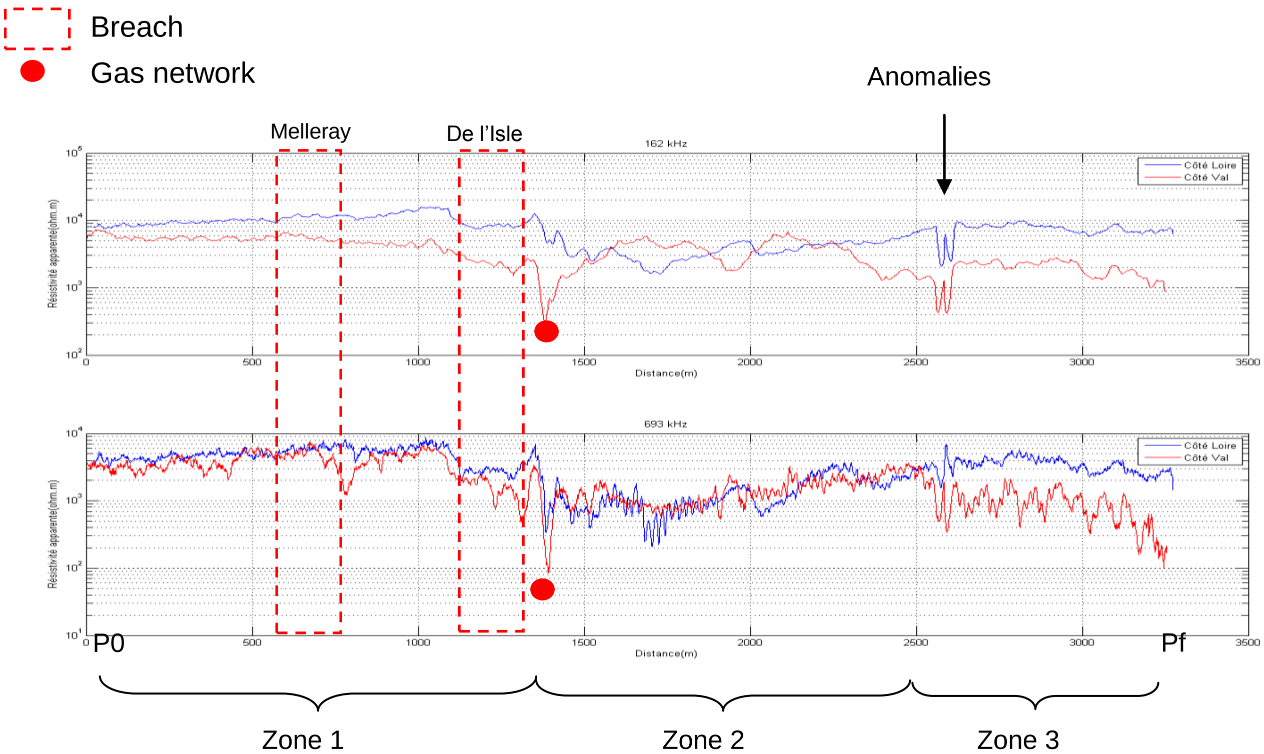


Figure 2.12 RMT results on the studied dike. Top: 162 kHz and bottom: 693 kHz. Red: land side of the crest; blue: river side of the crest

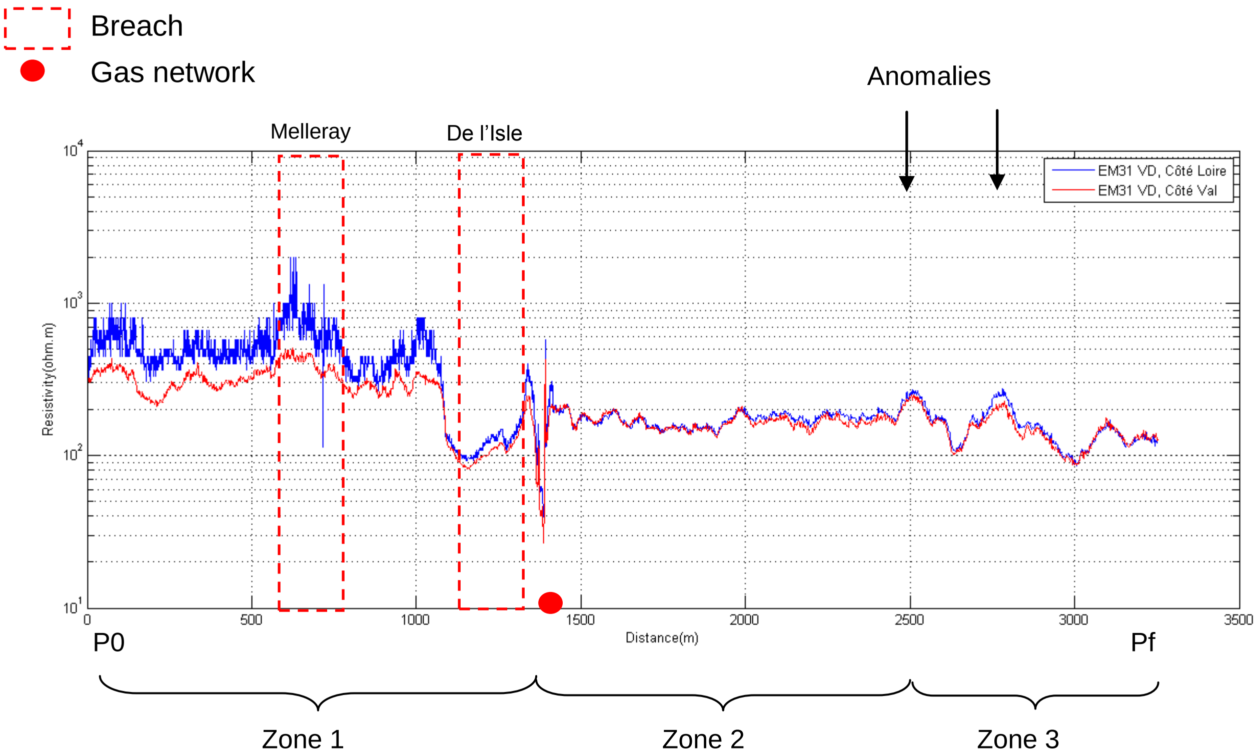


Figure 2.13 ***Slingram*** **(EM31, VD mode) results on the studied dike. Red: land side of the crest; blue: river side of the crest**

The GPR reveals also the multilayered structure of the dike which is potentially a weakness point because layers contact often defines a preferential path for leakage through the dike. A heterogeneous area is present at the beginning of the profile and other parts with higher clay content show attenuated signals. The results on the location of the breach of "de l'Isle" exhibits an absorbed response of electromagnetic waves and delimited a clayey dike body as the *Slingram* measurements show between 1100 m and 1300 m. A zoomed-in result around the gas network location is finally presented and one can easily recognize the two hyperbolae generated by two buried metallic pipes. The GPR horizontal resolution is finer than that of the two methods previously presented.

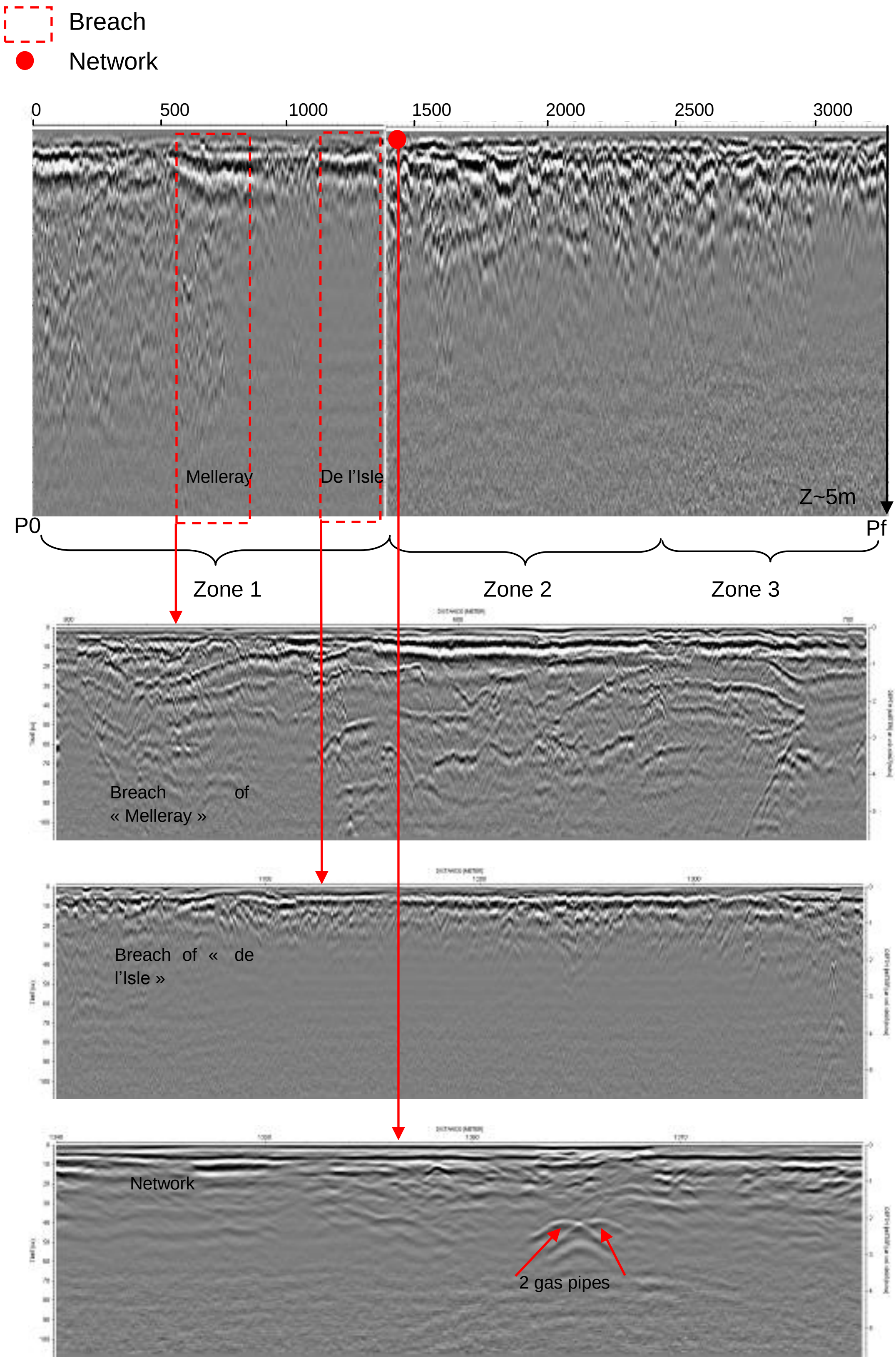


Figure 2.14 GPR measurements at 200 MHz. On top, whole profile and zoom on the breaches and the gas network.

2.4.3.2 Second zoning with ERT lower speed, less cost-effective, higher resolution, lower risk

A detailed investigation has been implemented with the Electrical Resistivity Tomography method alongside the crest and across the dike at given locations. This ERT survey was positioned according to the previous *Slingram* and RMT measurements. An example of results is shown in Figure 2.15. The longitudinal ERT profile gives an internal map closed to the material distribution. The pink dashed line is the dike bottom and the measurements show that the resistivity of materials are quiet homogeneous till the resistivity values decrease at 88 m, corresponding with the beginning of the location of the breach of “de l’Isle”. This part appears again as a clayey dike body, in accordance with the previous results (*Slingram* and GPR methods). The ERT measurements provide also the estimated location of the transition between the dike body ant the substratum. It shows also an irregular limestone bed, where karstic phenomena could occur. In the same figure, ERT cross section clearly shows the distribution of materials. This last result reflects how the dike was built and/or repaired. It can also show how the dike construction follows the rule book to match the required properties of permeability in both sides of the dike: a low resistive part corresponding to clayey sand at the river side, and a sandy gravels part at the upstream side of the dike. The core of the dike is made of globally resistive sand and gravels.

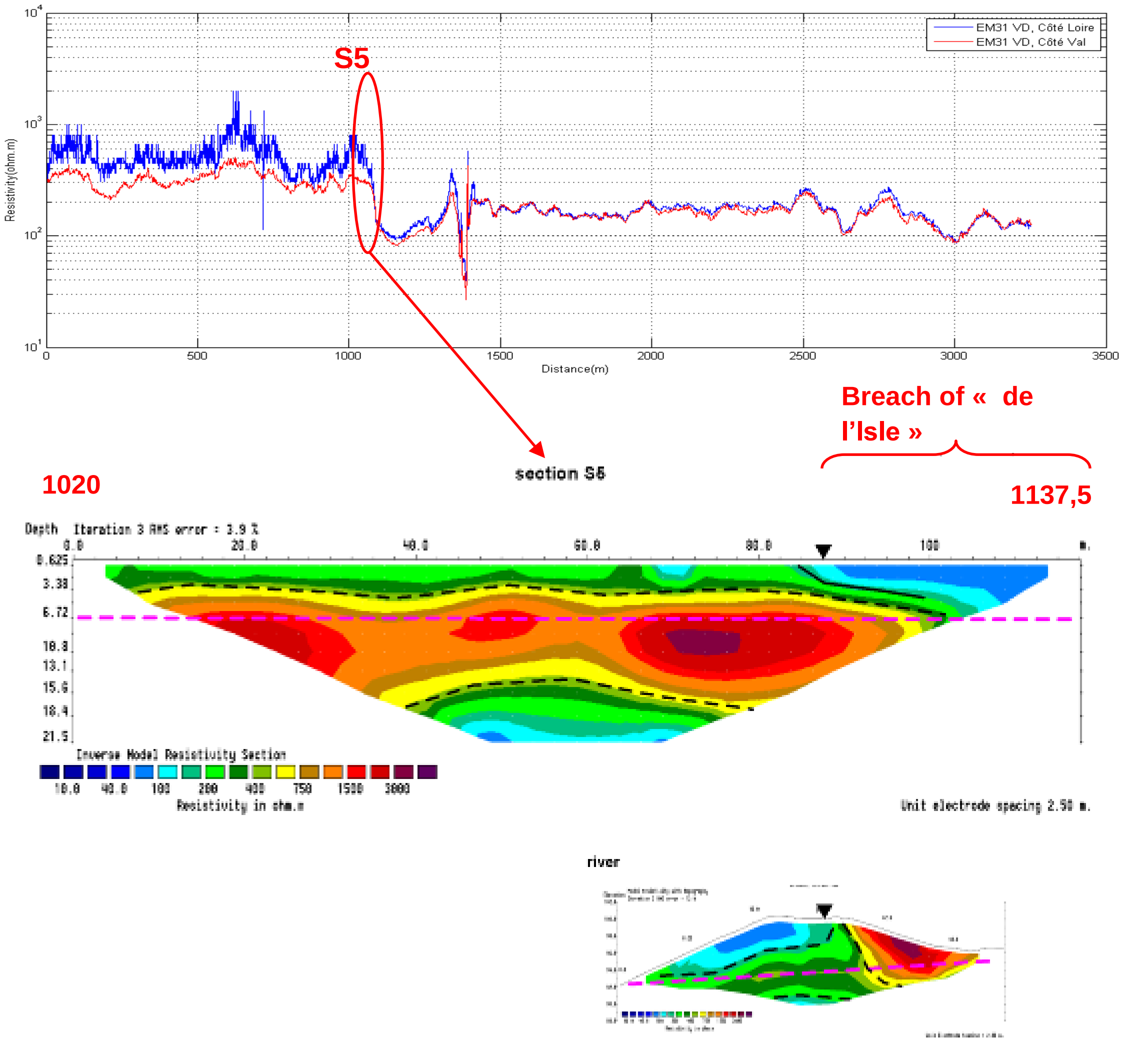


Figure 2.15 ***Slingram*** **and ERT measurements at the transition with a known old breach.**

2.4.4 Conclusion and interpretation of the geophysical investigation: providing a detailed dike model to stakeholder

A complete interpretation of the different measurements is summarized in Figure 2.16. The rapid and cost-effective methods (*Slingram*, GRP and RMT) lead to a first zoning of the dike that is subdivided in quasi-homogeneous parts with a given apparent resistivity. The materials distribution is closed to the crossing ERT profiles results carried out at specific locations in those parts. The GPR measurements allow a precise location of the breaches boundaries. As the dike is situated on a karstic area, sinkholes and collapses can occur and complementary methods such as the microgravimetry should be carried out.

The measurements show that the dike is mainly composed of sand and gravels materials, globally resistive with local variations related to the presence of old breaches and a gas network. The crossing ERT profiles give an insight on how the dike was built following the good work practices and/or repaired at a given time of its history.

For the stakeholder, the geophysical survey gives a « picture » of the dike reliable at the time of measurements. It brings an accurate location of the breach boundaries. This information is important because new breaches often occur where old breaches were. It also underlines the danger that manmade structures in the dike body such as a crossing gas network represent in case of flooding. These results should be stored and might be used as *a-priori* information for further studies.

Furthermore, the interpreted geophysical results (in the form of a dike model at the time of the geophysical survey) can be added to the asset support system in order to contribute to the dike safety assessment and to the dike surveillance.

2.4.5 Acknowledgements

We would like to warmly thank REC CR (Beneš et al., 2011) who carried out the ERT measurements and provided the results shown in this work. We are very grateful to Laboratoire Régional de Saint-Brieuc who implemented the *Slingram* and RMT measurements. Finally, we would like to DREAL-Centre who supported this study.

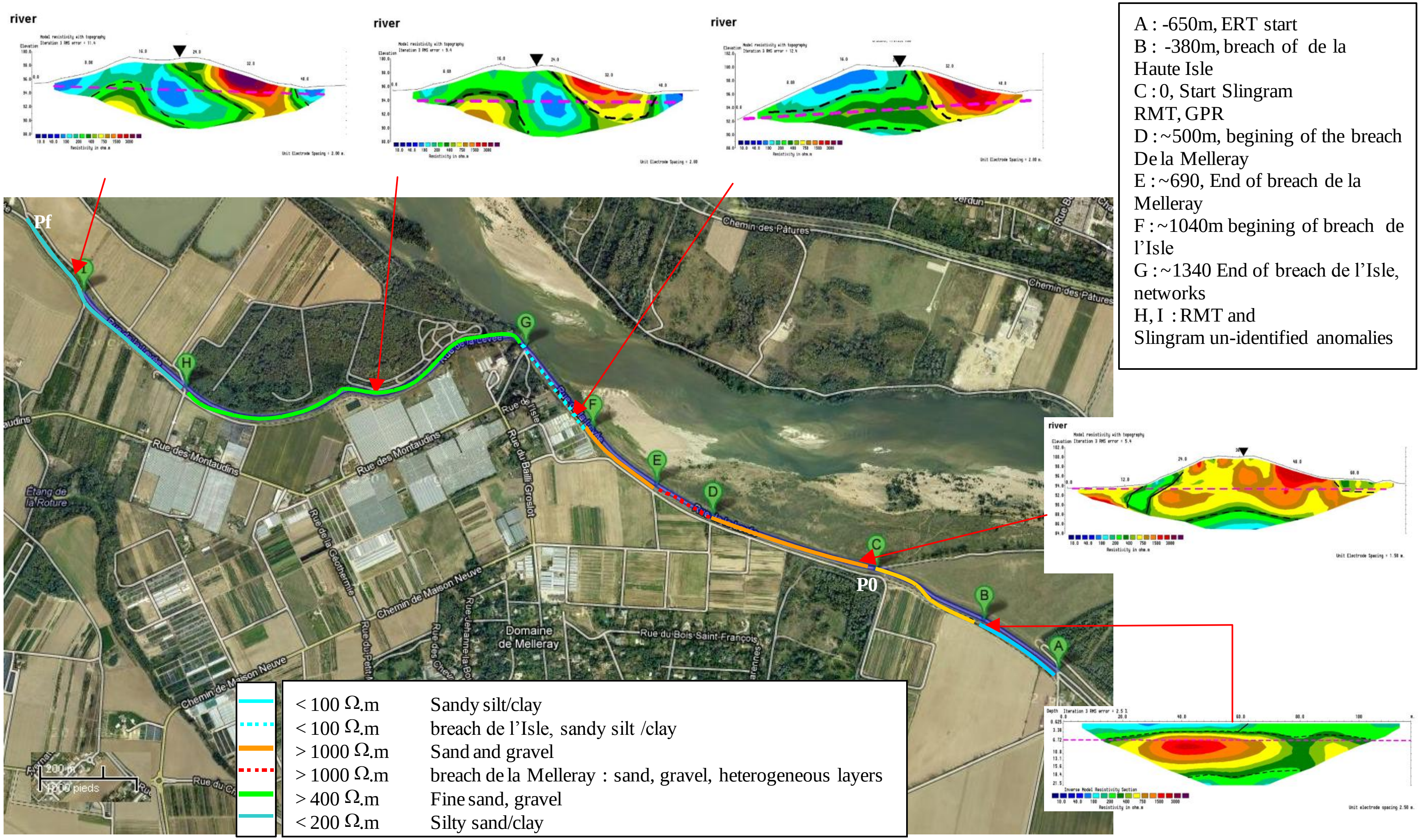


Figure 2.16 Dike model and interpretation deduced from geophysical measurements

2.5 A real case study in the Hull pilot site (UK)

2.5.1 Introduction of the selected sites and measurement methodology

The Humber estuary region has been chosen as a pilot site to perform quick geophysical survey methods (Geophysical Monitoring System – GMS) on the salt exposed as well as fluvial embankments. To cover different types of levees/embankments three different sites were selected and several geophysical methods have been applied to assess the embankment conditions and validate the applicability of these methods under different geological, geochemical and hydrological conditions. The selected sites are stated in Figure 2.17.

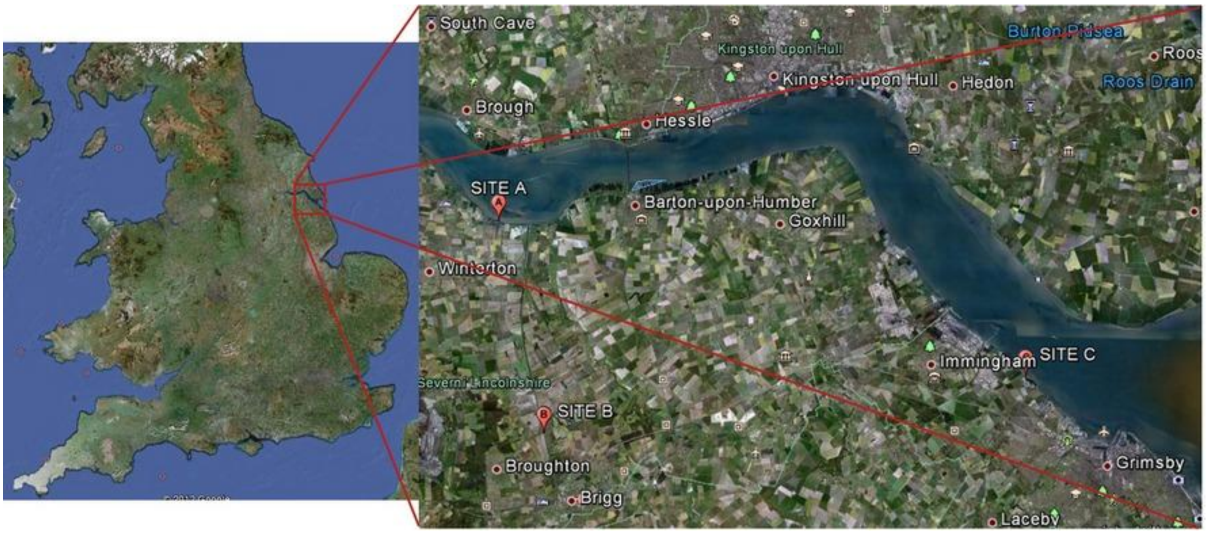


Figure 2.17 Sites in Humber estuary; Hull (UK)

The general information about the selected sites and measurements performed is as follows (methods according to the Appendix 2):

2.5.1.1 Tidal Embankment Humber Estuary, New Winteringham (Site A)

Date of measurement: 7. - 14. June 2010

6. - 10. May 2012

GPS: +53° 40' 45.83", -0° 32' 54.69"

Type of levee: earth estuarial tidal embankment

Length of levee assessed: 3000 m

Levee height: 2 - 4 m

Methods performed: *Slingram*, ERT, SP

2.5.1.2 Fluvial Embankment New Ancholme River (SITE B)

Date of measurement: 7. - 14. June 2010

GPS: +53° 34' 57.43", -0° 30' 48.39"

Type of levee: earth river embankment

Length of levee assessed: 1200 m

Levee height: 1 - 2 m

Methods performed: *Slingram*, ERT, boreholes

2.5.1.3 Coastal Embankment Immingham (SITE C)

Date of measurement: 7.-14. June 2010

GPS: +53° 34' 57.43", -0° 30' 48.39"

Type of levee: reinforced concrete coastal embankment

Length of levee assessed: 1100 m

Levee height: 4 - 5 m

Methods performed: *Slingram*

2.5.2 Preliminary studies and research

The organization responsible for the flood issues and partly for dike monitoring in the UK is the Non-departmental Public Body - Environment Agency. In order to gather sufficient relevant information of the construction history, performed reconstructions, and recent state of the embankments the meeting with the representatives of the Environment Agency were held within both measurement campaigns performed in Humber estuary. The information obtained at these meetings have been used for better insight into the area of interest and the measured data, results and conclusions have been handed over to Environment Agency representatives for further use.

2.5.3 Tidal Embankment Humber Estuary, New Winteringham (Site A)

2.5.3.1 First campaign

The first campaign at the Site A has been held on 7. – 14. June 2010 by REC. The embankment has been analyzed by the *Slingram* GEM2 on the embankment crest and partly on both the riverside and the landside. During the measurements the locations of potential breach or seepage have been located, on these places the detailed ERT survey has been carried out.

The main idea was to locate the seepage of the salt water through the embankment body by registering a marked fall of the soil resistivity on the landside of the embankment.

Some parts of the measurement have been carried out at both the high and low tide to get the opportunity to analyze the underground water movements influenced by the tidal cycle.

The basic measurement (first zoning) using by the *Slingram* method proceeded at a profile on the embankment crest (Figure 2.18) and the selected embankment segment in a length of approximately 1000 m was subjected to the repeated measurement at low tide and high tide. Detailed measurement using the ERT focused on the selected anomalous embankment segments (Figure 2.19).

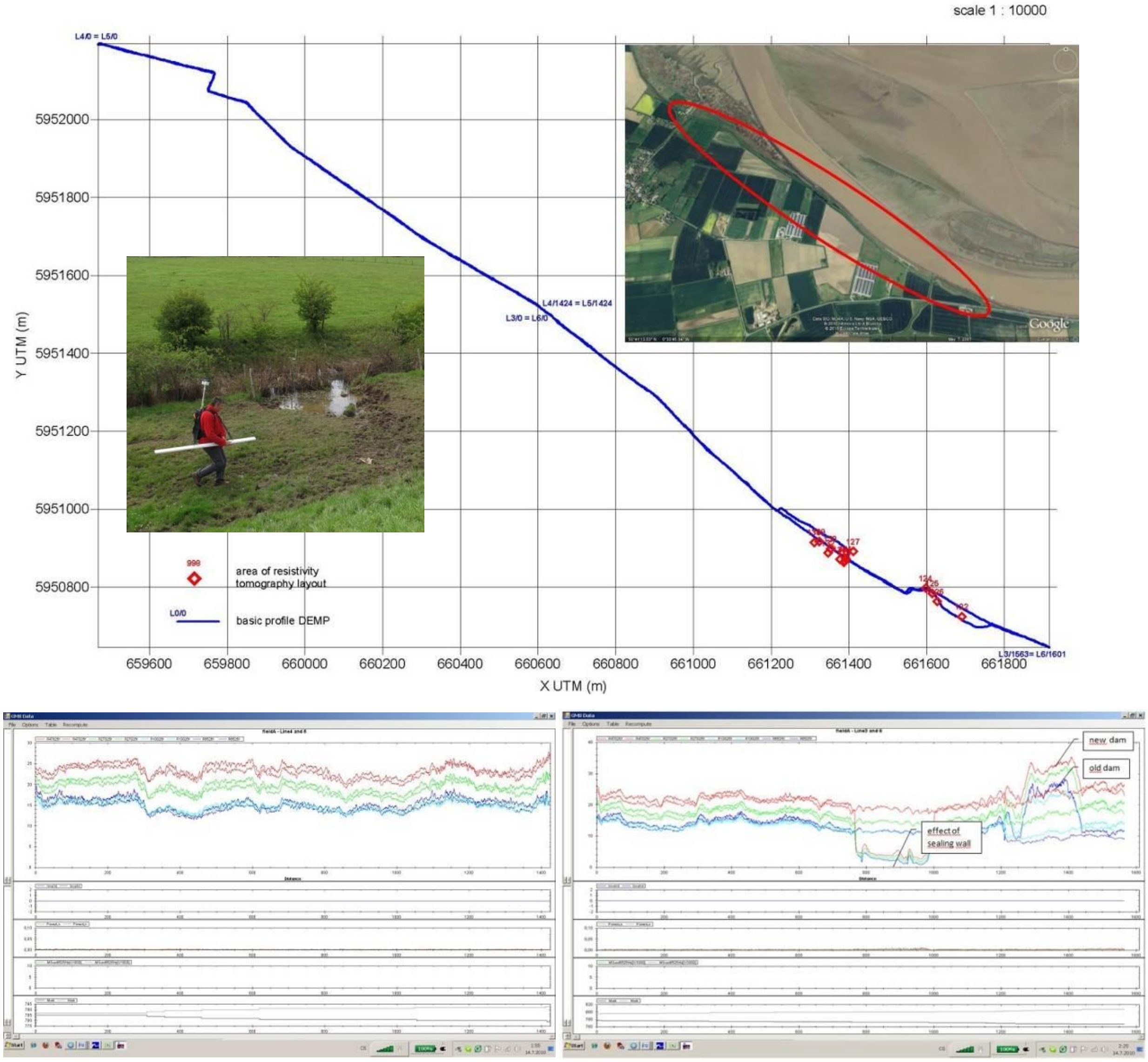


Figure 2.18 First zoning by the *Slingram* method (GEM2) at Site A

At the Site A, the measurement using *Slingram* method (including repeated measurements) was performed for approx. 12 km of profiles. In addition, 5 ERT layouts in a total length of approx. 400 m were measured

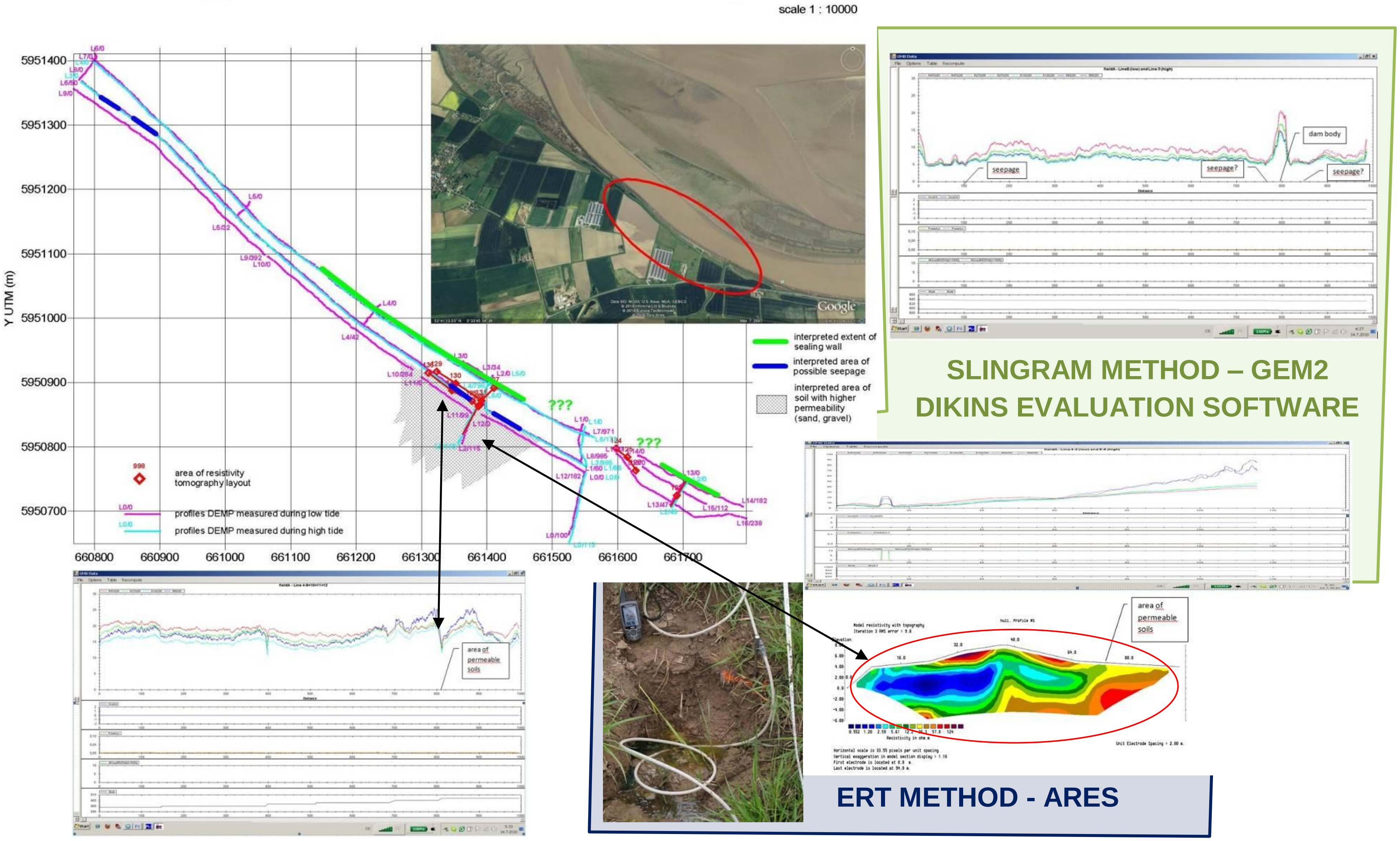


Figure 2.19 Overview of the detailed measurement and interpretation of possible problematic area

2.5.3.2 Second campaign

The second measurement campaign had among others two main ideas to be verified and further evaluated.

2.5.3.2.1 Long term repeated measurement of the embankment by the Slingram method to assess the possible monitoring potential of the GMS methodology on salt exposed embankments

The repeated measurement by the *Slingram* method has been performed on the same embankment in extent of approx. 3000m as in 06/2010. The profile measured by the *Slingram* method in 2012 with marked problematic segment with active seepage is stated in figure 2.20. The problematic segment has been further evaluated by the detailed measurement by ERT and SP methods.

Figure 2.20 ***Slingram*** **profile measured on Site A in 05/2012**

The data measured by *Slingram* has been evaluated and compared with the data measured in 06/2010. Based on this comparison of the measurement 2010 and 2012 the unstable segments of the embankment have been determined. The process of evaluation is stated in Figure 2.21.

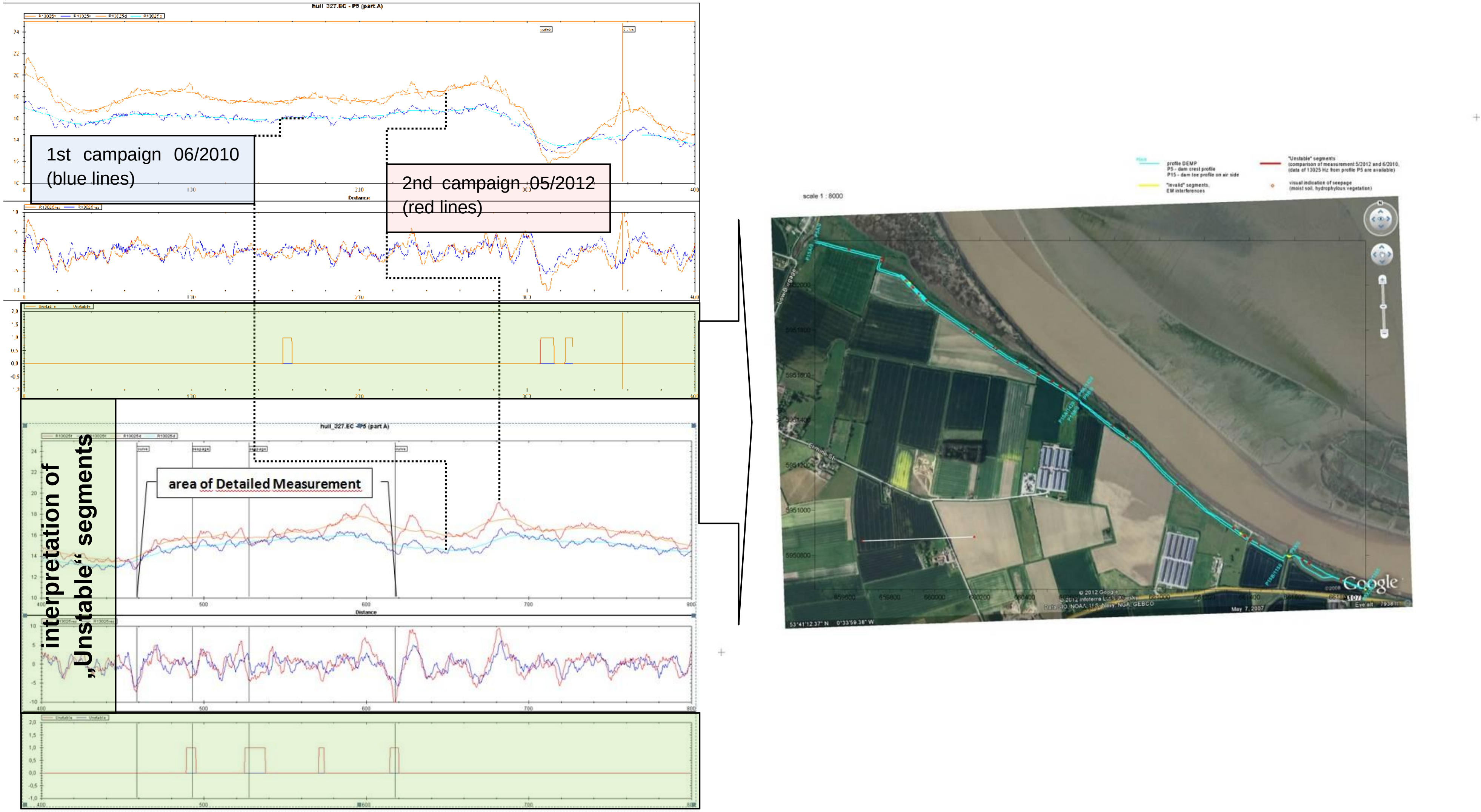


Figure 2.21 Examples of long term repeated / monitoring measurement – Site A - *Slingram* method – regional profile P5A

2.5.3.2.2 Short term repeated detailed measurement of the anomalous embankment segment with evident seepage by ERT and SP methods to assess the influence of the tidal waves

The anomalous segment was selected on the basis of results of visual inspection of the embankment which was carried out by the Environment Agency staff members in 2011. It is a segment in a length of approx. 160 m in the interval between meter 460 and meter 620 of the regional profile. In the anomalous segment there occur 3 local seepages reaching as far as approx. 1/3 (one third) of air slope of the embankment. Seepages occur at meter 0 (460), meter 30 (490) and meter 72 (532). The performed measurements served to verify the possibility of detection of seepages by the geophysical methods and also to monitor the effects of short-term changes in water level (high tide – low tide) on the mechanism of seepages by the repeated geophysical measurements.

The overview of the measurements and methods applied at this part of Site A are stated in figure 2.22.

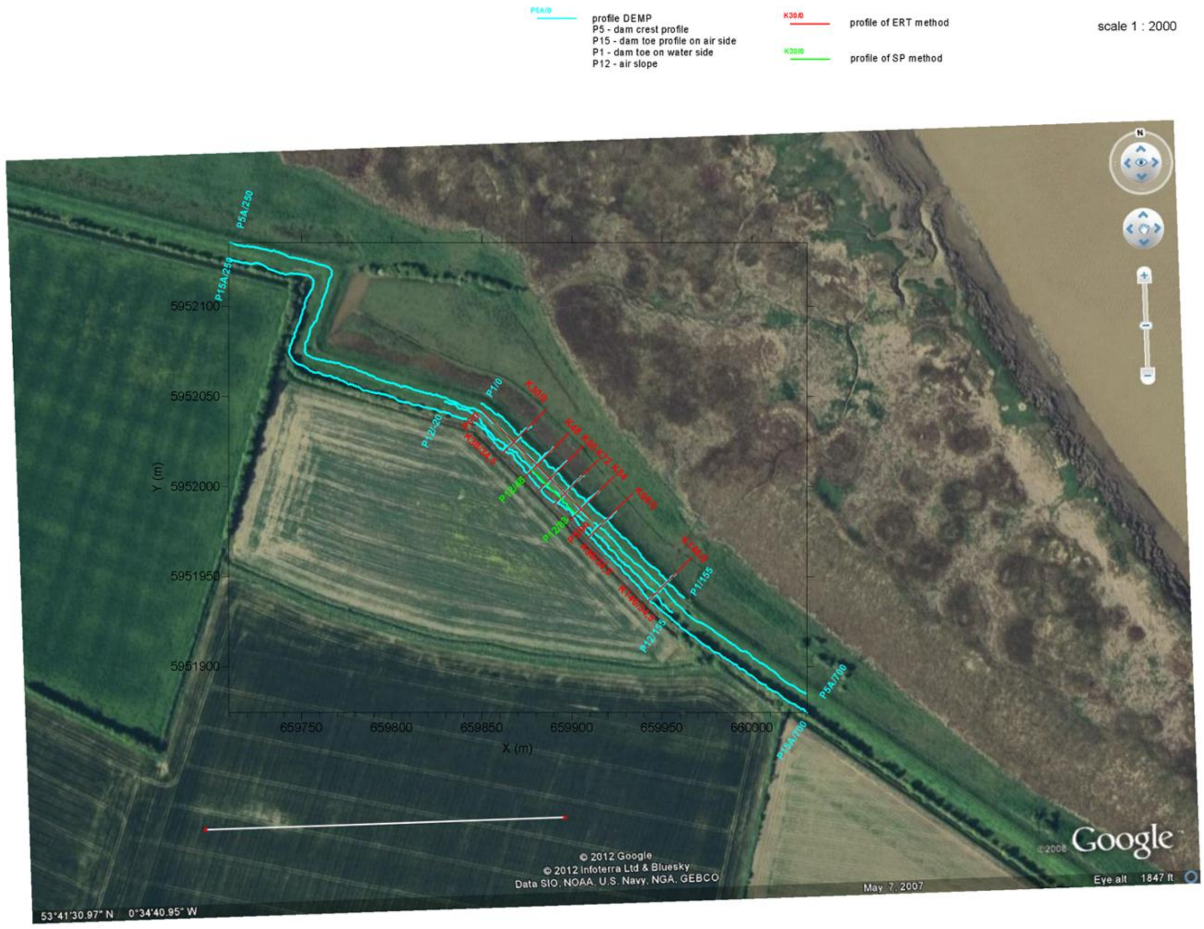


Figure 2.22 Methods and measured profiles within the detailed measurement at Site A

The *Slingram* – DEMP method was used in the anomalous segment to complement the measurements in the profiles at water toe of the embankment (P1), at air slope of the embankment (P12) and cross profiles at metre 30, 48, 60, 72, 84, 98 and 146. The ERT method was used for the measurement at a longitudinal profile in the embankment axis (segment between metre 0 and metre 94) and at perpendicular profiles K30, K48, K60, K72, K84, K98 and K146. The SP method was used for the measurement in the segment between metre 48 and 83 at the profile at air slope of the embankment (P12). The monitoring of the effects of high tide and low tide water level fluctuations on the mechanism of seepages was conducted on 8 May 2012 in the period between high tide and low tide (9:00 - 21:00). The repeated measurements by the ERT method at the profiles K48 (beyond seepage) and K72 (in the centre of seepage) and the repeated measurements by the SP method at the profile P12 in the interval between metre 48 and 83 have been applied. The measurements were carried out every two hours (i.e. a total of 7 repeated measurements).

Except the geophysical measurements additional research have been applied to collect sufficient data for the assessment of the embankment conditions and to identify the potential threatening mechanisms. The additional research comprised from the following activities:

- Measurement of water level fluctuation in the pond in a ground depression on the water side of the dike/levee and in the pool below seepage on the air side of the dike/levee
- Soil sampling using hand auger and determination of the following parameters:
    - Moisture content determination
    - Salinity determination – content of NaCl in soils
- Comparison of the content of NaCl and total dissolved compounds in the pond on the water side of the dike/levee, in the pool at a location of seepage on the air side of the dike/levee and in the water collected from the Humber River

2.5.3.3 Conclusion - Site A

The performed measurements have demonstrated that the areas of brackish water seepage through earth dikes can be well detected by the geoelectric methods. For long dike segments, the *Slingram* – DEMP method can be used very effectively. The places of seepage are manifested by local declines of apparent resistivities at air slope of the dike or at the toe of the dike. When conducting the investigation, it needs to be reckoned with the measurement for 3 profiles running in parallel with the longitudinal dike axis: profile in the dike axis on the top of the dike (assessment of material composition and homogeneity of the dike), profile at air slope of the dike and profile below the dike close to air toe of the dike (interpretation of moistening and salination of soils). The development of local seepages over time can be monitored by means of the repeated measurements by the *Slingram* – DEMP method, preferably at different water levels in the river (in dry period and during a flood or in the periods of high tide). In analysing the repeated measurements we assess local shape variations – declines of resistivity curves with time. It is however necessary to use apparatuses with a satisfactory repeatability of the device and sufficient accuracy of the GPS system.

To describe in detail the found seepage zones, especially the ERT method can be successfully applied, for active seepages (at high water level) also the SP method can be used. The results of the testing measurements show that to detect the reasons for and the extent of seepages it is necessary to perform measurements for a set of cross profiles or perform measurements in 3D format. Areas with seepages are manifested by an increased extent of areas of reduced resistivity at air slope of the dike, which corresponds to the seepage curve (or salination) of the dike, projecting at air slope of the dike. In longitudinal cross sections, the anomalies corresponding to seepages are not much obvious.

In performing the experimental short-term monitoring of the effects of high tide and low tide on the mechanism of active seepages at the site of Humber Estuary – Winteringham it turned out that cyclical changes in resistivity with the corresponding period of approx. 12 hours could be recorded. Thanks to the differential cross sections it was possible to detect the main seepage pathway running at the base of the dike (Figure 2.23). A surprisingly high rate of resistivity response on the air side of the dike to high tide and low tide water level fluctuation unambiguously shows that the mechanism of seepage is not a simple filtration through a porous medium, which is corresponded to by a rate lower by several orders. It is probably a combination of seepage area through saturated soils in the subsoil of the dike with the local system of cracks in the dike body. Cyclical character of the mechanism of seepage was also confirmed by the monitoring measurement using the SP method (Figure 2.24). The mechanism of giving rise to seepage, bound to the local occurrence of cracks generally increases the risk of possible deformation of the dike during a flood. The seepage may at high water level be of considerable intensity which along the cracks may lead to inner erosion of the dike.

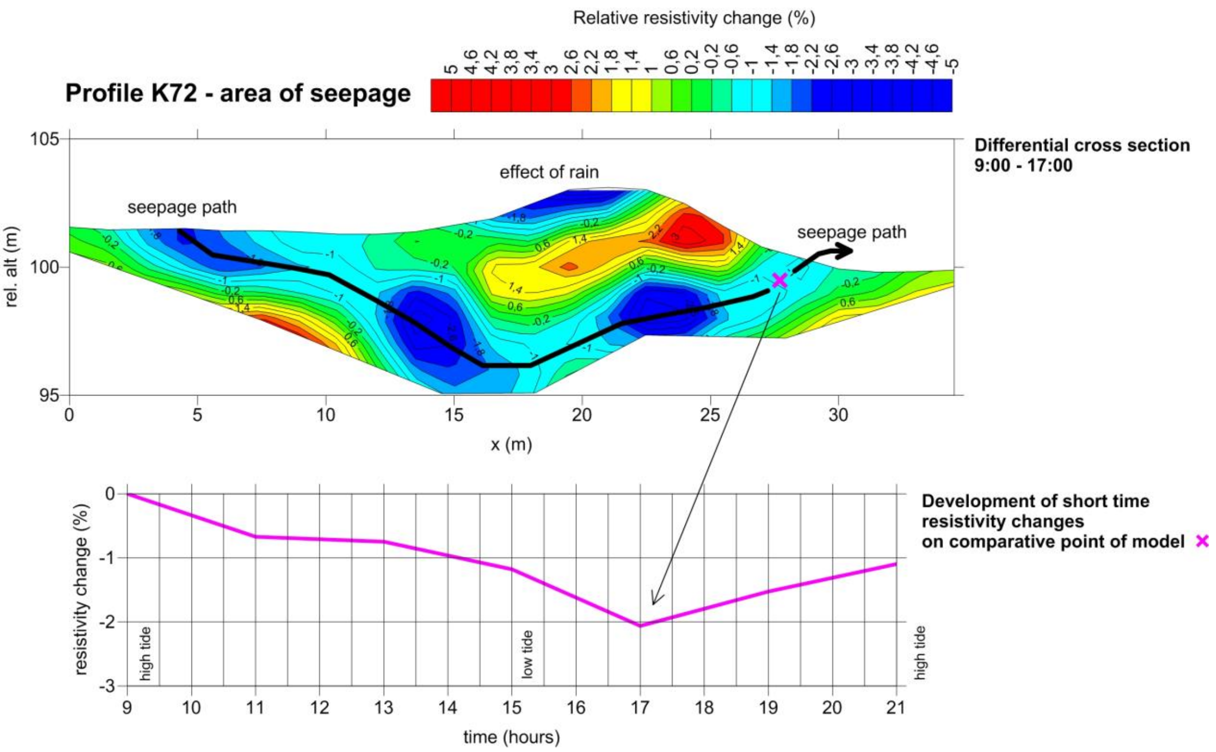


Figure 2.23 Detailed ERT result at Site A, profile K72.

The test geophysical measurements using the GMS methodology demonstrate that similar measurements may bring valuable information on the condition of earth flood control dikes in coastal areas with the occurrence of brackish waters. A suitable combination of rapid and cheap methods with more demanding detailed measurements in the anomalous areas contributes to the efficiency and pace of the investigation. The acquired data further serve to test the programme DIKINS for the analysis, storage and presentation of data measured at flood control dikes within the framework of the GMS system.

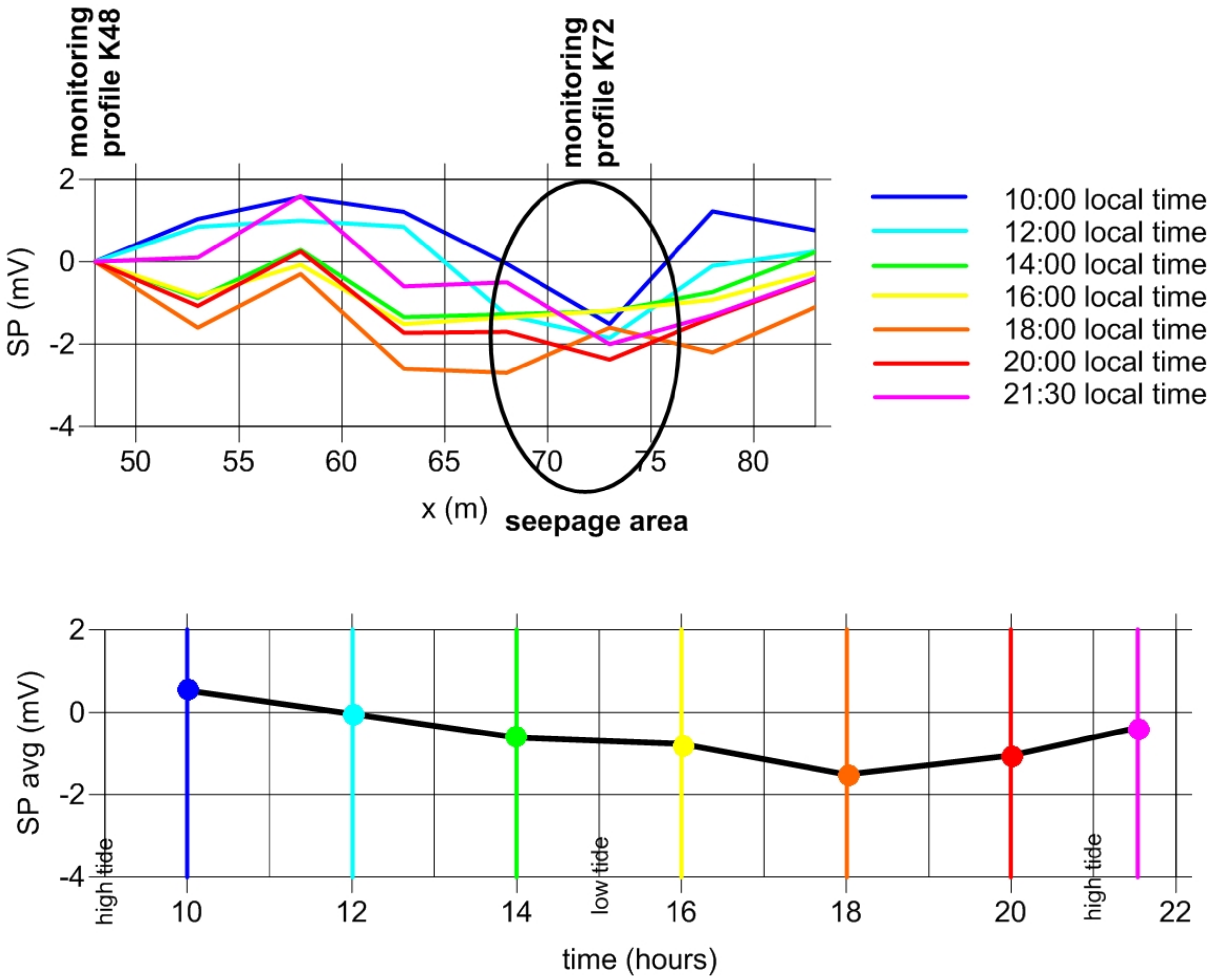


Figure 2.24 Detailed SP result at Site A: Repeated SP measurements along profile P12 (top) and time changes of average SP readings from P12 (bottom).

2.5.4 Fluvial Embankment New Ancholme River (SITE B)

The measurement by *Slingram* was performed on the embankment segment in a length of approx. 1200 m in the profile situated in the longitudinal embankment axis. The acquired data were preliminarily assessed in the field and 4 test boreholes for soil sampling were suggested. Two places were subjected to the measurement by ERT. The profile layout is presented in Figure 2.25. In total, the measurement using *Slingram* method (including repeated measurements) was performed for approx. 2.4 km of profiles and for 2 resistivity tomography layouts in a total length of 100 m. The measured profile and results of the detailed ERT measurements are stated in Figure 2.25.

The comparison of minor resistivity variations and brief test pit descriptions shows that even for very subtle differences in the resistivity structure there mostly exists logical geological explanation. Potentially very important, from the viewpoint of describing the embankment condition is the suggested relation of increase in resistivity values with the frequency of fissures close to the embankment surface. The same experience we acquired during the measurements performed at similarly homogeneous embankments in the USA, where a field-mouse colony and their holes came to light in a similar way. We assume that the interpretation of the mentioned defects might be further refined by repeated measurements under differing hydrological conditions (under condition of dried-up embankment and during flood). Under dry conditions, the area with fissures or holes will rather show as the local maximum of resistivity, on the contrary, at the moment of fissures filled with water during flood as the local minimum. Nevertheless, too little measurements performed in a similarly homogeneous type of embankments prevent us from drawing the generalized conclusion.

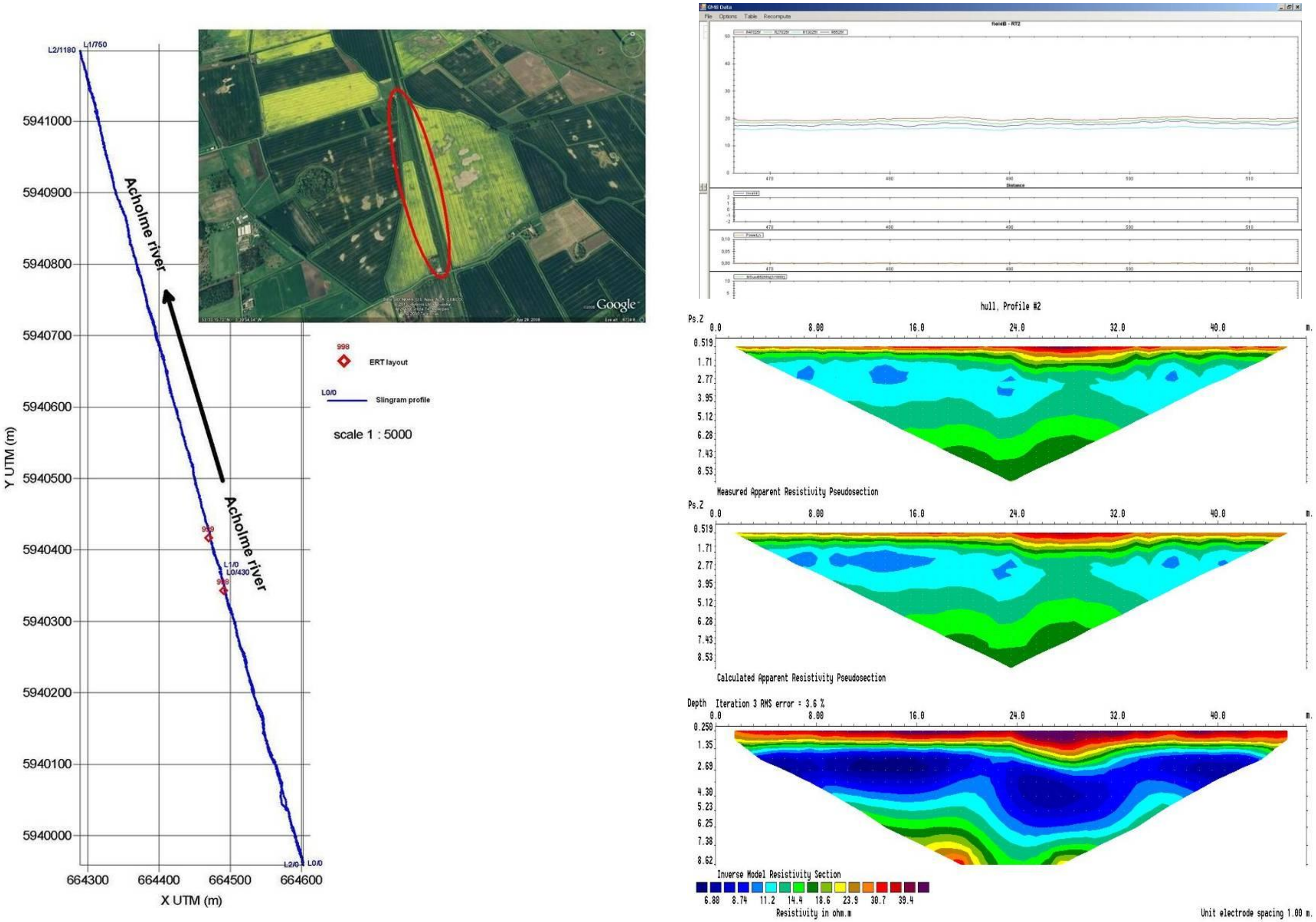


Figure 2.25 ***Slingram*** **profile and detailed ERT measurement at Site B**

2.5.5 Coastal Embankment Immingham (SITE C)

With regard to frequent occurrences of reinforcements in the embankment structure, the geoelectric measurements in the locality C were only experimental. The profiles were measured using *Slingram* method. The method of resistivity tomography was not applied due to hard surface covering most of the dike area, which disallowed to earth the electrodes.

The profile in the embankment axis (Figure 2.26) documents well the (negative) effect of reinforcement on the data measured by the *Slingram* method. Such measurement, nevertheless, may serve to check mere existence of reinforcement, or to check the density of the major reinforcement elements. Gradual corrosion of reinforcement elements might probably be documented by repeated measurements.

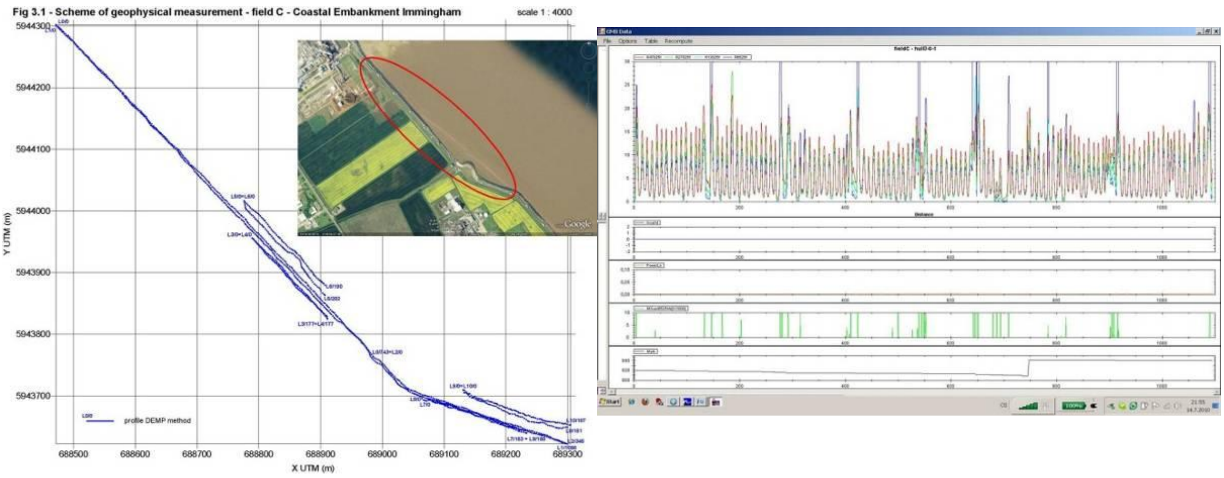


Figure 2.26 Slingram profile and results at the Site C

Generally, it can be stated that for the basic dike material description, *Slingram* method can be applied in places without reinforcement elements. The method can be used with no limitations in performing the measurement at downstream face of the dike for the investigation of subsoil geology.

GMS methodology reckons also with the investigation of similar dike types. However, appropriate methods need to be selected. Seismic methods can be recommended for describing the geomechanical condition of the dike. Frequently demanded is the detection of caverns below upstream dike slope reinforcement. For such cases we use the geological radar and microgravimetry.

2.5.6 Conclusion

Based on the measurements performed in the Humber estuary following conclusions can be stated:

1) The GMS methodology consisting from rapid zoning of the embankment and detailed measurement of the selected problematic segments can be successfully used in case

of brackish embankments for localisation of possible seepages and other inhomogenities

2) The *Slingram* method can be successfully used for the long-term monitoring of the embankment and concerning relatively low price per measured kilometre of the embankment it can be suggested for regular monitoring assessment of different embankments performed by the responsible authorities (dike managers, dike owners)

3) The detailed measurement can be successfully applied for short term repeated measurement in order to obtain real-time data about the dike conditions and tidal / flood wave influence

The information brought by this type of measurement can be very valuable input for the stakeholders, as it gives important information of the most vulnerable dike segments where in case of flood event the breach can occur. As well the long-term information from the monitoring measurement can be successfully used for the planning of dike maintenance and eventually even for the spatial planning in the adjacent areas.

2.6 Conclusion and prospects

It is now well accepted that geophysical investigations significantly and cost-effectively contribute to embankment dike condition assessment. Nonetheless, geophysical method selection and applicability is not always very clear and asset managers need more insight and confidence in order to more widely make use of geophysics. A FloodProBE task was undertaken on “Rapid, non-intrusive geophysical methods for assessing dikes”. This chapter contains guidelines on application to urban areas for managers to implement and integrate geophysical investigation results into the asset support system. If focuses on technical, practical and economical features such as geophysical method applicability, reliability, rapidity, limitations (particularly in urban areas) and cost-effectiveness. The guidance approaches the problem from both a ‘geophysics’ angle and a ‘stakeholder’ point of view. The core of the guidance holds within a purposely limited number of tables for stakeholders to comprehend the most important features and better interact with the geophysics expert. As implementing and interpreting geophysical investigations in a real situation is an expert work, it is obvious that the role of geophysics experts remains essential.

The guidance is based on the conclusions from the **FloodProBE International Geophysics Workshop** (FIGW, March 2011, Paris, France) together with state-of-the-art and results from recent key research initiatives (more particularly CRITERRE, DEISTRUKT, IMPACT, FLOODsite, GEMSTONE, ERINOH). Moreover, the geophysical approaches presented in this guidance were implemented in two pilot sites (Orléans, France and Hull, UK).

More than ten geophysical methods were reviewed during the FIGW and wider agreement was gained on the preferred methods for embankment dike investigation. Approaches based on method combination and comprising overall investigation followed by detailed investigation phases were confirmed. *Slingram* (electromagnetic induction) profiling and Electrical Resistivity Tomography are among the most preferred methods. However, all other methods can play important and specific roles, depending on the stakeholder requirements and the asset features and setting.

Temporal approaches have proved powerful tools for weak zone detection and monitoring and should be more widely used in the near future. Stakeholders also expect that geophysical methods and approaches will be more extensively used on sea dikes, where conditions (soil materials, type of water, load cycles) are different from those applying to river dikes. In this regard, the two case studies presented (on Orléans and Hull pilots) show currently applied approaches from a wider perspective.

Some methods that have potential for distinguishing materials according to specific properties (e.g. Induced Polarization or Magnetic profiling and mapping) should be more significantly tested on embankment dike applications. Progress in numerical modelling (e.g. dike geometry effects) and inversion (various 3D effects) is expected for improving geophysical data interpretation. Research and development efforts should also be made on seepage flow estimation, alert processes that include geophysical surveillance and integration of geophysical information into GIS asset support systems.

2.7 Appendix: Geophysical method technical sheets

This section presents technical sheets for some of the geophysical methods discussed. Further details have been widely published (e.g. Telford et al., 1990).

2.7.1 Slingram electromagnetic induction (EMI) profiling

2.7.1.1 Principle

The electromagnetic induction (EMI) system presented here is related to the *Slingram* method described by McNeill (1980). *Slingram* is based on the emission of a low frequency magnetic field by means of an alternating current generated in a coil (emitter) and the reception with another coil (receiver) of the secondary magnetic field generated by the interaction of the primary field with conductive materials in the soil (Figure 2.27).

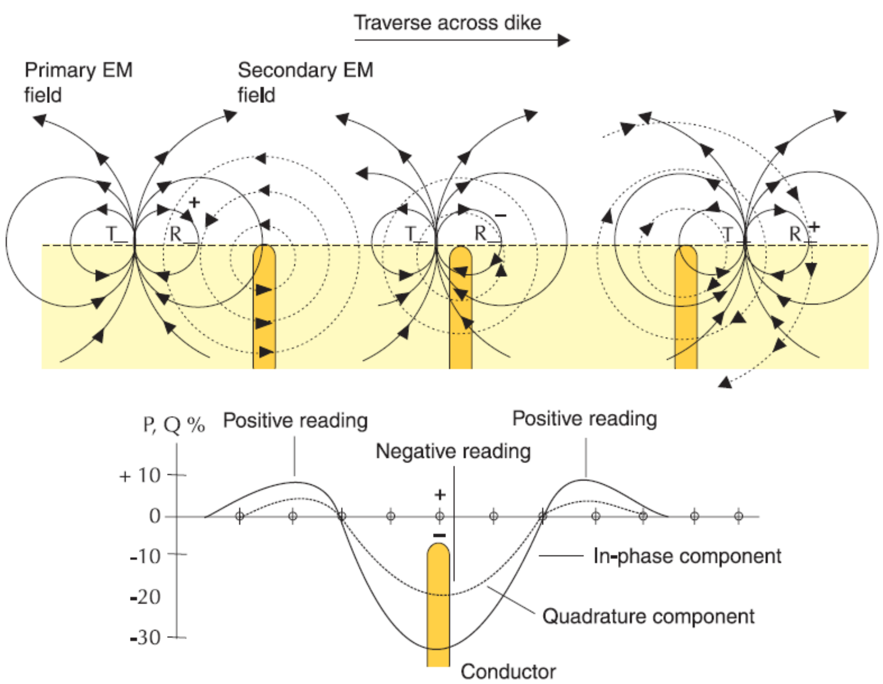


Figure 2.27 ***Slingram*** **principle in vertical dipole (VD) mode (Chouteau, 2001)**

The coils are placed at a fixed height above the soil. They are usually coplanar and oriented vertically (Horizontal Dipole or HD mode) or parallel to the surface (Vertical Dipole or VD mode).

2.7.1.2 Measured parameter

The measured parameter is the apparent conductivity σ_a (S/m). *Slingram* is a volume integrating method and this apparent conductivity results from the combination of the DC-electrical conductivity of the materials (soils) within the depth of investigation. The DC-electrical conductivity of a soil relates to the free charges distribution in the soil and also depends on its water and clay contents, temprerature, water salinity, soil porositiy and tortuosity. The apparent conductivity is a function of the separating distance between coils, the operating frequency and the ratio between the primary and secondary magnetic fields. The conductivity range for the common geological materials is given Figure 2.31.

2.7.1.3 Expected results of a survey

The expected result of a survey is a profile providing the apparent conductivity of soil in function of the distance. Several parallele profiles lead to an apparent conductivity map of the surveyed surface. Theoretically, if both VD and HD modes are used at various heights relative to the soil surface, the apparent conductivity data can be inverted in order to yield a multi-layered model. This process is bound to the assumption that the subsoil actually has a horizontally multi-layer structure, which is a specific case. In more general cases, the main results of a *Slingram* survey is a zoning showing apparent conductivity variations and zones where this parameter is approximately constant. An example is presented Figure 2.28.

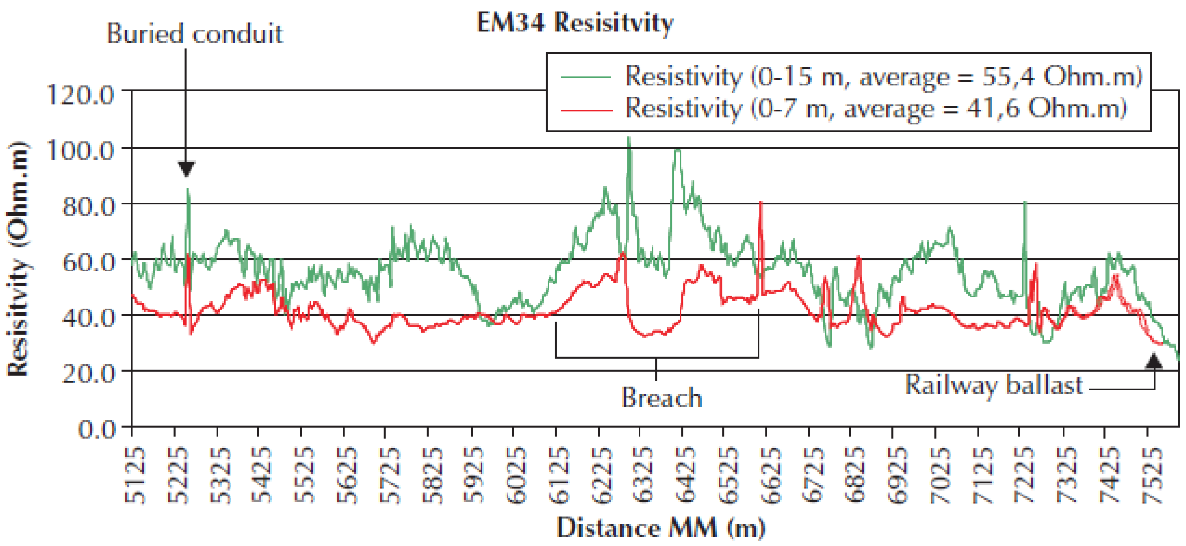


Figure 2.28 Example of *Slingram* measurement on a dike crest (Fauchard and Mériaux, 2007)

2.7.1.4 Implementation

Slingram is easily implemented on foot for smal devices (e.g. Geonics EM38 and EM31, Geophex GEM-2). As these devices are portable, they can be carried by a single user and the data recorded together with GPS georeferencing. When applied to dike investigation, profiles can be conducted on crest, toes and slopes.

2.7.1.5 Depth of investigation (DOI) and resolution

The DOI depends on the coils orientation and separation. With a single apparatus, in VD and HD modes, data for two different depths of investigation can be recorded. Slingram vertical resolution is poor for single acquisition modes (profiling with single coil separation, orientation and operating frequency). The horizontal resolution can be better than 1m and is related to the location of buried anomalies such as buried pipes or edges at transitions between electrically contrasted (resistive and/or conductive) volumes.

There exists commercial multifrequency apparatuses conceived for simultaneously reaching multiple DOI. Indeed, for multiple acquisition modes (multiple coil separation, orientation and/or multiple operating frequencies) the data allow some insight in the vertical distribution of subsoil electrical conductivity. Theoretically, inversion of such data may lead to a full 2D model of subsoil, although further research is still needed on the matter.

2.7.1.6 Output rate

The output rate is related to the speed of the user and barely exceeds 10 km a day. Higher rates are obtained if the *Slingram* device is towed by a vehicle on crest or at toes.

Airborne electromagnetic (AEM) devices also exist. Those are attached to an airplane or a helicopter (HEM technique). AEM or HEM spatial resolution is much lesser compared to ground based *Slingram* measurements, with much higher output rates and costs. When applied to embankment dike investigation, AEM or HEM allow for very rapid, although coarse, surveys of the full length of flood defense systems.

2.7.1.7 Limitations

The main limitation deals with the fact that this method is hardly applicable in urban context, because *Slingram* devices are very sensitive to metallic structures, electrical networks, and civil engineering structures made of concrete with metallic reinforcement.

In rural context, the method is not applicable in case of the presence of metallic barriers (e.g. crash barriers, fences) or sheet piling in the dike body.

2.7.2 Electrical Resistivity Tomography (ERT)

2.7.2.1 Principle

DC-Resistivity techniques are based on the transmission of DC-electrical current into the subsoil by means of a pair of stake electrodes hammered into the ground surface. Simultaneously, potential drops generated by this current flow are measured by means of other pairs of electrodes. Therefore a single measurement requires at least 4 electrodes, usually considered as “point” electrodes (Figure 2.29).

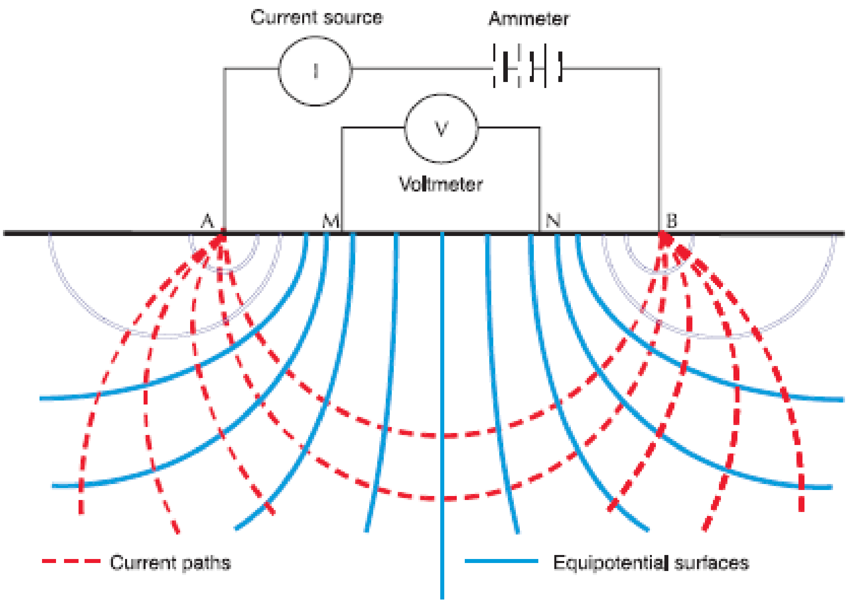


Figure 2.29 Schematic of a single apparent resistivity measurement using 4 “point” electrodes denoted A, B, M and N

Such a “quadrupole” investigates a volume of subsurface of which the size depends on the soil resistivity distribution and that increases with the electrode separation. Classical quadrupole configurations are shown Figure 2.30.

DC-electrical resistivity ρ (Ω.m) is a physical property related to the ability of a given medium to oppose a current flow. Its reciprocal is the DC-electrical conductivity σ (S/m). The resistivity of a soil mainly depends on its geological nature (particularly on the clay content), its porosity and tortuosity, moisture content, water salinity and temperature. The range of resistivity values in common geological and civil engineering materials is quite extensive, making resistivity a relevant property for detecting changes in material type or state (Figure 2.31).

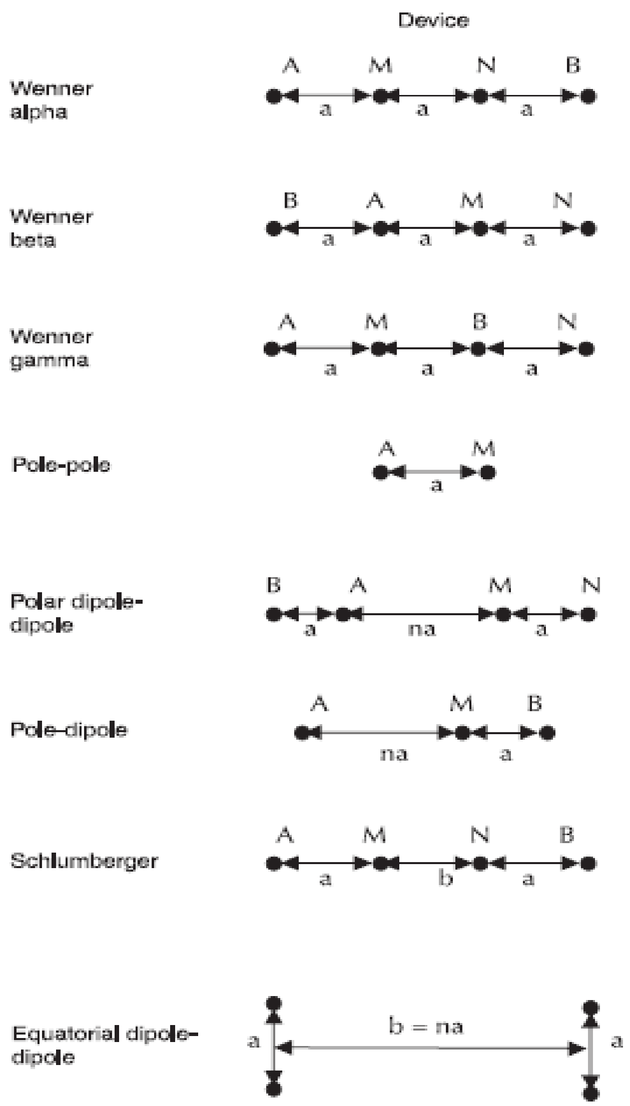


Figure 2.30 Common electrode configurations used in DC-resistivity techniques, including ERT

Among numerous DC-Resistivity techniques (e.g. Vertical Electrical Sounding, Lateral Resisivity Profiling) Electrical Resistivity Tomography (ERT) is the most elaborate as it allows for imaging the subsurface in terms of 2D or even 3D resistivity distribution models. A 2D-ERT makes use of a number (e.g. 48 or 64) of aligned and equally spaced electrodes connected to a resistivity meter. A series of 4-electrode combinations of variable spacing and lateral position on this line are scanned and the corresponding measurements are recorded in a so-called acquisition "sequence".

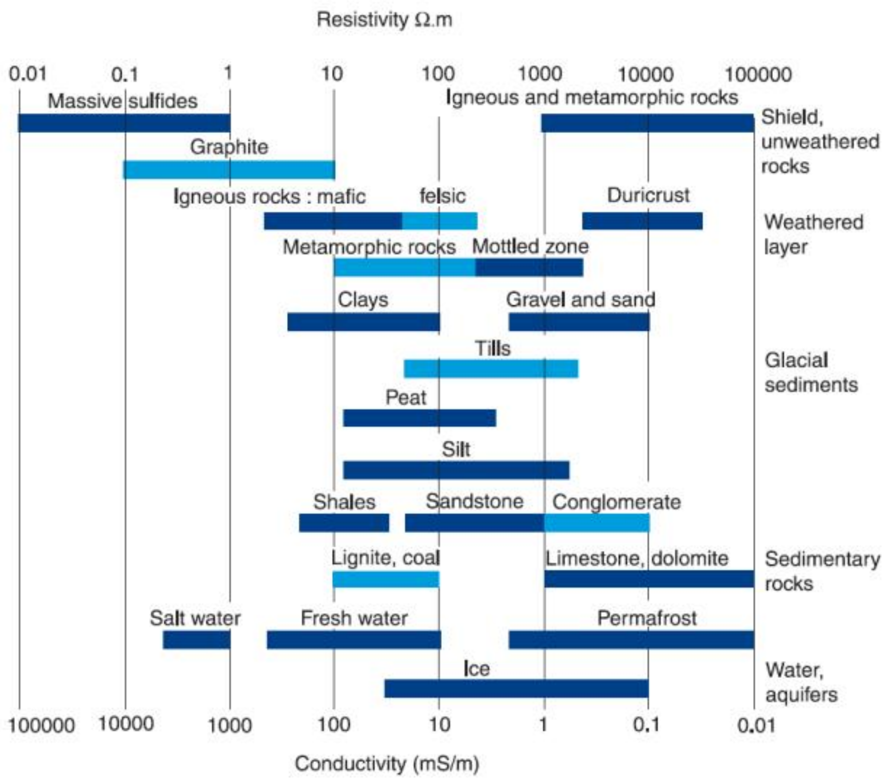


Figure 2.31 Resistivity (and conductivity) ranges for common geological materials (adapted from: Palacki, 1991)

2.7.2.2 Measured parameter

For each 4-electrode array (quadrupole) in the acquisition sequence, the measured parameter is the apparent resistivity ρ_a (Ω.m). The measurement is volume integrating and thus the corresponding apparent resistivity results from the combination of the DC-resistivity of the materials within the depth of investigation.

2.7.2.3 Expected results and post-processing

The raw result is the set of measured apparent resistivities that can be plotted for each electrode separation in order to analyse the data variability and quality (some smooting may be needed if data are noisy).

An inversion process (e.g. smoothness constrained least squares fit) is then needed for reconstructing a 2D resistivity model that fits both the measured data and all available information on the subsoil (including any geological, geotechnical and topographical knowledge).

The result of a 2D-ERT then takes the form of a vertical section showing a fitted 2D resistivity distribution model (Figure 2.32). The inversion process is a “ill-posed” problem that does not lead to a unique solution. Therefore the selected model should always be discussed, validated by direct observations (e.g. borehole data) and its reliability should be analysed.

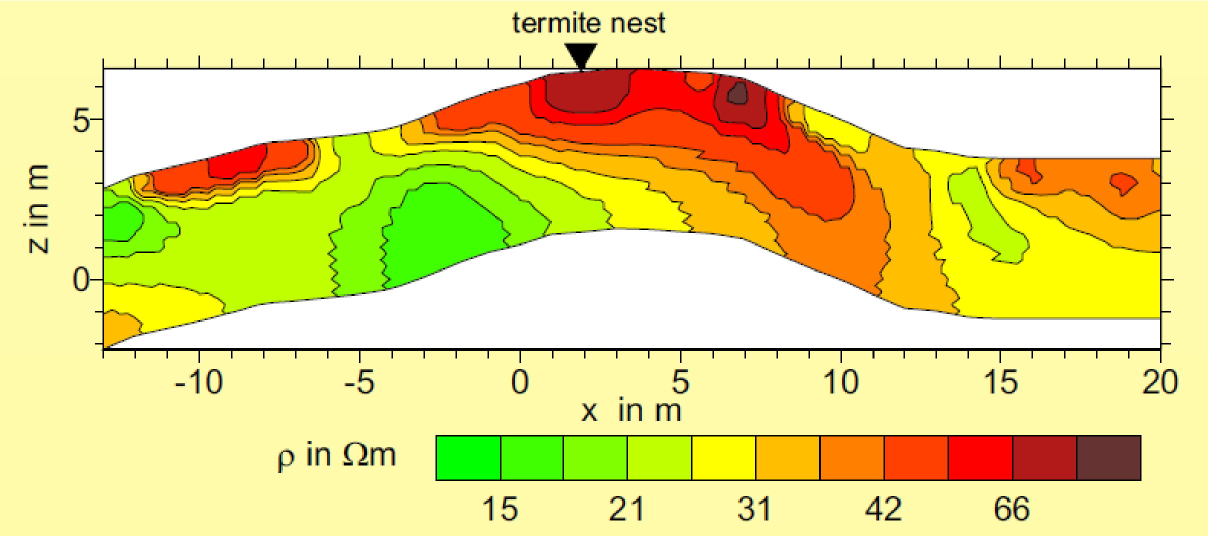


Figure 2.32 Example of ERT inversion results on dike for averaged Half-Wenner data with topographic correction (Hennig et al., 2005)

2.7.2.4 Applicability

ERT can be undertaken either along or across earth embankments. It is well-adapted for a mapping materials distribution. Therefore, one can implement ERT profiling on embankment dikes for zoning the dike body and ist foundation into horizontal and vertical segments of (approximately) homogeneous type and condition (e.g. soil layering, water table, repaired zones, etc). Under some conditions it is also suitable for detecting anomalies such as cavities, buried channels, embedded manmade structures. By implementing repeated measurements in contrasting load conditions, “time lapse” ERT is well suited for monitoring changes in dike condition and detecting, e.g., seepage areas.

2.7.2.5 Depth of investigation (DOI) and resolution

2D-ERT profiling is generally considered as a “high resolution” geophysical method because it is an imaging technique that delivers images of subsoil vertical sections. Although this assumption is obvious when comparing it to more rapid profiling methods (e.g. *Slingram*), the expected added value can only be achieved under some conditions.

The overall DOI and resolution of an ERT inverted section depend on the resistivity distribution of the investigated subsoil, on the amount, spatial coverage and quality of the measured data, on the total length of the electrode line and on the electrode configuration(s) used in the acquisition sequence (see Figure 2.30). The actual DOI needs to be qualified by means of cross-comparison to available observations, and the resolution should be quantified by numerical tools that help yielding a reliability map associated to the resistivity model.

2.7.2.6 Output rate

2D-ERT profiling is generally considered as a “slow” geophysical method compared to simpler profiling methods. Indeed, it can be time consuming due to the various implementation stages comprising the setup and removal of the multi-electrode line, the recording or the apparent resistivity sequence and finally the inversion of data and the interpretation of the final result.

The time consumed by the first and second stage respectively depends on the amount of personnel and equipment available at one time and on the resistivity meter functionalities (number of input channels). Therefore this time can be shortened by increasing the average budget per day.

Finally, the last stage (inversion and interpretation) requires expertise and cross-validation, and is difficult to accelarate.

2.7.2.7 Limitations

In load condition, the presence of the large volume of water along the dike must be taken into account in inversion (Fargier et al., 2012) in order to avoid possible artifacts in the ERT image.

Although the interpretation of data is usually given in the form of a 2D vertical section, one should always keep in mind that the real problem is 3D because of the dike geometry and the non-homogeneity of construction materials. Therefore, ERT interpretation requires expertise and cross-validation, as previously stated.

ERT profiling can be applied in urban context, but great attention should be paid to the existence of known metallic structures (networks, crash barriers, sheet piling) that are embedded or in contact with the subsoil.

2.7.3 Ground Penetrating Radar (GPR)

2.7.3.1 Principle

The principle of Ground Penetrating Radar (GPR) is based on the transmission, the reflection and the refraction of electromagnetic waves that propagate into the soil. The GPR produces very short pulses in the time domain toward an antenna that radiates electromagnetic waves into the ground. When waves meet a dielectric contrast, a part of the energy is reflected to the surface as another part is transmitted into the ground. An acquisition system measures the reflected waves in function of time and amplitude at a given location along a profile (Figure 2.33). The so-called result is a scan. The system then moves along the profile at a given step and new scans are recorded.

The result along a profile is called a B-scan which is an image of the near surface where the x-axis is the distance, the y-axis gives the two-way travel time, and the z-axis shows the amplitude in colour scale (Figure 2.34).

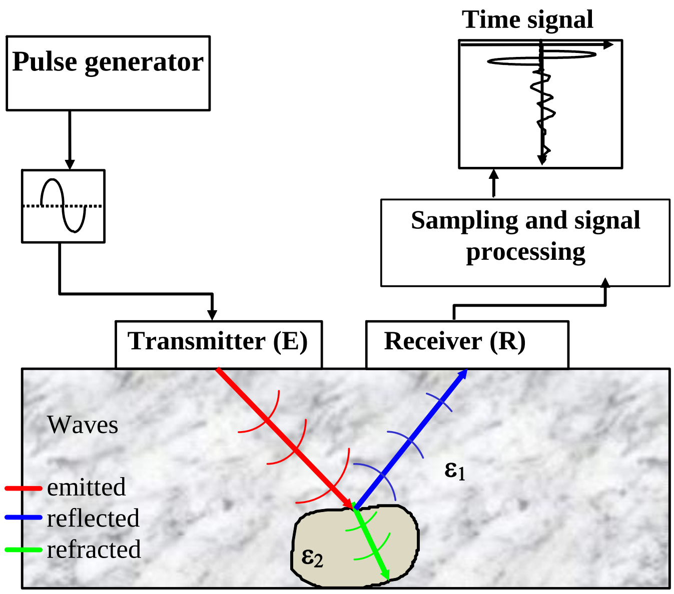


Figure 2.33 Principe of Radar (GPR) measurements

2.7.3.2 Measured parameter

The measured parameters are the travel times and amplitudes of reflected waves. These are related to a physical property of materials called complex dielectric permittivity ε^*. The real part of dielectric permittivity (ε') is related to the dielectric polarisation of bound charges in the soil and is directly related to radar wave velocity (see Table 2.4 for typical values of the dielectric constant in common materials; Note: dielectric constant is defined as $\varepsilon'/\varepsilon_0$, where ε_0 is the dielectric permittivity of void). The imaginary part of dielectric permittivity (ε'') reflects the relaxation polarisation due to dipolar moment and conduction of free charges and is directly related to attenuation. A dike body containing dry sand, dry limestone, gravels, or silt with low-clay content is an ideal medium for GRP application. Any earthen material with medium to high clay or water contents generally makes GPR less efficient.

Table 2.4 Typical values of dielectric constant for common geological and civil engineering materials

Material	Dielectric constant
Air	1
Fresh water	81
Dry sand	3 to 5
Fresh water saturated sand	30
Clay	8 to 12
Dry limestone	6 to 8
Concrete	4 to 10

2.7.3.3 Expected results of a survey

The expected results of a GPR survey are an interpreted B-scan (Figure 2.34). The y-axis representing the time propagation in the soil may be interpreted in terms of depth of investigation. This requires the knowledge of the wave velocity in the dike. An estimated velocity can be considered according to the literature data giving the permittivity of common geological materials. The velocity can also be estimated by Common Middle Point acquisition in the case of layered soil or by signal processing (e.g. migration if a punctual reflector such as a pipe is detected).

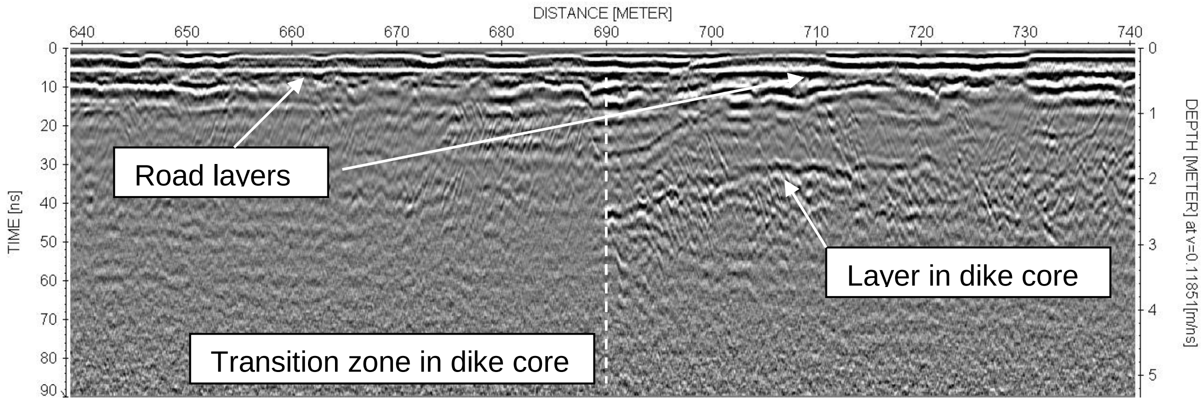


Figure 2.34 Example of B-scan. The road layers are continuous signals below 1 m. Notice at 690 m, a transition zone between an attenuating part of the dike and a sandy part of the dike

2.7.3.4 Implementation

GPR is easily applied for imaging a dike either from the crest, slopes or toes. It can be towed behind a vehicle or implemented on foot by one or two users (depending on the size and weight of used antennas) anywhere around the dike.

2.7.3.5 Depth of investigation (DOI), resolution and applicability

The DOI is generally less than 2 m in common dikes, except in very resistive soils (dry sand and gravel cores as in the Loire river dikes, France). The resolution mainly depends on the used frequency. Low frequencies allow a large DOI with a poor resolution. High frequencies give a limited DOI with a high resolution.

GPR is sensitive to contrasts in dielectric permittivity, thus it is sensitive to spatial changes in soil nature, moisture content and density. GPR surveys allow to detect transitions in material type and state (e.g. damaged areas). They also allow for the detection of structures in subsoil (cracks, layers, water table) and embedded structures such as voids, networks, built-in elements and metallic features.

2.7.3.6 Output

The output is generally in the form of a B-scan with some post-processing. The amount of data can be very significant and can render the interpretation very difficult. Complementary methods such as ERT, EMI (*Slingram*) or seismic methods are useful to make reliable the interpretation of GPR measurements.

2.7.3.7 Limitations

The main limitation concerns the clayey nature of the materials composing the dike. In such materials, electromagnetic waves cannot propagate and render GPR unsuitable. In urban areas, the presence of numerous structures (pavements, networks, etc) generally hides the relevant data required for dike assessment. Nevertheless, it is noteworthy that GPR can be performed both in rural and urban contexts.

2.7.4 Seismic methods

2.7.4.1 Principle

Seismic methods are based on the study of mechanic waves that propagate into the investigated subsoil. The basic principle consists of generating seismic waves with a controlled source and recording the propagation time for the waves to travel from the source to the geophones (sensors), generally set at the soil surface along a straight line (Figure 2.35). The knowledge of the travel times, the source and geophones locations leads to the evaluation of seismic waves velocities, which are directly related to the mechanical properties of the soil.

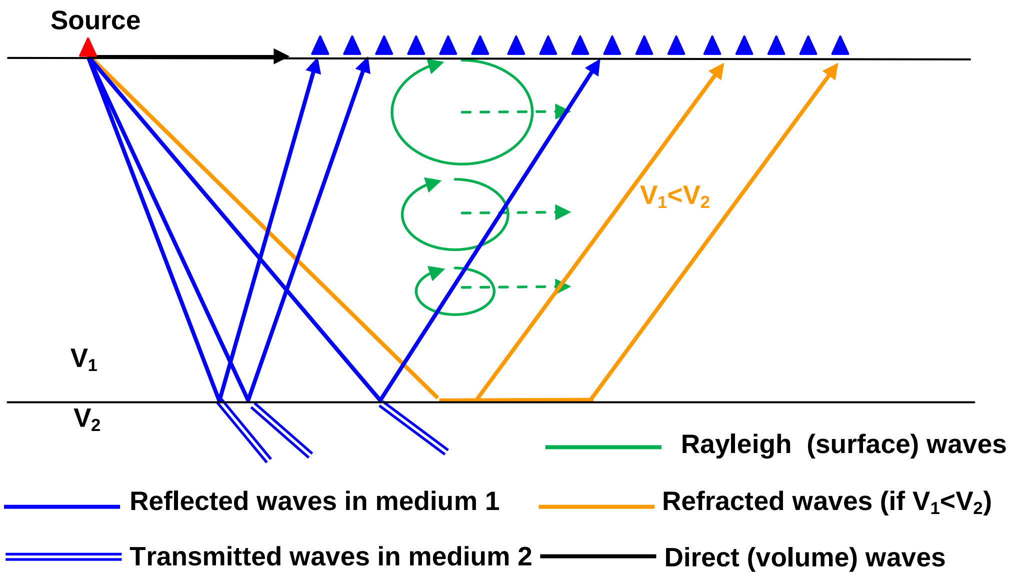


Figure 2.35 Schematic of methods based on seismic wave propagation

Seismic sources generate various types of waves depending on soil properties. The main seismic waves studied in the field of dike investigation are the refracted waves and the surface waves (here the Rayleigh waves), and less importantly, the reflected waves (Figure

2.35). The application of the latter to dike investigation has rarely been reported in literature. Therefore, the use of reflected waves will not be presented here.

The refracted waves generally occur when the distance between the source and the geophones is such that the angle of incidence of the incident waves at a shallow interface is greater than a critical angle. This angle is determined by the Snell-Descartes Law and only exists if the seismic velocity of layers increases with depth. In that way, seismic refraction is useful for determining the contact depth between the dike body and the substratum (foundation), as other methods such as *Slingram* may have much lesser depth of investigation and methods such as ERT may have lesser resolution.

The surface waves are the most energetic waves generated by a seismic source in an inhomogeneous medium. Their analysis, known as Multi-channel Analysis of Surface Waves (MASW), is based on the study of surface waves dispersion in a layered medium. Each frequency composing the surface waves travels at a specific velocity: the shallower and deeper parts of the medium respectively influence the higher and lower wave frequencies. In dike context, MASW is carried out for detecting weathered parts or voids in the dike body of foundation. Such anomalies then act as a bandpass filter in the frequency/velocity (dispersion) diagram representation provided in MASW typical results.

2.7.4.2 Measured parameter and expected results

For the seismic refraction method, the main measured parameter is the propagation time of seismic waves (head waves) as a function of the x distance (generally greater than twice the depth of the refractor interface) between the source and geophone locations. For instance, in a single layered medium (two layers of velocities V1 and V2), the picked arrival times of the direct waves as a function of x is a straight line with slope 1/V1. As the velocity increases with depth, the interface refractor generates travel time curves with lesser slope 1/V2 and crosses the y-axis (arrival time axis) at the intercept time t1. Then the critical angle θ_c is simply deduced from the ratio asin(V1/V2) and the depth of the interface can then be estimated. The expected result is a velocity map (vertical section) of the investigated medium representing the refracted wave velocity distribution as a function of the x distance and the calculated depth z (Figure 2.36). This type of result is generally based on 1-D inversion, meaning that the subsoil structure is assumed to be approximately one-dimensional.

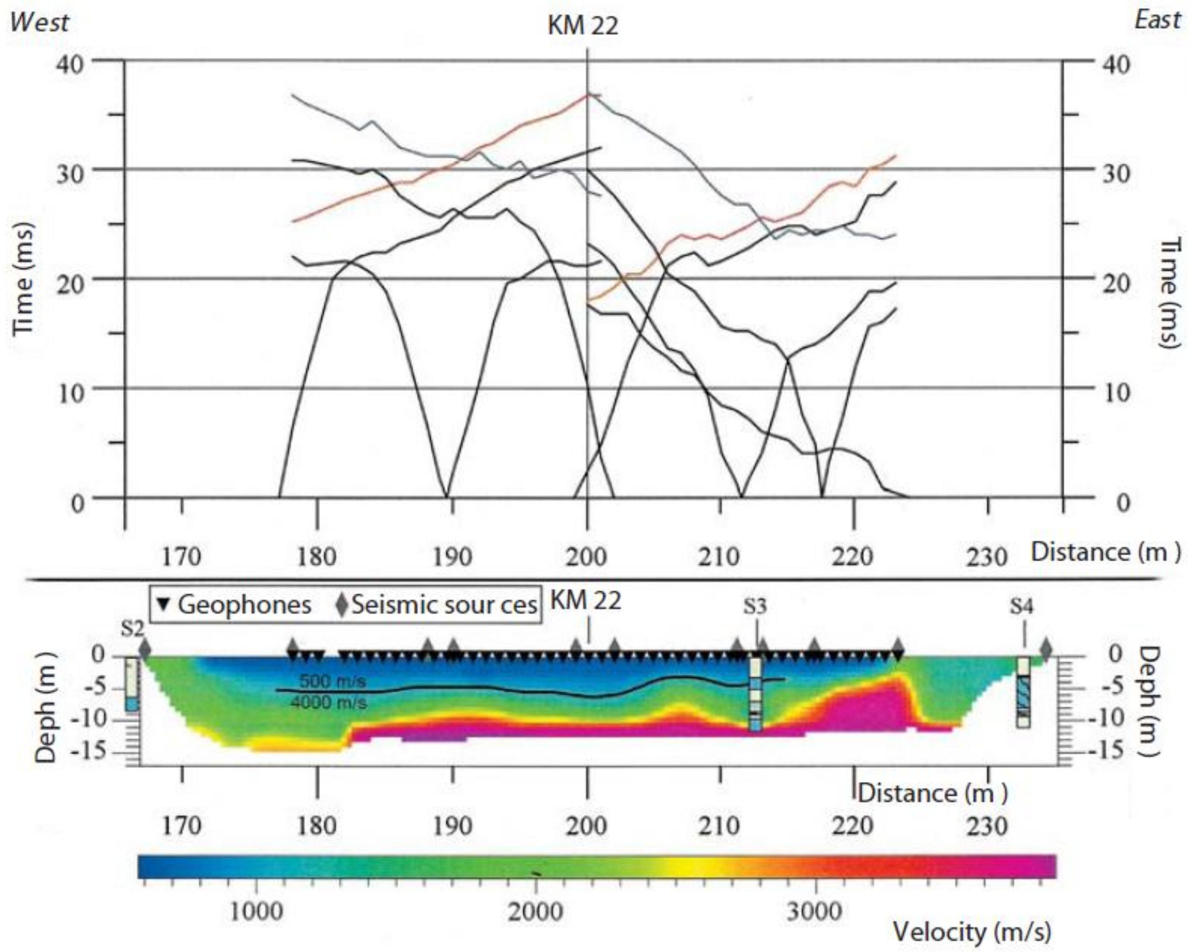


Figure 2.36 Example of seismic refraction survey results on a canal. Time-curve representation of refracted waves (top) and interpreted velocity map (bottom) as functions of distance and depth (or travel time). The interpreted contact between the dike body and the substratum (black line) was correlated with borehole data (Bièvre and Norgeot, 2005)

For the MASW method, a common shot gather is achieved at various locations along the x-profile, and the dispersion curve is calculated by using the slant-stack method, followed by a 1-D Fourier transform over the intercept time. Each dispersion curve is individually inverted into a depth/shear velocity profile. Then a velocity map (2-D contour plot of shear wave velocity field) in function of the distance x and the estimated depth z is provided. Another way to process the MASW data is to use the cross-correlation (CC) perturbation for reconstructing 2D high resolution velocity distribution, without systematically calculating the dispersion (see Bitri et al. in Coll., 2011). Figure 2.37 shows the surface-wave velocity cross-sections obtained from traditional inversion of MASW, the CC processing result and the geological interpretation.

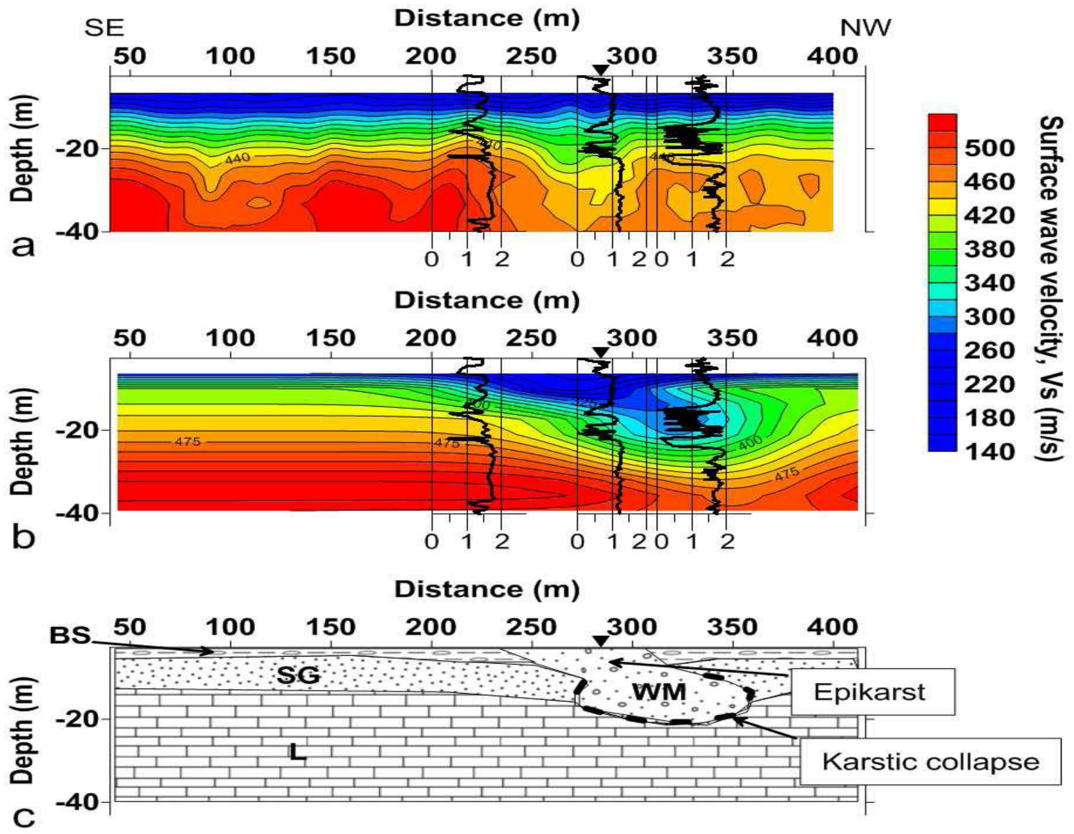


Figure 2.37 a) Conventional MASW method, b) Cross-correlation method, together with an interpreted geological section (c). The geology consists of brown silt (BS), graveled sandy alluvium (SG), limestone substratum (L). Weathered materials are marked WM (Bitri et al., in Coll., 2011)

2.7.4.3 Applicability

Seismic refraction is easily applied in rural context, and it seems that no applications has been reported in dense urban context yet. The main application is the detection of the depth of the contact between the dike body and the substratum (foundation).

For MASW, the application in both rural and urban contexts is possible with the use of specific geophones similarly to marine seismic refraction surveys. The main application is the detection of weathered parts of the dike body and voids in the foundation in karstic context.

2.7.4.4 Depth of investigation (DOI) and resolution

In principle, there is no limitation in terms of DOI for both seismic refraction and MASW methods. Field tests have shown a low-resolution estimation of the contact between the dike body and the substratum by means of the seismic refraction method when the interpreted results are given with a velocity map based on a 1-D assumption. The results provided by the MASW method appear as promising for void detection in karstic context.

2.7.4.5 Output rate

The seismic refraction method is time consuming and is only applicable to short stretches of a dike and for less than 0.5 few a day.

In comparison, MASW offers a higher output rate if it is implemented with towed land streamers (mobile geophones and source), making this technique more cost-effective than seismic refraction.

2.7.4.6 Limitations

The main limitation for seismic refraction remains the output rate of the method in the field. Although MASW has a higher output rate, this method requires high expertise for data processing and interpretation. The disturbance of dike geometry (field topography) on MASW results has been reported as negligible, although further research is needed.

2.7.5 Self-Potential (SP) techniques

By Alexandre Bolève (a.boleve@fugro.com), FUGRO Géotechnique, France.

2.7.5.1 Principle

The self-potential technique (SP) is a passive electrical method that consists of measuring the electrical potential distribution generated naturally in the ground. Self-potential signals can be recorded at the ground surface or in boreholes using a set of non-polarizing electrodes (Figure 2.38).

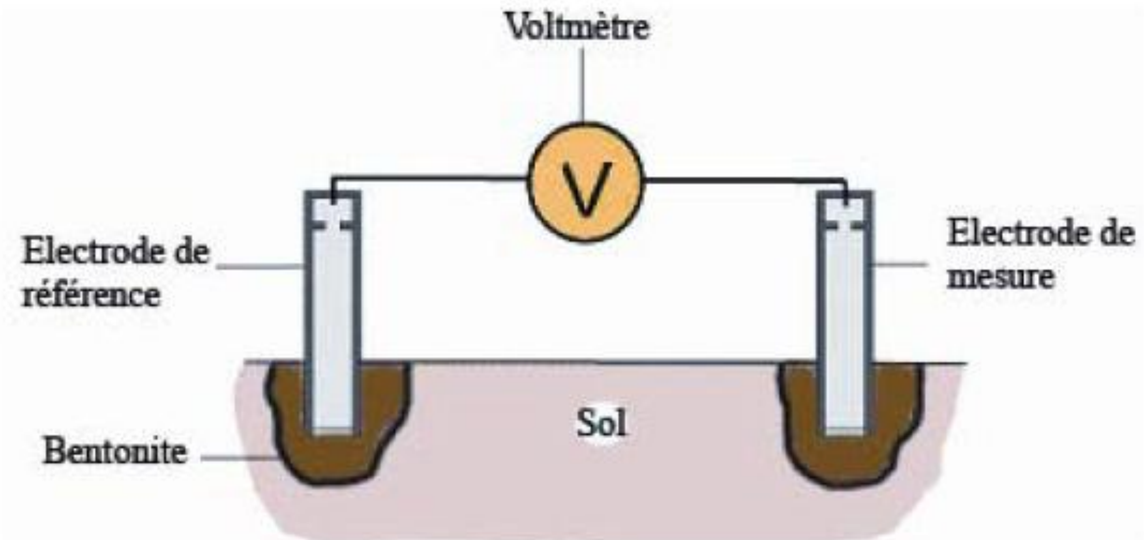


Figure 2.38 SP acquisition protocol using: a reference electrode, a mobile electrode, bentonite clay for plugging the electrodes into the ground surface and a voltmeter

2.7.5.2 Measured parameter

The physical measured parameter is the passive electrical potential of the ground (V). There are two main sources of passive electrical potential in the ground: (1) electro-redox and (2) electrokinetic sources. (1) Electro-redox sources are generated by oxydo-reduction phenomena while (2) an electrokinetic source is produced by a fluid flow in a porous medium. The electrical potential magnitude for electrokinetic sources is in the range of -100 to +100 mV (generally tens of millivolt).

2.7.5.3 Expected results

The SP data are sampled at the ground surface, in borehole or underwater according to a free mesh.

From a qualitative point of view, the expected result is a profile or map (with a colour scale) of the electrical potential distribution. The map is generally obtained with an interpolation software.

From a quantitative point of view, an inversion process allows to reconstruct the phenomenon from which the SP signal originates. The expected result is a map of the electrical current density distribution. It is obtained with a 2D inversion code that generates an electrical current density ($\mathbf{J}_s$) distribution in the ground (Figure 2.39) such that the calculated self-potential responses of this distribution, based on the given electrical resistivity distribution model, best fits the measured self-potential data.

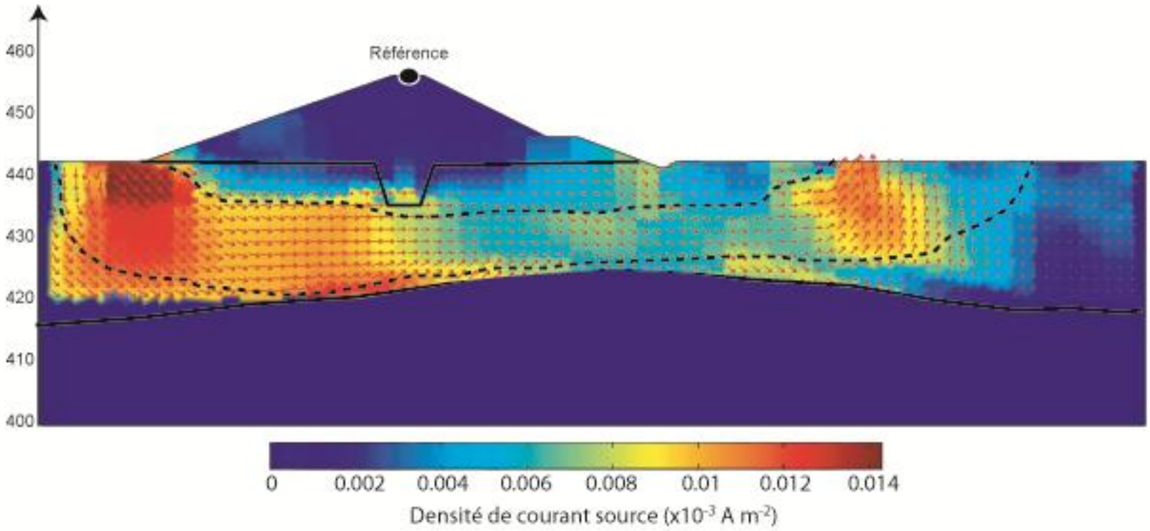


Figure 2.39 Example of 2D-SP inversion result: Vertical section of electrical current density J_s distribution

2.7.5.4 Applicability

The self-potential technique allows a variety of applications depending on the study goal and hydraulic structure configuration. The SP method is (with the exception of temperature and hydro-acoustic measurements) the only geophysical method that is directly sensitive to a flow of water in the ground.

In load conditions, SP profiling on the water side of the dike (by dragging non-polarizing electrodes) based on a high frequency data acquisition, provides a quick overview of water inflow locations (seepage areas) over several kilometers of dike length.

2.7.5.5 Data quality

In case of SP profiling, to insure data quality and because SP signals are sensitive to any electrical current perturbation, one way and return acquisitions are recommended to check data reproducibility. In case of SP mapping, some measurement stacking is recommended.

2.7.5.6 Output and reliability

Interpretation of SP profiles and maps in terms of leakage detection needs to be confirmed by other studies (temperature measurements for example) or direct observations.

Because the SP inversion process is an under-determined problem and depending on available electrical resistivity information (e.g. obtained by ERT), the inversion and interpretation should be done carefully. Final SP inversion result is one of many possible solutions and consequently needs to be confirm (or not) with other studies (drilling, borehole temperature data acquisition, etc.).

2.7.5.7 Limitations

Due to the method sensitivity to electrical perturbation and water salinity, SP techniques must be used cautiously in urban and costal contexts.

When applied to embankment dikes for detecting anomalous (seepage) areas, SP techniques applicability is limited to load conditions (flooding, high tide, or dikes submitted to permanent hydraulic head).

2.7.6 Ground Temperature Sounding and Tomography

By Barbara Heinemann and Jürgen Dornstädter (dornstaedter@gtc-info.de), GTC Kappelmeyer GmbH, Germany.

2.7.6.1 Principle

The existence of a reliable method for the detection of internal erosion is indispensable to anticipate the failure of embankment dams and dikes. Using the temperature of seepage water as a tracer, a reliable method is to monitor the in-situ temperature of the dike body. If different from ground temperature, the temperature of seepage water operates as a tracer and, when percolating the dam or dike body, provokes temperature anomalies within the fill-dike body. Because ground temperatures are lower than the temperature of retained water during summer, percolating water in the dike induces positive anomalies to the temperature distribution of the embankment. The contrary phenomenon appears during winter. As ground material has a low heat conductivity, temperature anomalies develop as soon as the pore velocities exceed 10-7 m/s.

A reliable localisation of seepage zones is provided by applying the technique of temperature probes installed on an array along the embankment crest as shown in Figure 2.40 andFigure 2.41 (Dornstädter, 1997). The probes are pulled off the ground after completion of the temperature measurements. The tomography is obtained by interpolating the temperatures measured in the temperature probes which set up a vertical section of the embankment.

For using the temperature of seepage water as a tracer, water retaining structures as dams, dikes or levees must be under water charge for a certain time. Due to the low heat conductivity of ground material, the temperature anomaly provoked by seepage water is recognisable within a time period ten times larger than the duration of the occurring high water level during a flood (memory effect). This phenomenon provides the opportunity to apply the technique of ground temperature measurements to embankement dikes and levees.

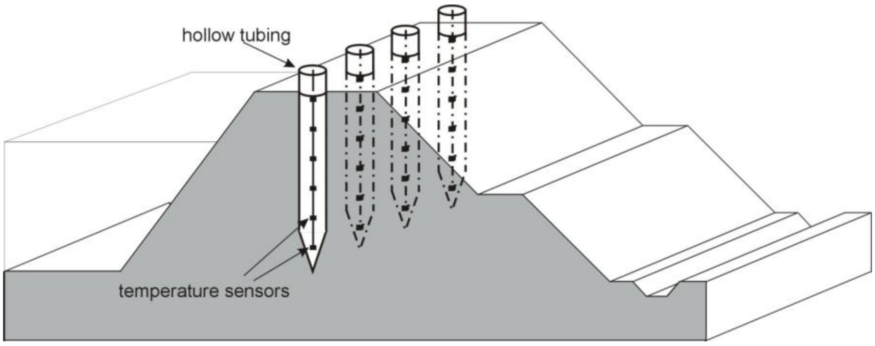


Figure 2.40 Schematic sketch of the ground temperature technique

Figure 2.41 Installation of an array of temperature probes along the embankment crest

2.7.6.2 Measured values and expected results

The measured parameter is the in-situ ground temperature. The measured temperatures are immediately mapped on a vertical section along the considered embankment as shown in Figure 2.42. Anomalies in ground temperatures indicate seepage zones. Vertical and horizontal boundaries of seepage zones are localised directly on site.

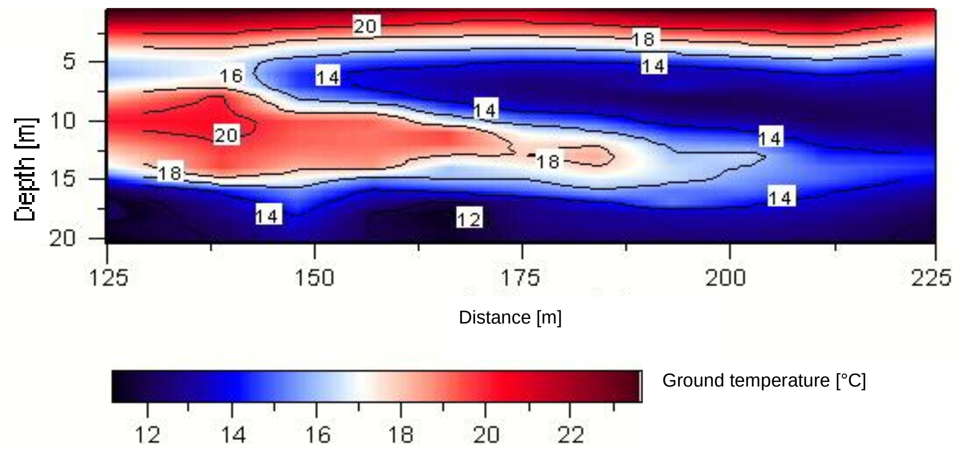


Figure 2.42 Temperature tomography along a vertical section of an embankment

Repeated surveys allow the evaluation of pore velocities at the location of the probes. Figure 2.43 shows for a water retaining embankment perturbations of ground temperatures versus time at different depths induced by seepage flow at depth. The temperatures of the water reveal temporal variations which reappear in the trajectories measured within the seepage zone, more or less attenuated dependency of the flow distribution. The pore velocity at a measurement point is estimated by dividing a suggested length for the seepage path by the identified time shift between an evident variation detected in the graph of water temperatures and in the trajectory of ground temperatures (Dornstädter and Heinemann, 2012; Garandet et al., 2012).

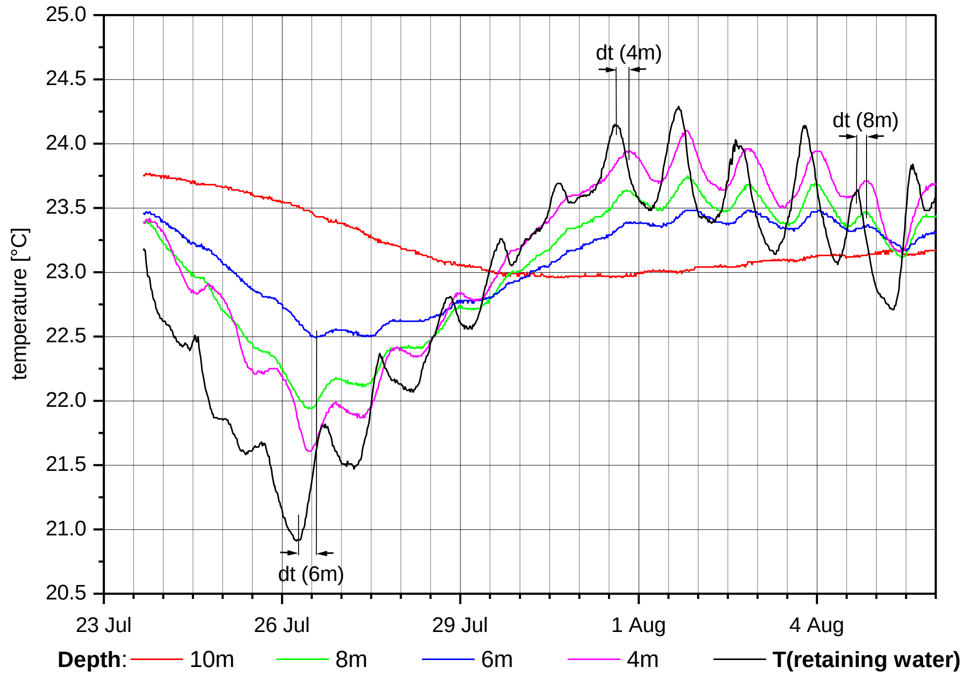


Figure 2.43 Temperature versus time at different depths for seasonal and daily variations

The integral of the estimated velocities obtained for each measuring point on the vertical section reveals a quantitative discharge through the considered section.

2.7.6.3 Applicability, depth of investigation and resolution

This technique provides temperature measurements in sediments and embankments down to depths in excess of 30-40 m. Chains of temperature sensors generally spaced at 1 m intervals are inserted in the tubes.

Investigations show that an average probe spacing of 20 m is sufficient to detect temperature anomalies in sand and gravel in a first step. The lower the permeability of the material, the narrower the probe spacing must be, e.g. a spacing of 10 m is recommended in silt. As the measured temperatures are immediately mapped on the field-computer, the initial spacing of the temperature probes can be reduced where temperature anomalies are detected.

2.7.6.4 Output rate

Depending on the subsoil composition, the ramming of the probes into the ground and the pulling of the tubings off the ground may be more or less time consuming. Likewise might be the needed adaptation time of the tubes temperature to ground temperature. Dikes and levees are commonly earthfill structures and ramming into earthfill embankments is comparatively easy.

In these conditions a team of five manipulators manages to work through an array of about 1 km length (51 probes of length 5-6 m and at a spacing of 20 m) in one day. The method has proven practical applicability, reliability and cost effectiveness.

2.7.6.5 Limitations

The levee (dike) has to be under water load for a while (minimum 1-2 days) to allow ground temperature anomalies to develop.

The investigation is possible within a time period ten times larger than the duration of the flood, and the method is applicable in urban areas.

3 Using Helicopter Borne LiDAR to Contribute to Levee Assessment - Experiment on “Val d’Orléans” Pilot Site

3.1 Topographical data is essential to levee assessment

3.1.1 Levees in Urban Areas

In urban areas liable to flooding and riparian to a watercourse, an insufficient right-of-way usually led to the building of flood protection dikes immediately next to the river. Such levees are then protected on the watercourse side by **a wall or a masonry facing** made of stones or concrete and based on a secant or sheet pile cut off. This type of composite work (embankment and masonry) is subjected to the same pathological mechanisms as previously described; the rigid structure on the watercourse side is itself exposed to specific break mechanisms (e.g.: sloughing, overturning, etc.) or damage mechanisms (e.g.: slump, cracking, wear, erosion, …) that undermine its protective function.

In a number of towns riparian to watercourses, some districts are built, sheltered from floods, down a higher land or on a topographically high area of the flood plains (such area is referred to as “mound” in the Loire Valley). In front of such areas, the levee is often replaced with **a quay wall.** Although this structure remains subjected to specific pathological mechanisms (overturning on the river side at fall of the water level, erosion or face cracking, undercutting or under-sampling of fillers within the foundation, etc.), it no longer works as a water retaining structure but rather as a protective or supporting structure for the bank and infrastructures located thereupon (road, harbor facilities, buildings, etc.). It appears difficult to draw up a assessment process (or in-depth diagnostic) for this type of hydraulic works in urban areas since the high level of density in terms of housing and construction often precludes a clear understanding of the actual work: a levee, strictly speaking, a composite structure or a mere quay wall. In addition, transition areas between the levee and the quay wall - located up and down the topographically high area(s) and sometimes hardly identifiable, as indicated above - are just so many structural weak spots with regard to pathological mechanisms, including internal erosion. Indeed, most of these areas - which shall hereinafter be referred to as interfaces or transitions – have been settled a very long time ago, and no specific construction plans thereof are available.

3.1.2 High Resolution Topographical Data Required

All four damage or break mechanisms, as outlined above under Section 1.1, are more or less strongly connected to topographical items in relation to the levee (See Table 3.1 below):

- From the one part, because topographical irregularities have produced them, contribute to them or make them worse;
- From the other part, because they change the structure topography or environment due to their direct or indirect effects.

Topographical Items / Mechanisms	Aggravating Topographical Irregularities	Effects On Topography
Internal Erosion	. Narrow levee cross-section (too low height/width right-of-way ratio at levee bottom). . Crossing works in operation or disused within the levee body or foundation: identified by their inlets, gates, sight holes or adjoining pumping stations. . Interface or transition areas between two different types of levees. . Trees[3].	. Sink hole. . Slump on the top or slope. . Potential temporary leak sealing works (e.g.: stacked sandbags).
Overflow	. Points or lower areas on the levee top longitudinal profile. . Tightening of levee-limited flood plains (raising the flow line during floods).	. Levee top, slope or toe erosion on the land side (in the event of a proven overflow). . Temporary raising or shut-off works on top.
Sliding Slope	. Steep slope. . Narrow levee cross-section	. Slope irregularities, widening or slides. . Wall tilting.
External Erosion	. Steep slope on the river side. . No protection wall on the river side . Irregularities, structures sticking out of the face	. Eroded bends (vegetation gone). . Sliding slope (see above). . Undercuttings (only visible from underwater topography).
Proven Breach (background)	/	Depression or pond at levee bottom on the land side (former breach scour hole).

Table 3.1 Connections between Topography and Levee Damage or Break Mechanisms

[3] Trees and woody vegetation are typically identified and localized on topographic plans (except for large digging animal lairs which are also a major cause of internal erosion).

Acquiring, and subsequently analyzing, an accurate and exhaustive topography of the levee and its environment will efficiently contribute to producing an in-depth, valuable and reliable assessment (or diagnostic).

Topographic campaign deliverables typically include:

- Longitudinal profiles;
- Cross-sections with uniform screen density on specific areas;
- Topographic plans;
- Topographical items related to flood plains.

These will be consecutively reviewed hereafter, and their contribution to the assessment process will be pointed out.

3.1.3 Levee Top Longitudinal Profiles Against Maximum Headwater Level During Floods

Overflow often leads to the formation of breaches. Such a risk may be assessed by comparing flow lines during floods and the levee top profile.

Therefore, an accurate topographical survey of the levee top will help determine the freeboard available against the flood from which a protection is sought (a so-called protection project flood), and highlight all sections where the freeboard would be inappropriate. For lack of any hydraulic study, an analysis of the levee longitudinal profile will be sufficient to identify, in a first step, all points and lower areas where the overflow should start in the event of a major flood. Such a piece of information is important to define potential protective or preventive measures.

If there is a raising linear earth ridge or parapet (called "banquette" in the Loire Valley) on the crest of the dike, the longitudinal profile should also be surveyed on the same basis as previously indicated.

3.1.4 Cross-sections

During floods, the levee is designed for maintaining the difference in water level between the levee-limited bed and the land. Apart from the overflow, the failure mechanisms to watch out for are piping (internal erosion) and instability of the slope on the land side during flood and on the river side when the water level falls. In either case, the risk analysis requires good knowledge of the levee cross-sections so as to build up their geometrical model. Geophysical and geotechnical explorations aiming to identify and quantify any material, mechanical strength and permeability heterogeneities within the levee and its close foundation shall indeed provide for the essential and complementary information on the structure internal construction, that are necessary as numerical models for calculating the stability or resistance to internal erosion (see D3.1).

Ideally, the cross-sections should cover about twenty meters on both sides of the levee toes, including underwater on the river side if the levee touches the low-water bed. The latter would then require specific survey techniques: sonar bathymetry, bathymetric Lidar, etc.

Cross-sections also provide basic data for potentially necessary reinforcement study (stability calculations with reinforced levee, representation of reinforcement works).

3.1.5 Topographic Plan

Drawing up a topographic plan on a large scale (typically 1:500) proves to be particularly useful when the levee comprises a great number of irregular points. Such a document, for which one shall ensure the limits will overflow by at least twenty meters on both sides of the levee toes, may be used according to the following stages:

1. Highly detailed preliminary identification of the levee, especially when no high resolution aerial photographs are available;

2. Visual inspection preparation: the levee external construction and spatial variables are pre-identified and thereby will help plan for the field study stage and the material to be carried along (type and number of survey sheets, selection of small equipment, etc.);

3. Accurate location of geophysical and geotechnical investigations **before and after** prospecting and sounding;

4. Reporting all information from field study stages (visual inspection, geotechnical investigations).

Topographical data is also useful for:

- Performing a cartographic summary of the assessment process (plan view) ;
- Locating the reinforcement works: on cross-sections and plan view ;
- Checking whether new levee or reinforcement of levee was constructed according to design plans.

3.1.6 Flood Plain Topography

The flood plain topography between the levees is required for performing hydraulic calculations of flow lines during floods. With regard to the geomorphological study, such topography will help calculate the flow velocity along the levees, and thereby assess hydraulic loadings on the river side faces, and contribute to calculating the potential undermining depths. It shall also prove to be useful to describe alluvial deposits and islets found in the waterbed. However, the change in such deposits – which is important for drawing up a geomorphological diagnostic - may be assessed only using consecutive aerial photography campaigns or by repeating topographic campaigns several years apart.

As for the protected flood plains topography, it should provide basic data for performing hydraulic calculations of a slow flooding by backing up or spillway (existing or to be created) or of a flood wave resulting from a simulated breach, with the results thereof being subsequently made available on GIS as public information material. It will also help the geomorphologists identify and specify all topographically high areas or mounds.

Decimeter accuracy is usually sufficient for acquiring and using topographical data in flood plain.

3.1.7 Conclusion on the importance of topographical data

Topographical data is essential to any levee assessment; mostly when the survey technique used helps produce large scale or high resolution documents: theodolite land survey with high point density or high resolution Lidar. This report shall later describe the existing remote sensing techniques that may be used to acquire accurate topographical data on large surfaces and with high-level output on the field.

3.2 Remote Sensing Technologies Contributing To Levee Assessment

3.2.1 Remote Sensing Overview

Remote sensing, in its broadest sense, refers to measuring or acquiring information on a specific object or event, using a measurement instrument that is separated from the object. It refers to the use, from a distance (for instance an aircraft, a spacecraft, a satellite or a boat), of any type of instrument capable of acquiring information on the environment. Instruments such as still cameras, lasers, radars, sonars, seismographs or gravimeters are frequently used [source: techno-science.net].

For the study of alluvial valley environments and structures, the most frequently used techniques include:

- aerial photography or satellite imagery;
- mono- or multispectral photogrammetry;
- traditional Lidar and bathymetric Lidar;
- radar;
- high resolution infrared thermography;
- sonar.

These various techniques, either passive (photography, thermography) or active (Lidar, Radar, Sonar), and their potential applications to levee assessment shall be outlined in a summary table at the end of this chapter (Appendix 3.1) and Lidar technologies shall subsequently be described in further details.

3.2.2 LiDAR

3.2.2.1 Definition

LiDAR (Light Detection And Ranging) is an “active” remote sensing technique based on light transmission from a transmitter/receiver. The light is partly radiated or absorbed into the target environment while the remaining light is backscattered towards the receiver. The technique is based on measuring the lengths between the laser source and the object or environment (typically the earth surface). The signal is transmitted from a laser fitted on an airborne (helicopter or airplane) or a ground platform. The signal wavelength ranges, depending on applications, from 500 nm (e.g.: bathymetric Lidar) to 1,550 nm, that is with a close infrared signal (e.g.: Airborne Laser Scanning).

The Lidar technique is efficiently used in various applications: for instance to study river valleys (Comes-Pereira & Wicherson, 1999), woodlands or farming areas (Haugerud & Harding, 2001), the changing coastline (Collins & Sitar, 2005), slope stability (Collins & Sitar, 2004), linear works or infrastructures (access roads, electric lines, levees) or to perform explorations on volcanoes (Kayen et al, 2004).

3.2.2.2 Airborne LiDAR

The laser system is carried onboard an airplane. Traditional ground resolutions are provided in decimeters with densities amounting to a few points per square meter. This type of Lidar survey is now commonly used in France for acquiring topographical data on river valleys, and gradually for studying coastal areas.

Very high over-flights (up to 6,000 m) were impossible until recently. They help cover very large surfaces although the point density on the ground (< 1 point/m^2) and measurement precision are far lower than at lower altitudes. In addition, at such an altitude, the airplane velocity is usually higher and the signal greatly reduced from crossing the atmosphere.

3.2.2.3 Helicopter-Borne LiDAR

Specifically in mountain areas where low altitude over-flight by plane proved difficult, airplanes have been gradually replaced with helicopters to take the Lidar system on board. Generally speaking, helicopters offer the advantage of flying at lower altitudes and slower paces, allowing the measurement of high point densities on the ground (> 50 points/m^2). On the contrary, the scan swath (that is, strip or corridor width as measured on the ground) is narrower and, if necessary, several adjoining return flights are to be planned to cover a given surface according to the flight height: the helicopter-borne Lidar technique is indeed particularly suitable for performing surveys or following up linear infrastructures such as access roads, electric lines or levees.

Finally, at least in France, flight clearance procedures are less restrictive for helicopters than airplanes from the moment that the flight altitude above the ground remains under visual flight conditions (< 1,000 feet). However, it should be noted that flying over built-up areas may be subject to local restrictions.

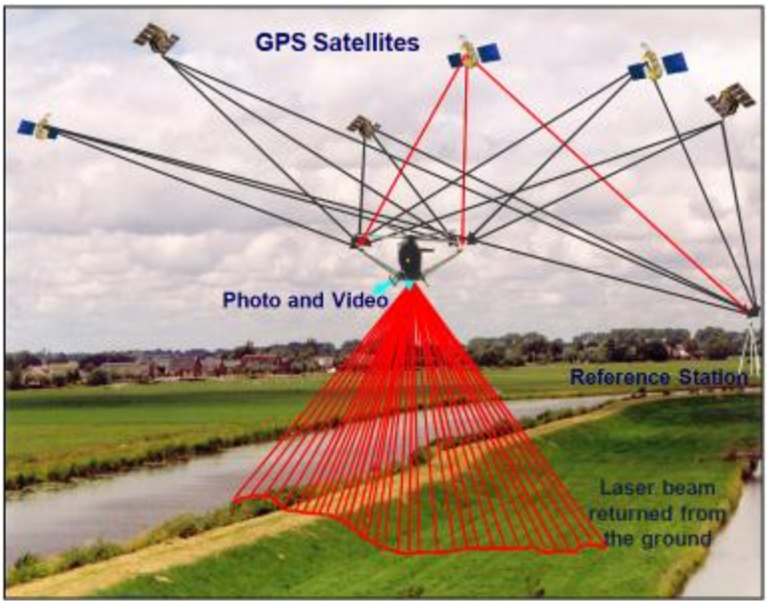


Figure 3.1 Helicopter-Borne LiDAR Acquisition Principle [source: Fugro-Geoid©]

In the Lidar-Flimap (Fugro-Geoid©) high resolution technique as implemented on FloodProBE pilot site in Val d'Orléans, the laser performs three scans forward, nadir and backward, respectively, on the helicopter (Figure 3.2). This scanning feature provides for an improved coverage of the overflown area; the signal may indeed reach items on the ground that are partially covered (for instance by vegetation), which would otherwise be impossible with a unique vertical scan plane. The Flimap system offers a specific feature which consists in the Lidar acquisition being associated with high resolution aerial photography and high definition video recording.

The flight path and laser source position can be known using onboard GPS systems.

Therefore, coordinates for each point surveyed on the earth surface may be calculated by determining the helicopter position and the distance and direction between the scanner and the measured point. Thanks to an inertial unit, helicopter movements may be recorded and induce subsequent post-process corrections.

This laser system comprises three key items: a laser scanner, a GPS and an inertial unit.

- **Laser Scanner**

It is also referred to as laser radar. Indeed, this system is similar to any conventional radar (Radio Detecting And Ranging) system although, as the name implies, it sends out fine pulses - or light beams - instead of radio waves. Most systems operate within near infrared wavelengths (from 1,000 to 1,500 nm).

The measurement principle is based on recording all data stemming from the first pulse or first echo, and from the last pulse or last echo. First echo data will show, for instance, the vegetation top whereas last echo data will show the ground underneath this vegetation.

➢ **GPS System**

An onboard GPS will indicate the helicopter position at any time, and more specifically the scanner position. This will then provide X, Y and Z coordinates for each post-processed point. It is also recommended to have at least one GPS station set up on the ground, near the flight area, for improving sensor's geographical precision.

➢ **Inertial Unit**

An inertial unit is a device featuring gyroscopes, accelerometers and a computer that will calculate the helicopter's altitude and acceleration.

The point density per square meter is contingent upon acquisition frequency and flight height. With the FliMap 400 device as implemented in this study, acquisition frequency is 375 kHz. The point density is then higher than 80 points per square meter for a 150 m high flight. Such a high laser point density makes sure that beams will cross the vegetation cover and reach the ground for exploring the topography underneath the canopy (Figure 3.2).

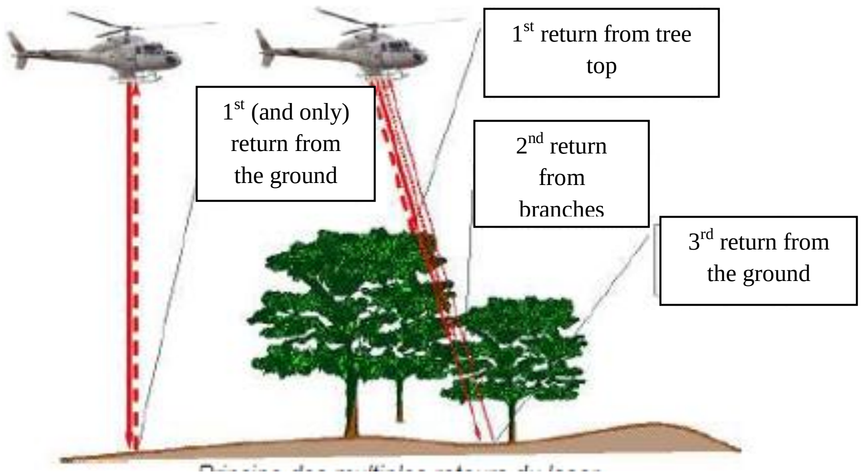


Figure 3.2 Laser Multiple Return Principle [source : Fugro Geoid©]

3.2.2.4 Land LiDAR

It is a 3D laser scanning technique operated from a scanning station fitted on the ground. This method consists in transmitting and collecting laser signals to and from surface objects in order to create a file compiling all three dimension points.

The technique may be used in horizontal or oblique sighting from multiple separate stations to survey mountain slopes, caves, tunnels, walls, etc.

3.2.2.5 Bathymetric LiDAR

The goal is to achieve underwater and land topography.

There are only a couple of bathymetric Lidar systems in the world. All of them transmit a laser beam with two frequencies: one is in the green (532 nm), so that the signal is not blocked by water, and the other frequency is reflected from the water or the ground. Thereby, both the river/sea bottom and bed bank/coast topographies are obtained, and the water level is measured.

Measurement vertical precision ranges from 10 to 50 cm, according to the flight conditions or the overflown environment.

The bathymetric Lidar remains scarcely implemented on continental watercourses (Feurer & al., 2008), since laser beams hardly ever enter turbid water; however it is used on clean water coastal areas for 3D mapping at 2-30 m depths.

3.2.2.6 Examples of Applications on Levees

As part of levee follow-up procedures, Lidar techniques were first used in the United States and the Netherlands. In France, the first experimental application dates back to 2006, to the best of our knowledge.

- **In the Netherlands: Helicopter-Borne Lidar**

As an archetypal home to levees, the Netherlands have been implementing for many years the high resolution helicopter-borne Lidar at regular time intervals so as to monitor physical changes in levee tops [bibliography to be completed]. Indeed, levee managers are required to regularly provide the State Control department with their levee top longitudinal profiles in order to confirm, for instance, that no settlement has occurred.

- **New Orleans Levees (USA): Land Surveys**

A land Lidar survey was performed on a number of levees in New Orleans (Coll. 2006) following Katrina hurricane in 2005. Data acquisition was performed over 5 days, from October 9th to 14th, 2005. Such Lidar acquisition campaign was meant to achieve precise earth surface measurements for mapping any ground movements on each site, any inconsistent levee heights, erosion areas and damages on rigid structures.

The instrument used to do so was fitted on a three-legged stand. In order to improve the imagery and make it easier to carry the instrument, the tripod was attached to a platform set on a car roof. Raising the device height by 4 m would reduce the shadow areas and increase the acquisition surface. In some cases however, the tripod was directly set on the ground or on a wall.

- **Levees in Lower Rhône River Valley (France): Recent Helicopter-Borne Surveys**

In March 2006, as part of an experimental research project funded by the Provence-Alpes-Côte d'Azur Region, a high resolution LiDAR helicopter-borne flight along a corridor was performed by Fugro-Geoid design office in the lower Rhône river valley over 50 km levees and banks covered with more or less dense a vegetation (Clément & Mériaux, 2007).

Overflown works included:

- some of the Petit Rhône levees, managed by SYMADREM (*Inter-regional Syndicate for Camargue Delta Levees*);
- the hydroelectric installation levee by CNR *(Rhône National Company)* in Vallabrègues on the Rhône river, downstream Avignon;

- the Palière levee on the Durance river, in Avignon, managed by the City of Avignon and the SMAVD *(Syndicate for Land Planning in the Durance River Valley).*

During the following year (summer 2007), the SYMADREM, since they were confident that such technique was relevant, had their entire levee fleet (about 250 km, including 5 km of urban levees and docks in Arles) surveyed by the Flimap 400 system: flying 275 m high above the ground, 30 points/m^2 density, 5 cm precision.

- **Mid-Loire Valley: Airborne Lidar**

From 2002 to 2003, the DREAL Centre had a medium resolution topographical survey performed by airborne laser over the Mid-Loire Valley, with 1 point for 4 square meters as minimum point density, each DTM grid pixel being 1 m by 1 m.

Thereby, the DREAL Centre may perform, among others, a GIS mapping of areas liable to flooding, improve hydraulic modeling and understanding of the Loire river flood plains and low-water bed, and design information material for the general public with regard to floods spreading into dales that are protected by levees.

- **Bès Mountain Stream, Near Digne: Airborne Lidar Connected with Photogrammetry**

This braided mountain river was subjected to a comparative study between photogrammetric data obtained from an orthophotograph acquisition campaign carried out in 2000 and data stemming from an airborne Lidar survey performed in 2008 in order to identify geomorphological changes, including changes in torrential deposit volume (Génin, 2009).

This site does not comprise any levees but appeared of interest in this study since it shows how relevant repeated Lidar acquisitions can be for studying geomorphological changes in watercourses with high sediment transport (Cavalli & al., 2008): this type of study may be transposed into the assessment process for flood protection dikes located along torrential rivers.

3.2.3 Summary Table

See Chart in **Appendix 3.1**.

3.3 Methodology for Using High Resolution Lidar Data

3.3.1 Val d'Orléans Pilot Operation – Overview

3.3.1.1 Pilot Site Selection

As part of FloodProBE WorkPackage 3 (Task 3.2), the very high resolution helicopter-borne laser remote sensing technology has been identified as suitable for contributing to the assessment process (topography, determination of embedded structures and vegetation) of urban and suburban levees. Such technology is not in common use until now in France and in most of European countries.

The French pilot site selected for performing and operating an experimental helicopter-borne survey over levees and related works in urban and suburban environments is Val d'Orléans.

This is one of the most challenging dales along the Loire River, with several Orléans districts or boroughs located on areas liable to flooding by the river (65,000 inhabitants).

On the selected pilot site, a railway embankment in the Loire flood plain was also an opportunity to extend the project research to linear infrastructures other than levees.

Two types of dikes stand out on Val d'Orléans left bank:

- ♦ Levees or embankment dikes, in rural and suburban areas (50 km), either touching the low-water bed (10 km), or more or less distant from the said low water-bed (40 km) with a "franc-bord" (*freeboard*) covering the area between the low-water bed and the levee. Compared to traditional dikes, the Loire river levees typically feature a "banquette" (earth ridge or parapet) on top, either on the river side or on the land side (and sometimes on both sides);

- ♦ Embedded stone or embankment-masonry composite dikes or docks in urban areas (4 km), either topped or not with parapets or curbs and including or not many singular works (flashboards, wedges, pipes or sluices).

Furthermore, other hydraulic works or embankment structures are involved in the dale operation in the event of a flood:

- Jargeau spillway, located upstream the town of Jargeau;

- Orléans-Vierzon railway embankment, including several singular works.

3.3.1.2 Specifications Preparation and Lidar Acquisition

On November 17th and 18th, 2010, Fugro-Geoid's Lidar Flimap 400 system flew over 70 km levees in Val d'Orléans (including 60 km on the left bank and 4 km in urban environment) and 6.5 km over Orléans–Vierzon railway to acquire laser topographical data and high resolution remote sensing images along a 105 m-wide corridor mainly lined up with the works right-of-way.

As this was a pilot operation, the specifications drafted for this specific assignment during summer 2010 were made relevant for all assignments and translated into English for use in other helicopter-borne laser operations as part of waterway levee in-depth diagnostics (**see Technical Specifications Template for LiDAR aerial acquisition on dike**).

The map in **Appendix 3.2** shows Flimap flight coverage by mid-November 2010. Planimetry and altimetry control surveys were performed on November 19th, 2010.

Flight Parameters

Considering the corridor mapping width (105 m, that is 52.5 m on both sides of the flight axis, typically the levee axis) and the final deliverables specific characteristics, including SDMs and DTMs, the following flight instructions were adopted:

- Acquisition system: FLI-MAP 400;
- Flight altitude: 150m high above ground level;
- Maximum speed: 65 km/h (35 knots);
- Flimap Lidar system with three scanning angles (7° forward, nadir, 7° backward) to reduce shadowing in the flight direction;
- Two high resolution video cameras 0.4 Mpixels (forward and nadir view);
- Two high resolution digital still cameras 16 Mpixels (forward and nadir view);
- Point density: > 80 points per square meter.

These flight parameters will eventually help achieve a 5 cm accuracy for planimetry and 3 cm accuracy for altimetry, in good surface conditions, regarding the surveyed points.

3.3.1.3 Acquired Data Overview

FliMap assignment deliverables include the performance and provision of digital elevation and terrain models, high resolution geo-referenced and ortho-corrected photographs and videos pertaining to works located in the corridors flown over by helicopters and, for some outstanding levee sections, a set of topographic plans on a scale of 1:500 and longitudinal profiles or cross-sections. The topographical dataset is drawn up using RGF 93 map projection system LAMBERT 93. The related altimetry baseline system is NGF IGN 69 (namely “standard” altitude).

Raw Laser Points

The raw laser point density higher than 80 points per square meter helps display all visible and identifiable topographical items with an image size that is more than 1 mm on a scale of 1:500. The FliMap system features a camera built in the laser for real-time coloring of all measured laser points. Laser point color is the natural color of the object obstructing the first laser return path. There is no need to wait for ortho-photographs to read into the laser points.

Figure 3.3 Plan and 3D Views of Natural Colored Raw Points of Left Bank Abutment Area

High Resolution Photographs and Ortho-mosaic

Taking aerial photography is very helpful to identify and specify any visually indicated damages (external erosion, etc.), specific works (walls, water discharge or intake, etc.) and irregular surfaces (woodlands), and to map then on a large scale plan. These are taken with 50% overlap and are provided as JPEG files. Pixel size is 25 mm on ground. The still camera front-end set-up helps visualize the ground in perspective, which is very useful to project managers trying to analyze specific objects that otherwise might be “squeezed” under vertical view.

Based on raw vertical aerial photographs and laser data, a geo-referenced and ortho-corrected photo mosaic was drawn up for levees, docks and Orléans-Vierzon railway embankment. An index chart displays slab outlines with their identification number (Figure 3.5). Ortho-mosaics ground resolution is rounded to 25 mm. Files are in ECW format. Photographs may be viewed from a conventional image reading or editing software and on ArcGis through FliMap Analyst plug-in.

Figure 3.4 Oblique and Nadir Raw Aerial Pictures Upstream Capucins Levee

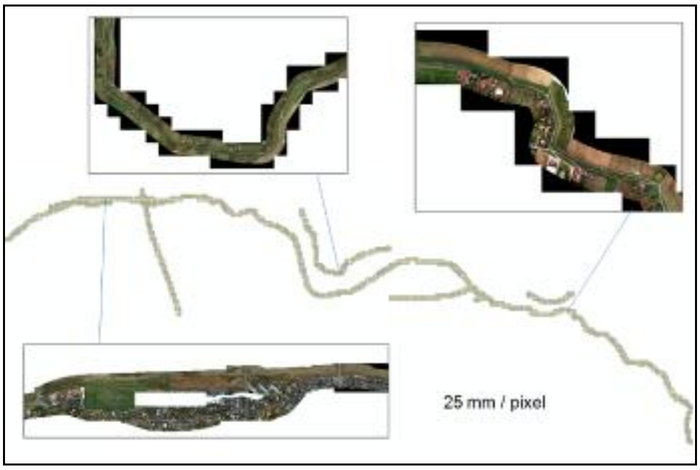


Figure 3.5 Ortho-Mosaic Index Charts

High Resolution Videos

Geo-referenced videos of levees, docks and railway embankment were produced as MPEG files. Geo-referencing may be done using FliMap Analyst software. In the manner of front-end photographs, front-end videos help identify and assess all objects in perspective.

Digital Elevation Model

General definition reminder: a Digital Elevation Model (DEM), a Digital Surface Model (DSM) or a Digital Terrain Model (DTM) is an image of a ground area topography that is adjusted as required for using such representation on a computer. A DEM or DTM (usually) uses a square regular mesh that is referred to as a grid.

The digital elevation model (DEM or SDM) contains information transmitted by the radar first echo from the vegetation and frame cover. Items such as cars and people are filtered. Underwater topography is not shown on the SDM as this type of laser does not reflect water.

For the sake of FloodProBE experiment, other SDM products were created: a no-vegetation SDM to show only the constructions; and conversely a no-construction SDM to show only the vegetation (Figure 3.6). This will help improve the constructions and vegetation analyses with a GIS.

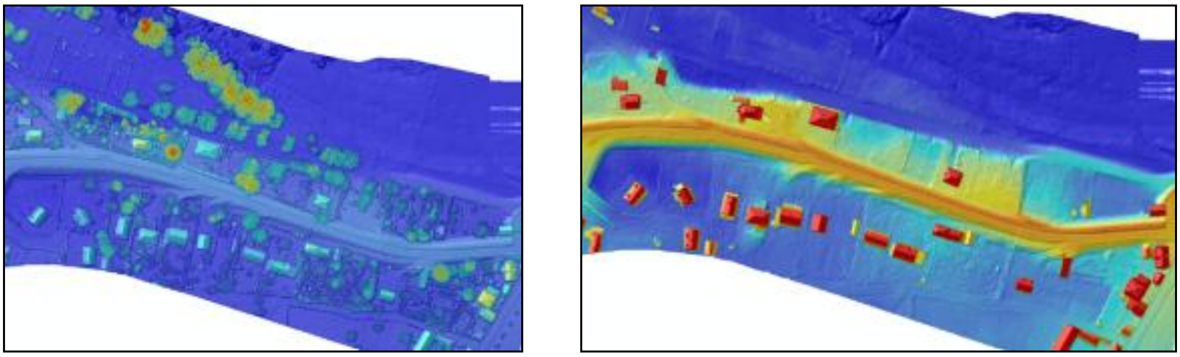


Figure 3.6 Left to Right, SDM and No-Vegetation SDM from the Same Area

Following tests performed on three types of grids (0.5 m, 0.2 m and 0.1 m screen densities) to measure information display time on a GIS, a 0.10 meter screen density was finally maintained for all three SDM products.

Digital Terrain Model

The digital terrain model contains filtered laser data to show only the topography. It includes levees and the railway embankment as well as all constituents or related hydraulic works (parapets, earth ridge, ballast).

Laser recorded data are filtered so as to remove all items unrelated to the ground topography or the hydraulic work, such as vegetation, buildings not on the levee, cars, etc. (Figure 3.7). As in SDMs, the grid mesh size is 0.10 meter.

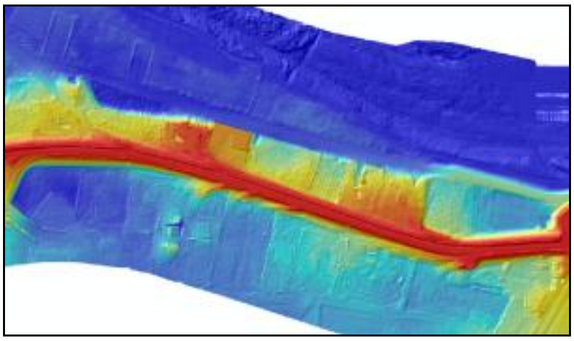


Figure 3.7 DTM of Same Area as Above

Topographic Material

Top and toe longitudinal profiles up and down the embankment, cross-sections and topographic plans were drawn up on a number of selected specific levee sections along the overflown alignment. Below is an example (Figure 3.8) with Jargeau spillway topographic plan.

Figure 3.8 Abstract from Jargeau Spillway Topographic Plan

3.3.2 Proposed Method to Contribute to a Levee Assessment

Three specific areas have been particularly studied on Val d'Orléans, which permits to suggest a method for using data stemming from Lidar acquisition and aerial imagery so as to successfully contribute to a levee assessment. Each methodological item shall be backed up with an example derived from the November 2010 Lidar operation on Val d'Orléans levees.

3.3.2.1 Operating Aerial Photographs and Videos to Explore the Levee, Pre-Identify the Areas of Interest and Pre-Split them into Sections

As a first deliverable from this operation, high resolution aerial photographs and videos of the overflown corridor are provided in oblique and nadir views.

Initial Levee Zoning

First, viewing videos helps identify a number of key items indicating the levee construction or condition: different types of works (embankment or masonry), woodland, embedded buildings or "levee toe/watercourse" junction or connection areas.

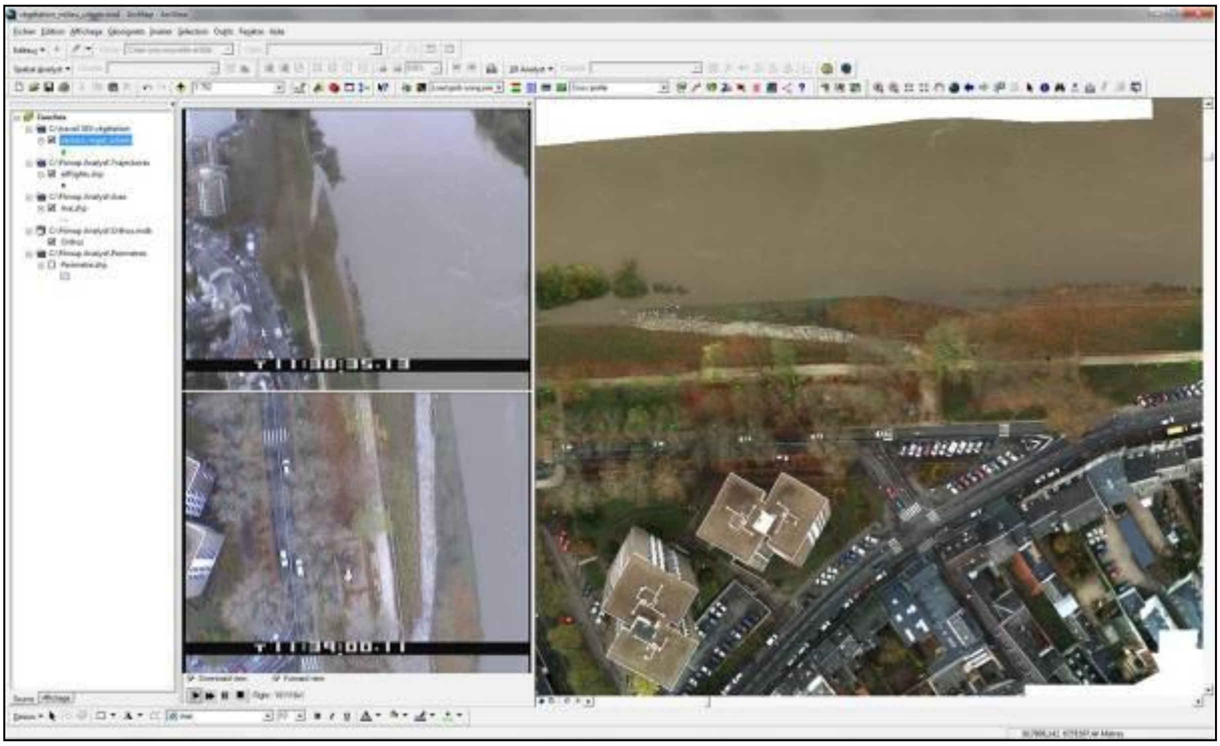


Figure 3.9 Playing Geo-Referenced Videos with FliMap Analyst Plug-In

To do so, the simplest way is to use FliMap Analyst[4] plug-in with ArcGis (Figure 3.9) to play and run geo-referenced videos.

The benefit of using videos is that it provides a quick view of the entire area to be reviewed. Video playing may be stopped at any time to observe items or irregularities, or to rewind the video. The oblique view will provide both a preview of future alignment (before switching to vertical view) and a view in perspective for a better assessment of vegetation or frame heights.

[4] DTM, SDM and imagery operating software tool offered with Fugro-Geoid's Flimap products.

Aerial photographs in Flimap Analyst are geo-referenced and ortho-corrected. Therefore, zooming in on the aerial photograph index chart (Figure 3.5) will display them. Below are examples of nadir view operations.

Figure 3.10 Nadir Photograph of a Levee with a Curb in Urban Area

Figure 3.11 Nadir Photograph of a Vegetation Block on the Levee

Concerning vegetation, due to trees extensive crown growth, it is not possible to see if some of the stumps are growing down the slope, strictly speaking. Zooming in on the photograph in the upper right corner will help identify the type of trees.

Figure 3.12 Nadir Photograph of a Farm Embedded in the Levee

Figure 3.13 Nadir Photograph of a Breach in the place named "la Brèche"

On aerial photographs, it is rather easy to identify potential former breaches: indeed, if the scour hole has not been filled following the accident, there remains up the levee toe on the land side a water pond or a pseudo-round depression, if any, as shown on the DTM.

Figure 3.14 Left to Right: Oblique Video and Nadir Photograph of a Junction with Watercourse down the Levee Toe

Special attention must be paid to this river/levee "connecting" section due to external erosion or scouring hazard.

Cross-Checking Against Historical Data

In addition to operating aerial images, historical data must be considered.

a) Breach Identification

Old maps dating back to 1856 were designed after the flood that occurred on the same year. Those include information on 1856 and 1866 floods (incorporated in the sequel): flood geographical limits, breaches indicated by an arrow across the levee, submerged levee sections and flood marker locations. Such maps are a valuable source of information for levee managers as they indicate all damages caused by the 19th century highest floods. Indeed, experience shows that a breach most often appears where a former breach has occurred and previously affected the levee.

Figure 3.15 below shows an old map of an area between the railway embankment (already existing back in 1856) and Georges V Bridge, in Orléans urban district.

Figure 3.15 Old 1856 Map Showing Information on High Floods

b) Reinforced Area Identification

Below is a reminder of the main reinforcement works that have been or are implemented on Loire river levees (Lino & al, 2000):

- Shell land side thickening, on drainage blanket;
- Sealed shell river side thickening, with cut off-based protective lining (riprap, masonry);
- Sheet pile cut off driven from the levee top;
- Creation of a bentonite-cement diaphragm wall
- Compaction by vibration (Johann Keller system) for sand and gravel sections

Generally speaking, no documents or comprehensive database compiling all reinforcement works on French levees are available. Yet, previous topographic plans indicating some of the work areas may be retrieved. The main issue is that such plans are seldom if ever updated.

With regard to Val d'Orléans, since the levees are state property, government departments (DDT or CETE) have plans that include information on the levee reinforced areas. Access to this type of information is also likely to become easier in the coming years with the development of SIRS Digues – a GIS software tool designed for levees and provided to local services.

In the absence of former topographic plans, high resolution aerial photographs may be used. However, internal reinforcement works such as sheet piles will not be visible in theory.

c) Comparison with Former Aerial Photographs

A great number of aerial photograph acquisition campaigns were carried out over the Val d'Orléans area. But former photographs are not very useful since high resolution Lidar focuses on the levee and does not include flood plains (entire dale). The former photograph resolution is too low to be compared to the current Lidar. However, these may prove helpful for river geomorphological studies, including sand bank movements. Between 1955 and 2002, no major change in the Loire flood plains horizontal alignment has been identified; bank erosions have most probably developed on a local basis but are too small to be observed and monitored on such conventional aerial photographs. Yet, this type of changes might be analyzed in the future by repeating high resolution photographic and Lidar campaigns similar to the November 2010 assignment.

Finally, former photographs help understand the changes in urbanization over time.

3.3.2.2 Topographic Plan

The 1/500-scale topographic plan is basic material used for identifying items on the ground. It serves as a support for visual observation. In exploration studies, as already mentioned (see I.3.3) the plan is used to implement geophysical and geotechnical soundings **before** and **after** they are performed, and reinforcement works later on. In addition, large-scale topographic plans are particularly useful for levee monitoring and maintenance.

Figure 16 below is derived from this topographic plan, located 300 meters downstream the railway embankment. This is an interesting area owing to constructed entities embedded in the levee body (no slope toe can be seen on the land side).

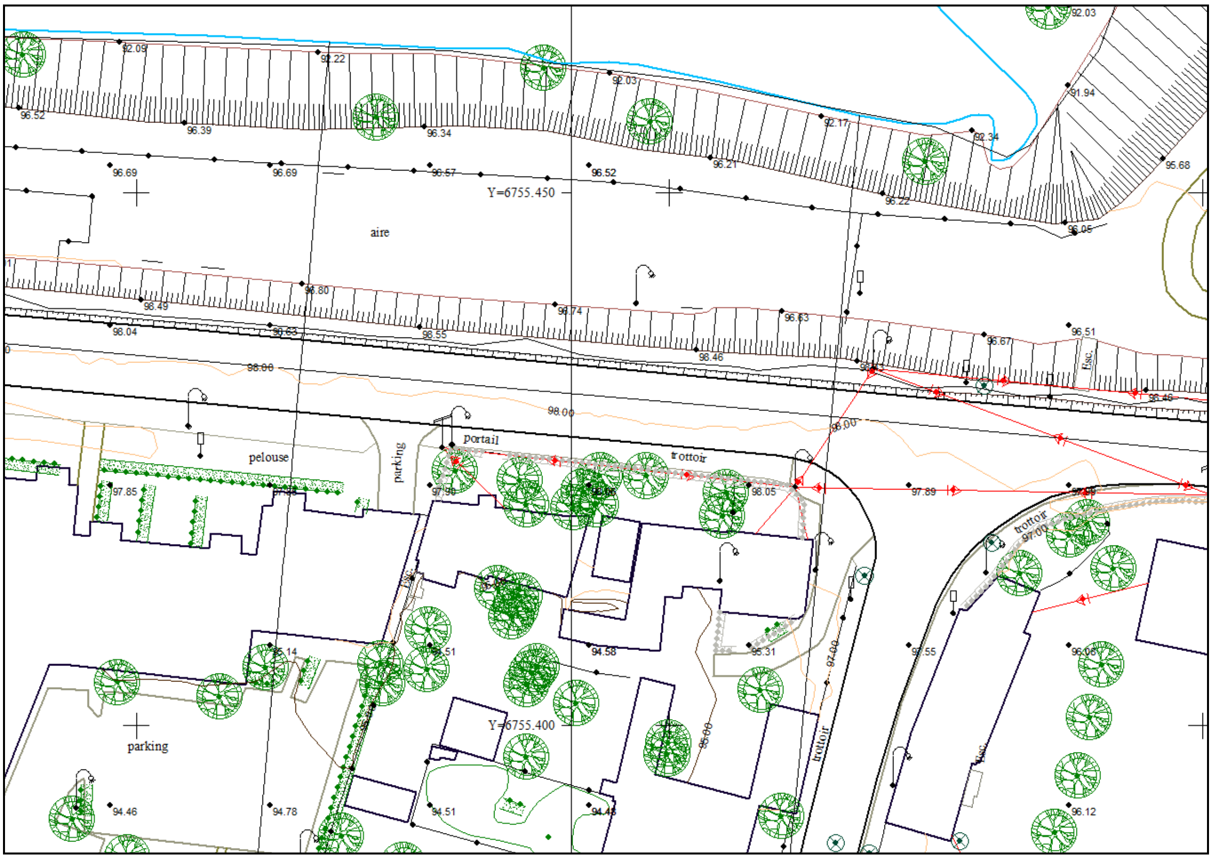


Figure 3.16 Example of 1/500 Topographic Plan on Capucins Levee

Thereby, even the smallest items are displayed (e.g.: signs, boundary markers).

A plan was drawn up using both raw laser points, DTMs and aerial photographs, **but no ground visual inspection was performed**.

Raw laser points are used to identify top lines and show regular random points on a map.

Digital terrain and elevation models undergo specific treatments (slopes, level lines) so as to display slope tops and toes, level lines, free-standing trees, constructed entities, etc.

Aerial photographs are used to identify flat items such as limits, road system or items with undetermined function (boundary marker, signs, etc.).

3.3.2.3 Using LiDAR Data to Assess Levee Sensitivity to Various Break or Damage Risks

Internal Erosion Risk

As recalled in section 3.1, the main internal erosion risk factors are as follows: buildings embedded in levees, galleries or pipes crossing the levee, woodland and interface or transition areas. The purpose is to identify such factors based on their external features and determine them from Lidar data.

a) Embedded Constructed Entities

SDM data are provided as 100x150 meter raster plates. To produce a layer showing only constructed entities, each no-construction SDM raster (including vegetation) must be subtracted from SDM (including vegetation and constructed entities).

The Raster computer feature in Spatial Analyst plug-in with ArcGis GIS software should be used to subtract both rasters: Spatial Analyst > raster computer. Select all relevant data and subtract them. A construction-only raster is produced. Colors have to be changed for a better viewing. This method calculates the construction height (in meters), not the absolute altitude which is the default unit.

Figure 3.17 shows an example of a house embedded in the levee slope on the land side (orange circle). It is located in Guilly, just before the levee separates from the river downstream. In this instance, only one house is identified.

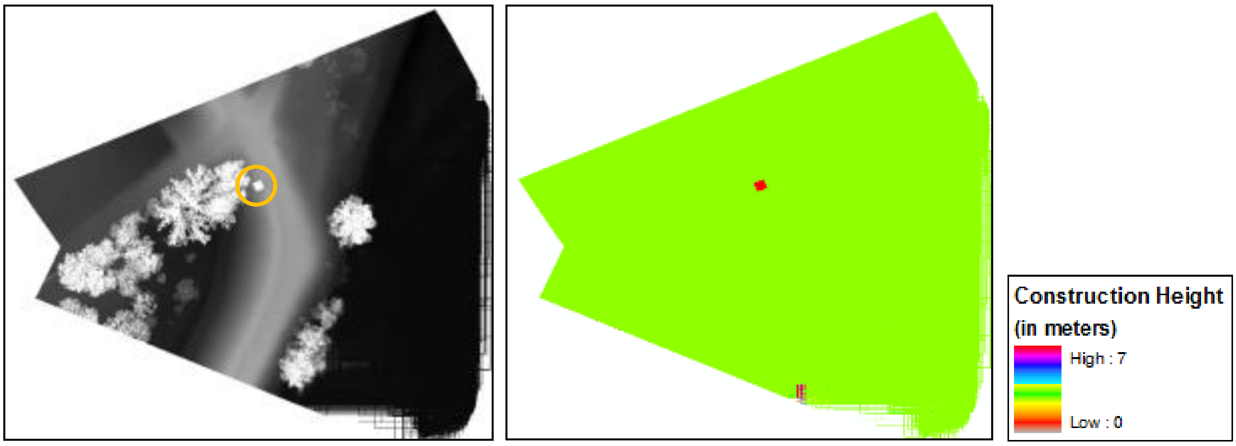


Figure 3.17 SDM (Left) Result from SDM/No-Construction SDM Raster Subtraction

Another treatment may be carried out on SDM raster to make the relief more visible: this is referred to as shadowing: Spatial Analyst > Surface Analysis > Shadowing. Figure 3.18 results from superimposing SDM over shadowing raster.

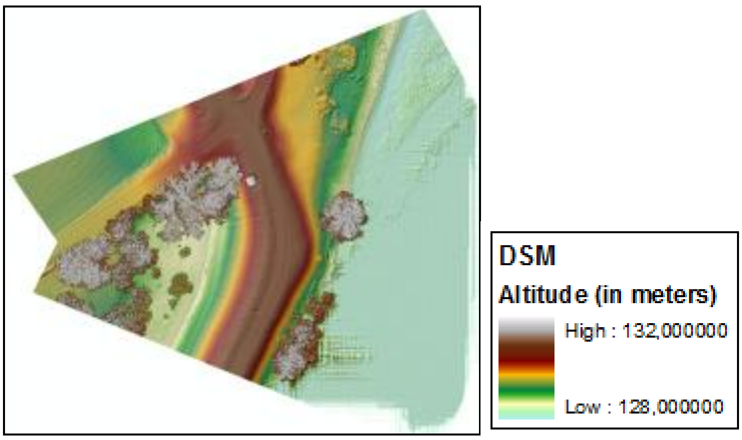


Figure 3.18 SDM with Color Shadowing

b) Crossing Works

Based on the SDM, crossing galleries or pipes may be identified by their related external works such as sight holes (concrete well, covered with a removable lid, to access the piping) or entrance works (river or land side inlet or outlet).

To identify such works, the following may be used:

- No-vegetation SDM with shadowing. Indeed, SDM will retain the works, and the absence of vegetation makes for a better viewing;
- Isolines superimposed over slope map;
- Ortho-photographs.

Let us see for example a crossing work on Capucins levee (Figure 3.19). Two sight holes appear on the left side of this work.

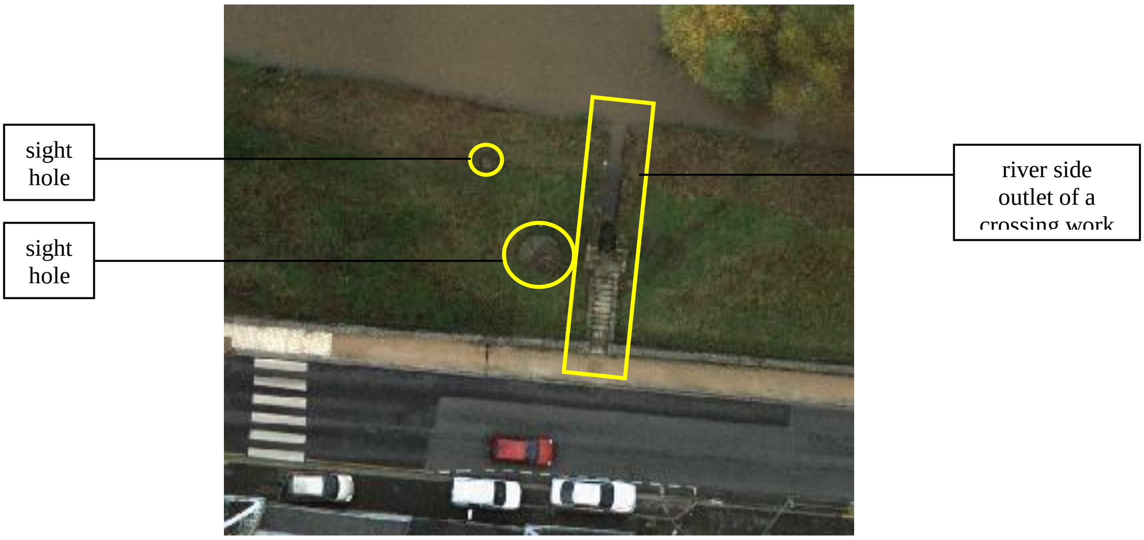


Figure 3.19 Photograph of Sight Holes and Outlet on Capucins Levee Crossing Work

A couple of different treatments were produced with Arcgis: Spatial Analyst > Surface Analysis > isolines / slope / shadowing. The following was achieved (Figure 3.20):

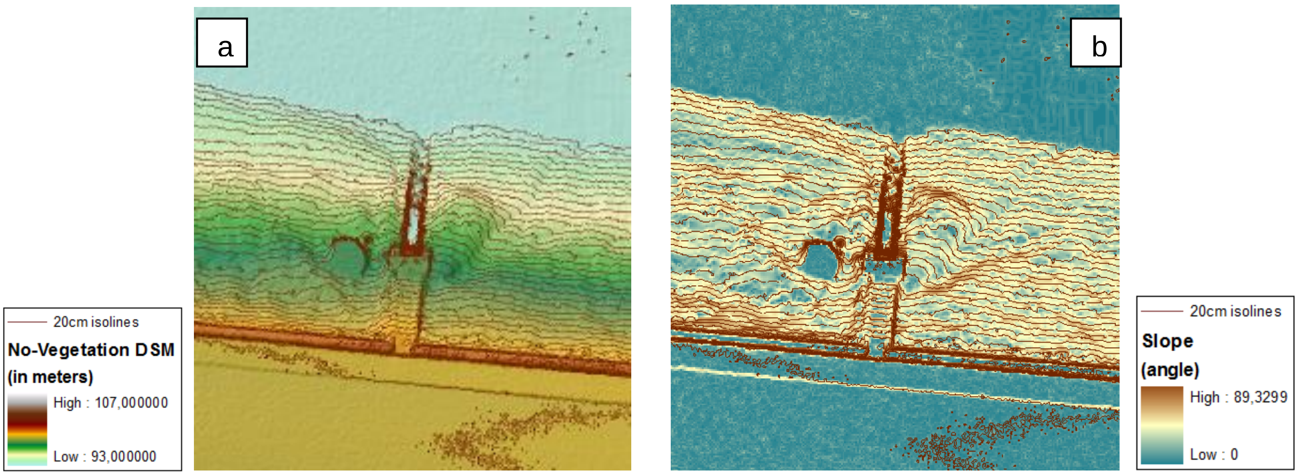


Figure 3.20 Treatments Performed with ArcGis on Figure 3.19 Area.

The two figures are isolines superimposed over SDM with shadowing (a) and isolines superimposed over slope map (b).

SDM-only does not highlight the work type. Some shadowing is required. Isolines clearly delineate the work items.

The slope color stresses flat surfaces (blue), indicating sight holes and road. Yet, when compared with aerial photograph, one item is not shown on any of these treatment figures: the sight hole in the upper left corner of the photograph.

In conclusion, priority should be given to isolines with no-vegetation SDM or isolines with slope to identify levee crossing work items, although it is essential to view orthophotographs that may provide additional information.

c) Ligneous Vegetation

Using the same process for creating the construction layer, the vegetation layer may be obtained from the raster computer: SDM (vegetation and construction) – no-vegetation SDM (that is, with construction only).

The example below is located on the Loire river right bank, in Châteauneuf-sur-Loire. Most faces on this levee area are overrun by woodland. Figure 3.21 shows the result obtained from no-vegetation SDM being subtracted from the SDM.

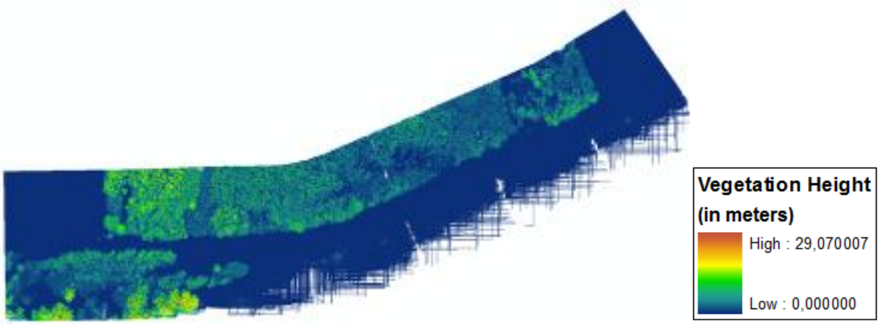


Figure 3.21 Example of SDM/No-Vegetation SDM Subtraction to Display Vegetation

Vegetation heights may be classified for a better determination of forest canopy strata or structures (trees, bushes, hedges, etc.).

d) Transition Structures

A transition is typically a connection area between two civil engineering structures or works with different construction or geometrical profiles. These may be linear, surface or gradual transitions (See D3.1). Also, they may be hidden, included but partially visible, or entirely external transitions. With Lidar technology, only **external or partially visible transition structures** shall be displayed.

To identify such structures, the following may be used:

- Ortho-photographs;
- No-vegetation SDM with shadowing;

- Regularly separated cross-sections plotted on the levee: a change in slope may also indicate a transition area.

Below are examples of transition structures on Val d'Orléans left bank levee: Cables and piping in continuous section are not displayed since the Lidar cannot cross the ground. Only surface items are highlighted. Figure 3.22 shows a junction between a wall and a house adjacent to a levee.

Figure 3.22 Photograph and SDM of Sample Transition Structure

High resolution aerial photographs help quickly identify all works on levees, junctions, changes in lining, etc. Lidar data make it possible to measure terrain elevation, which would otherwise not be possible with aerial photographs, and shadowing is required for a proper viewing of the structure geometry. No-vegetation SDM data must be used to display curbs and works included in the levee as removed in the DTM.

e) Topographic plan contribution

One of the topographic plan qualities is that it brings together all visible items from a given area (see III.2.2), and particularly structures or irregularities that are potential sources of internal erosion risk: crossing works (inlets, gates, sight holes, and pipes) trees, and transition structures.

Overflow Risk

In the matter of internal erosion, overflow is a major cause of breaches, at least for embankment levees.

a) Comparison between Flow Lines during Floods and Levee Longitudinal Profile

Overflow risk may be assessed by comparing flow lines during floods and the levee top longitudinal profile. The levee longitudinal profile can be drawn up on top of the earth ridge (levee upper point) or merely at the point of contact between the earth ridge toe and the carriageway. Indeed, earth ridges, considering the type and geometry thereof, are not to be considered as reliable with regard to a flood level that is close underneath the surface; these are wave walls. The levee safety level is therefore taken down to the earth ridge toe level or halfway across the carriageway (without regard to the earth ridge). It is relevant to compare the reference flood water level with this levee safety upper level to determine the freeboard available against the flood from which a protection is sought, and highlight all sections where the freeboard would be inappropriate.

Flow line and longitudinal profiles should be easily and accurately associated with the same level and MP repository (NGF) to analyze the reference flood water levels with regard to levee geometry.

Let us see for example the levee located on the Loire river left bank, near Châteauneuf-sur-Loire (Figure 3.23). Red dots indicate reference water levels known from 1856 flood. Unfortunately, there is no longitudinal profile of the flow line during floods available with closer points. Therefore, there are only three water level values available for this flood on a 3 km longitudinal profile.

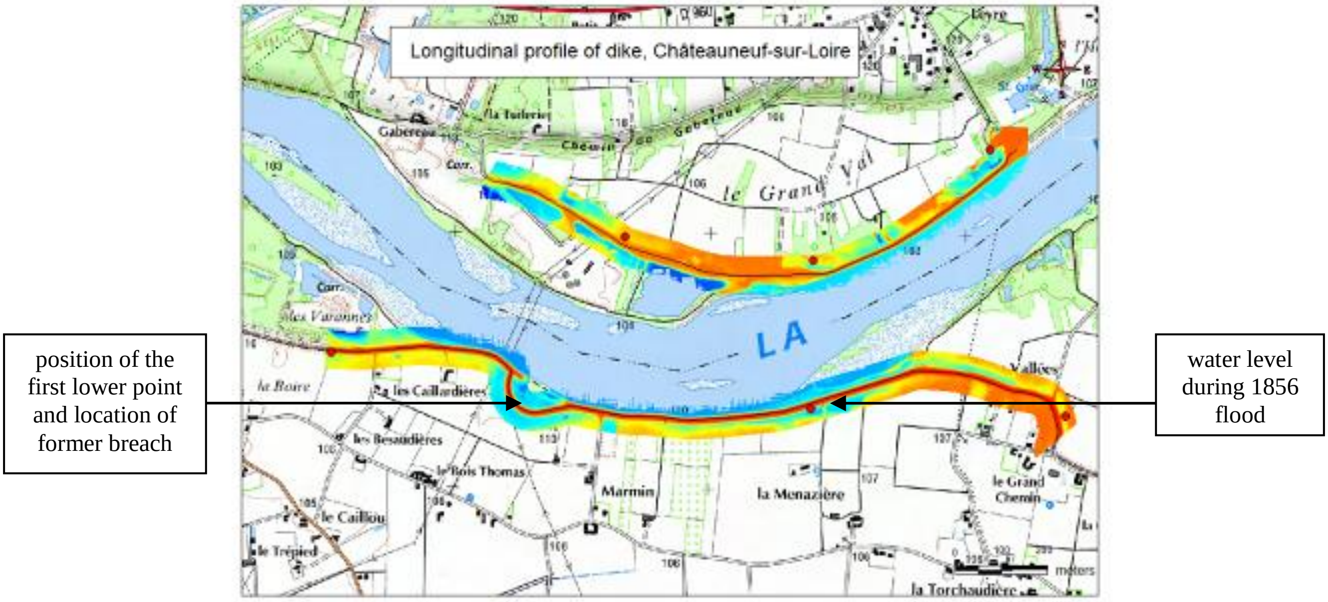


Figure 3.23 Châteauneuf-sur-Loire Location Map

The following diagram (Figure 3.24) includes the superimposed items:

- ➢ levee top longitudinal profile (halfway across the carriageway) of the left-hand side;
- ➢ 1856 flood water level (extrapolated polyline from three points).

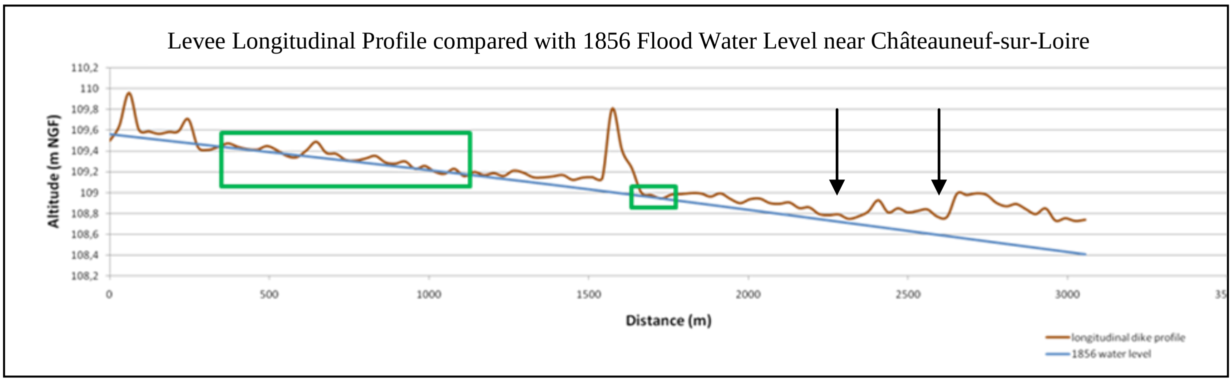


Figure 3.24 Diagram Showing 1856 Flood Water Level and Levee Profile from Point A to Point B on Loire River Left Bank

It appears on the graph that the 1856 water level crosses the levee top DTM for two sections of levee: see green rectangles between 350 - 1100 m and just after the high spot (1700 m).

For these sections of levee, the freeboard is insufficient.

Furthermore, the levee top is far above the water level just downstream the point where the levee separates from the Loire River (black ring on the map). There is a lower overflow risk at this location. However, from the name "la Boire" given to the place located down this area, one may infer that, in the past and most certainly during the 1856 flood, this area was most probably flooded by a levee overflow.

This result must be considered cautiously as the “1856 water level” polyline was drawn from 3 points only and uncertainties bearing upon this polyline are unknown.

If we focus only on the levee top longitudinal profile, we can identify lower points generating an overflow risk. Such lower points may be associated with a construction fault, the foundation settlement or anthropogenic activities. The two lower points on the graph are pointed to dark arrows. The first one (2300 m) corresponds to a former breach.

b) Settlement Monitoring through Regular Lidar Acquisitions

Potential levee settlement issues (e.g.: compressible layer settlement in the foundation) or slumps (e.g.: movements due to karstic sloughing in the foundation) may be identified only by comparing topographical data recorded over time. These types of movements usually change, at a more or less slow pace, over several years. In order to identify and follow them up, high resolution Lidar acquisitions should be repeated at regular intervals, every 2 to 5 years for instance. Follow-up processes of this type are applied to levees in the Netherlands.

Instability Risk

a) Low Levee Width and Steep Slope

It should be reminded that there is an overall instability risk on any one of the levee faces when several factors are brought together, particularly with a narrow levee cross-section and steep slopes (over 0.65% angle or batters lower than 3H/2V). Such adverse factors are quite frequently observed on former breach areas due to rush repair works.

The example shown on Figure 3.25 is located on Val de Bou levee, on the right bank, where the levee comes close to the Loire river. A breach occurred in 1866 a little bit further upstream. The right-hand figure shows the slope treatment produced on the raster, highlighting the relevant critical cross-section (slope on the land side > 0.65%).

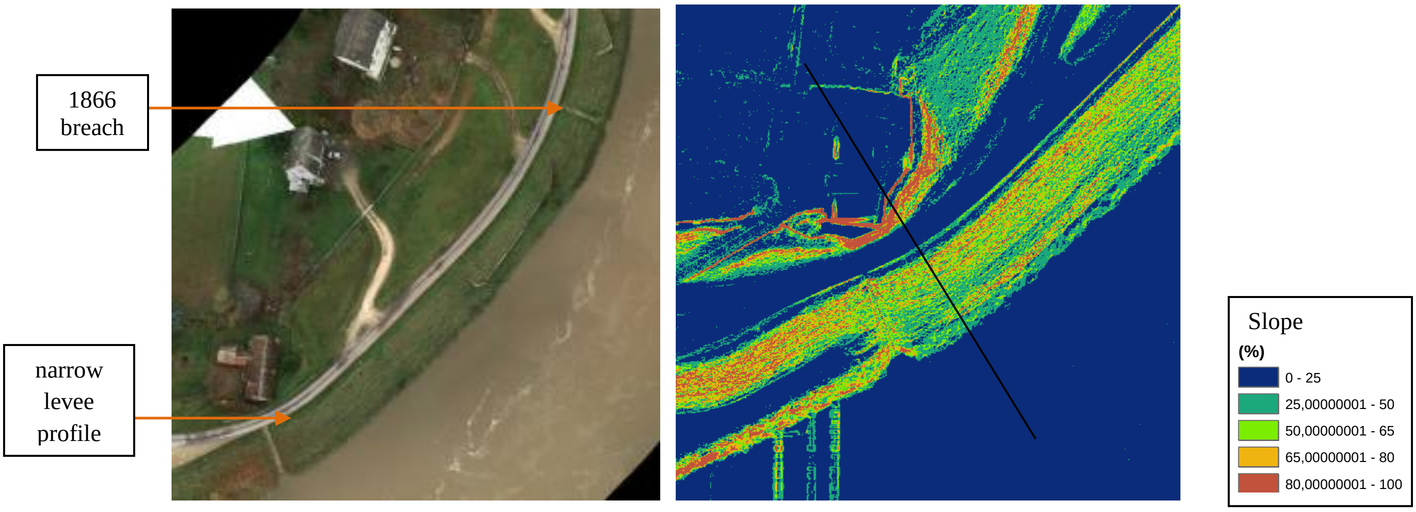


Figure 3.25 Example of a Narrow Levee Profile on the Loire River Right Bank, in Val de Bou

The house embedded in the levee slope on the land side makes the levee cross-section narrower. The black line on Figure 3.25 indicates the cross-section drawn up with FliMap Analyst (Figure 3.26).

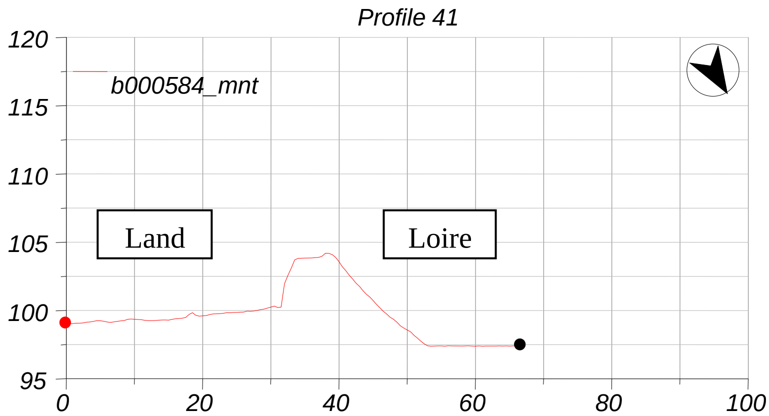


Figure 3.26 Cross-Section along Black Line (Figure 3.25)

The land side slope is steep and the top is rather narrow. Such irregular profile is due to the house and conveys a high instability risk, all the more so as many breaches have occurred in this area.

With a view to determining such an instability risk and collecting input data for the purpose of performing a potential geomechanical modeling work (stability calculation), cross-sections should be produced at regular intervals so as to identify more accurately the profile geometrical changes. Yet, most levees in Val d'Orléans have a wide profile: it is therefore relevant to search for localized instability risks through a preliminary study of the slopes.

This study must be carried out in conjunction with a work type analysis: for instance, any embedded stone pitching[5] may, indeed, efficiently contribute to improve the stability of a weak-looking levee slope.

b) Irregularities and Ancillary Works

All irregularities and ancillary works on slopes or near the levee toe are just so many potential weakness points in relation to levee or section of levee mechanical stability: for example, earth ridges, spillways, wedges, flashboard paths, pipe or gallery lock walls, etc. Figure 3.27 shows an example on Val d'Orléans levee: a flashboard gallery (Val de Bou).

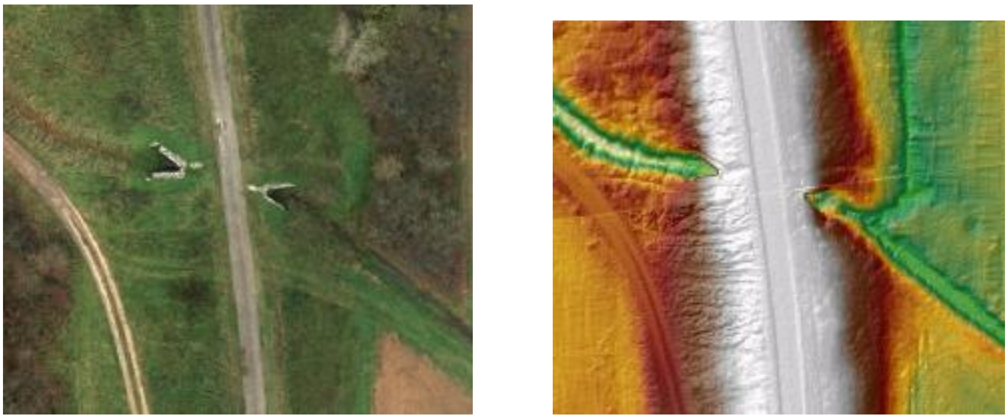


Figure 3.27 Flashboard Gallery on Val de Bou

SDM or DTM with shadowing may be used to identify such irregularities. Works are clearly identifiable through DTM as they induce a change in the ground shape.

c) Topographic plan contribution

One of the topographic plan qualities is that it brings together all visible items from a given area (see III.2.2), and particularly structures or irregularities that are potential sources of instability risk.

External Erosion and Scouring

It should be reminded that the levee being close to low-water bed bank is a risk factor with regard to external erosion caused by hydraulic stresses applied by the river, particularly during floods. Other levee sections, located where the levee-limited plain floods are narrowed, are also potentially affected by erosion risk on the river side slope. Lastly, trees, bridge piers or any construction item sticking out of the face on the river side of the dike induce a scouring risk.

Levees located immediately next to the low-water bed are particularly exposed to internal erosion or scouring risks. Such risks may be analyzed by comparing current geo-referenced

[5] Caution: such pitching might be covered with a top soil layer, making them invisible through Lidar technique or aerial photograph.

aerial photographs resulting from Lidar flight (2010) with aerial photographs stemming from previous campaigns. However, the resolution of former photographs is far lower than those provided from 2010 Lidar acquisition. Although external erosion risk was already known at the time of these campaigns, erosion attack geometry may not be determined from these photographs. Ideally, a comparison of high resolution-only aerial photographs taken at various points in time should be carried out to determine localized changes in erosion areas on the river side or any change in morphology. In addition, one should consider that photographic acquisitions have been performed at different times in the year, with different Loire river levels, and therefore may distort or complicate external erosion analysis on some specific areas.

Figure 3.28 shows sample aerial photographs of levee located immediately next to low-water bed on Val d'Orléans. The compared photographs are acquisitions dating back to 2010 and 2006. Woodland growth is different on both pictures: trees have leaves on 2006 photographs, and the 2010 photograph resolution is substantially better. The tree line along the river is gone, most probably removed by man.

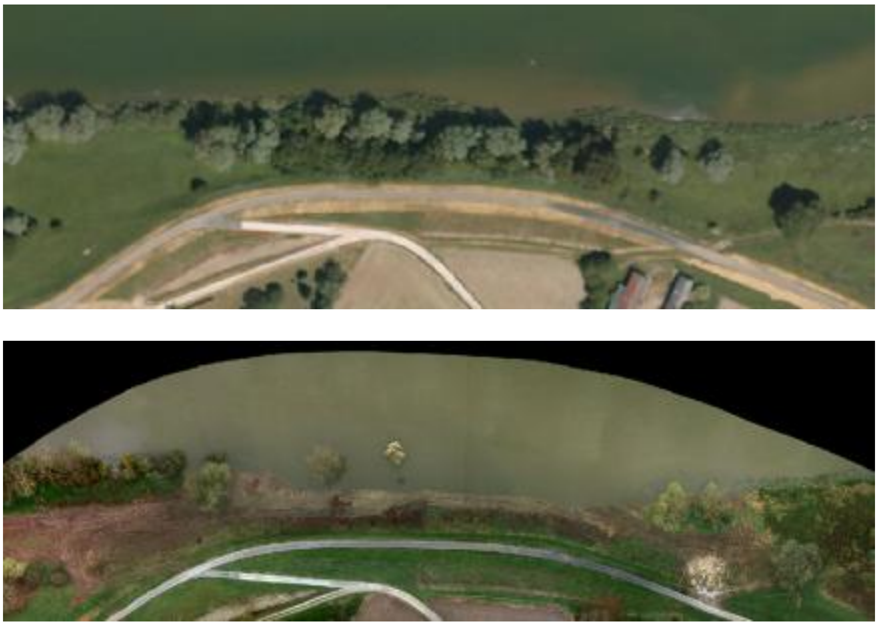


Figure 3.28 2006 (Top) and 2010 (Bottom) Aerial Photographs in Location "Maison Vieille"

3.4 Conclusion

3.4.1 Relevance to Practice

In support of a real case study ("Val d'Orléans" Pilot Site), our research work provide a methodology for using remote sensing LiDAR data and high-resolution aerial imagery – acquired in "dry conditions" (e.g. not in a flood context) - to contribute efficiently to a rural or urban flood defense structure diagnostic or assessment.

The main objective of our task 3.2.2 is resolutely operational: To put in practice the developed methodology, it is necessary to dispose high-resolution LiDAR data that our task deliverable “Technical specifications template for LiDAR aerial acquisition on dikes” allows to operate.

Topographic data furnished as deliverables of a LiDAR acquisition campaign are precious information tools regarding levee maintenance and operations.

3.4.2 Remaining gaps in Knowledge

Complementary means or investigation remain essential to lead to a complete assessment (or diagnostic): historical study and documentary analysis, visual inspection on field and geotechnical soundings and testings.

It should be interesting to compare topographical data recorded over time. Potential levee settlement issues or slumps would be identify through high resolution LiDAR acquisitions repeated at regular intervals, every 2 to 5 years, for instance. Considering the Z accuracy of 0.03 m in good surface conditions, the height displacement should be more than 0.05 m.

The presented methodology -both for LiDAR data acquisition terms and further utilizing data-could be adapted to emergency levee monitoring. Indeed, remote sensing LiDAR and helicopter-borne imagery, in association with extended spatial coverage and high-resolution, turns out to be potentially effective to contribute to a diagnostic during - or following - a flood event [Mériaux & Royet, 2007]. Indeed, waiting few days after a major flood allows clearing up the river side slope. So bank erosions would be characterized by LiDAR.

To complete the assessment of near watercourse located levees, a bathymetric LiDAR could be combined with the airborne traditional LiDAR to obtain data under water. The problem (for now) is that there is no available high-precision method of aerial bathymetric LiDAR essentially because the laser couldn’t cross trouble waters. So it remains necessary to use sonar techniques to collect under water topography.

3.4.3 Summary table of the methodology

See Chart in **Appendix 3.3**.

3.5 Appendixes to Chapter 3

Appendix 3.1: Remote sensing techniques Table

Appendix 3.2: Cover of flight for LiDAR acquisition on Orléans pilot site the 17th and the 18th of November, 2010

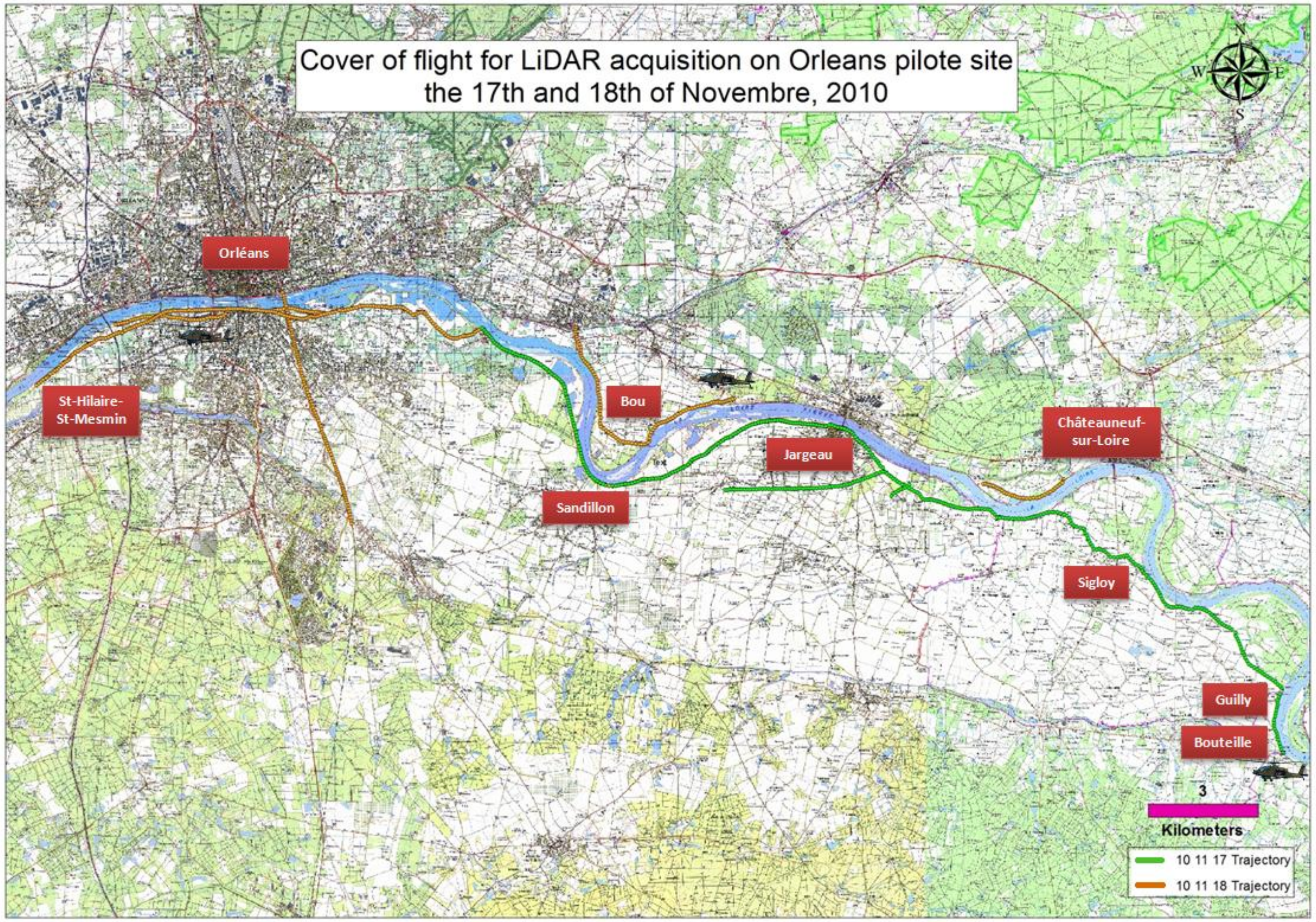
Appendix 3.3: Methodology for using high resolution LiDAR data Summary Table

Additional document related to task 3.2.2: “Technical specifications template for LiDAR aerial survey on dikes”

Appendix 3.1: Remote sensing techniques Table

Type of technique	Sensor or technology	Technology description	Remote sensing technique	Details on the sensor	Technique used for processing data or signal	Platform carrying the sensor	Regular applications	Known applications to levees (sources, references)	Measurement precision (planimetry and altimetry)	Sensor-driven spatial sampling frequency	Output	Costs	Limits
passive	Optical	Black-and-white, false color or color photos or videos	Traditional aerial photography (nadir or vertical sighting)	Typically a visible sensor with RGB (red, green, blue) or panchromatic matrix, and less frequently a linear sensor (still camera with only one sensor line)	Camera, GPS and IMU (Inertial Measurement Unit) are used to produce orthocorrected images (geo-referenced photograph) With manual corrections, photogrammetry may help detect items that are unidentifiable by lidar Requires more post-processing than the lidar	Airplane, helicopter, satellite, balloon, ULM, drone	- Imagery-driven topographical maps and field analysis - Orthocorrected aerial photographs (orthophotographs) commonly found in geomorphological mapping - Primary method for studying objects down the water bed	- Overall vegetation mapping - Recent instance of application to CNR levee with 1 cm anticipated resolution - Example of application to torrential geomorphology (CEMAGREF and CEREGE)	High: >1 with a few pixels/m² precision highly dependent on flight altitude and technologies used for geo-referencing images	Depends on sensor and flight altitude	Different output according to sensor, resolution, acquisition type (surface, linear, etc.) and restricted by weather conditions, desired contrasts, etc.	Highly variable, according to measured surface. Although high fixed costs for sensor and aircraft procurement. For very high aerial resolution in optical application (from 3 to 30 cm), average costs range from 20 to 100 €/m²	Requires unobstructed view of the surface Limited by weather conditions (clouds, fog, heavy rain, shade) Unable to cross vegetation
			Oblique aerial photography	Often a video sensor, typically a visible sensor with RGB or panchromatic matrix, and less frequently a linear sensor		Airplane, helicopter, satellite, balloon, ULM, drone, oblique ground platform	Used to produce images for communication purposes (impact reviews, landscape analysis)		Low: panning effects induce larger pixels as the horizon is approached The viewing angle reduces underwater visibility (refraction)				
			Stereophotogrammetry	At least doubled images vs traditional aerial photography (for stereo or multiview)		Aerial images taken by airplane; ground platform or onboard a vehicle	- To retrieve relief and topography - To identify potential small-scale changes or strains	Geometrical properties of an object on a levee	High precision planimetry; lower for altimetry (~half lower)				
			Near infrared photogrammetry	The sensor is sensible to near infrared spectrum (most frequently 0.7 to 1µm)		Airplane, helicopter, satellite, balloon, ULM, drone, oblique ground platform	To determine crop types	- To determine vegetation (water and vegetation are identified with near IR spectral reflection factor) - Bare soils are more visible (FRMRC)	High precision				
			Multispectral photogrammetry	Captures an image in several wavelengths (multi, super or hyper, depending on the number) of the visible or infrared electromagnetic spectrum (0.3 to 30µm)		Any ground, aerial or satellite vector	Refined determination of ground, water or vegetation properties (depending on the wavelengths used)		Variable according to wavelengths				
			Satellite imagery			Satellite	Numerous scientific, civil and military applications: meteorology, environment evaluation and monitoring, global climatic and environmental change assessment	Used for break hazards in the event of a crisis (flooded area)	Low precision	Suitable for large surfaces			Unable to produce images underneath cloud cover
			Video	For visible, black-and-white and color images		Helicopter, balloon, ULM, drone: low altitude devices		To determine vegetation					
	Passive microwave	Passive micro wave detection for moisture content sub soil	microwaves			Helicopter, balloon, ULM, drone: low altitude devices		Soil moisure detection on levee	Low precision				
	Thermal	Infrared photographs or videos to identify areas with thermal anomaly (temperature discrepancy between the surface ground and resurgence areas)	High resolution thermography	Can reach the far end of the spectral infrared strip		Helicopter, balloon, ULM, drone, mobile or fixed ground platform	- To identify subsurface issues in a great number of materials (concrete and masonry) - EDF to determine the hot water network impact downstream the plants	- Application tests for hydroelectric installation levees (EDF, CNR) and waterway levees (DREAL Centre) - Application to identify damp areas on levees	Precision affected by material properties (thickness and dampness)	Depends on flight altitude, sensor optics and resolution; resolutions are 10 times rougher than in optical application	Different output according to sensor, resolution, acquisition type (surface, linear, etc.)	Expensive	
active	Topographic and bathymetric Lidar	From an aircraft or a ground station which position is precisely known (DGPS + IMU for onboard systems), a laser beam is transmitted towards the relevant area and an analysis of the backscattered signal (route duration between transmission and return signal reception is analyzed, as well as specific features thereof) will derive information on the topography Can fly over non-navigable channels NB: lidar technology may be used for other applications (DIAL, doppler…)	General	Wavelengths used from green, UV and NIR (near infrared)	The main steps for deriving information on topography include: 1- Achieving a geo-referenced scatter diagram (X,Y,Z) 2- Treatments to produce digital models for raster surface from the raw scatter diagram 3- A field digital model may be generated following the classification of points that helps identify points on the ground (frequently semi-automatic step during production: automatic treatments are manually reprocessed)	Helicopter / airplane / ground platform / onboard a vehicle	Topographic and bathymetric lidars help determine all natural and anthropogenic items (surfaces and water): topography, erosion, volcanism, faults, infrastructure follow-up, archaeology, urban items, vegetation and water, etc.	- To map areas liable to flooding by coupling hydraulic models and lidar DTM - Levee geometry - To localize small items such as walls - Multitemporal surveys for determining the river geomorphological processes (e.g.: identification of changing altitudes through 2 sequences of Lidar surveys over a braided river in New-Zealand - Lidar survey over Petit Rhône river in Arles	High precision, depending on aircraft altitude and path as based on the overflown area and the desired precision. 5 to 25 cm for altimetry and tens of cm for planimetry. Far more precise than Radar technique.	Point density depends on the lidar transmission frequency, the scanning system and the airplane or helicopter height or velocity.	Fast: hundreds of km² over a few days	More expensive than standard Lidar	Depends on weather conditions
			Helicopter-borne topography	NIR		Helicopter	Primary application: linear infrastructure topography and survey (for example: electric lines) (source: Fugro Geoid)	- To identify and determine small-sized items on levees, vegetation, irregular works, etc. (source: CEMAGREF and CEREGE) - To determine geomorphological changes in a braided river section near Digne	More precise in high density lidar such as FLIMAP 5 cm for altimetry 25 mm/pixel (with 150 m flight height)	Over 50 points/m² if helicopter flies at low altitude and slow pace Lower density: 1 to 10 points/m²			Requires a great number of aircraft flights across the area (limited scan swath)
			Airborne topography (Airborne Laser Scanning)	Laser wavelength ranges from 1,064 to 1,550 nm		Airplane flying 200 to 6,100m high	Topography, DTM, particularly for river valleys	- Val de Loire 2002 - Rhône River Valley, late 2000's	15 to 20 cm for altimetry and 0.3 to 1 m for planimetry	Point density lower than 10 points/m², and sometimes lower than 1 point/m²		Fixed costs: €12,000 per site + €200/km² (estimated in 2006)	
			Static (Terrestrial Laser Scanning)	Green or NIR		Tripod	To specify small-scale structures such as slope and dam operation, architecture, forestry, civil engineering, etc.	- To survey cross-sections over river beds - To determine the root system for levee woodland	Far more precise than on helicopter; airborne or onboard a vehicle	Density is very different according to the distance between the system and the object of interest	About 1 ha/day	€1,000/day	Requires time for broad surfaces
			Land vehicle (Mobile Laser Scanning)	Green or NIR		Car	Urban 3D mapping,	- Levee strain in New Orleans: precise measurement of ground movements on levees	Distance from scanner to target is a precision factor	Riegl minimum angular pitch is 0.0024°	Extended spatial coverage		Requires access road for vehicles
			Airborne bathymetry	Laser beam operates with two frequencies: one is in the green (532 nm), so that the signal is not blocked by water, and the other frequency is reflected from the water so as to record other topographical data	The recorded waveform (signal) results from the interaction between the signal (gaussian pulse), the water surface (gaussian surface echo) and the bed when the beam reaches the bottom (depends on depth and turbidity, bottom echo). The water column that is crossed back and forth by the beam also contributes to the return signal. Adjusting models to waveforms helps retrieve the various components and specifically determine the depth.	Airplane / helicopter	Technique used to measure a coastal area topography and bathymetry; developed on the coastline, specifically through 3D mapping with depth ranging from 0.5 and 60 m	- Not much developed over continental watercourses - To continuously determine damp bed geometry (e.g.: hawkeye Gardon experiment) - Applications to levee control	15 cm deep (Z), although low depths are overestimated and great depths are underestimated	1 point/10m², and up to 1 point/4m² when altitude and velocity are optimized	20 km²/hour spatial coverage	Fixed costs: €20,000 per site + €250/km² (estimated in 2006)	Identification is contingent upon the wavelength used (green seems to be more suitable) and the environment features (sediments, etc). Bathymetry is not easily estimated for lower than 50 cm depths. Constraints in rapid flow rivers,
	Radar	Synthetic Aperture Radar (SAR): produces a DEM on large-scale grounds	InSAR (radar interferometry), PS INSAR(deformation)	Microwave frequency sensor (with long wavelength: from 1mm to 1m)	Can produce a digital elevation model (DEM)	Satellite, airplane or ground platform	- To examine the ground surface and provide topographical information - Ability to identify ground movements over time	- Watercourse and flood mapping - May ensure levee elevation or slump monitoring through InSAR-	Depends on the platform: satellite/airplane/ground platform. Altimetric precision > 50 cm. Precision by a couple of cm for elevation change through inSAR - deformation on mm scale by PS Insar	- TerraSAR: 1mx1m spatial resolution - RADARSAT-2: 3mx3m spatial resolution	Can produce 24 hour images (depends on platform)	€2,500/image - TerraSAR: 10kmx10km - RADARSAT-2: 30kmx30km In future for free (SENTINEL Program)	No limits : sensor under any weather conditions and at anytime Unaffected by cloud cover or darkness Limit : satellite image once a week/month
	Sonar	Sonar and ultrasound scanner are used for measuring underwater topography	Sound Navigation and Ranging	Uses specific sound propagation properties in water to identify objects under water and sandwaves	The sonar sounds a tone burst and listens to its echo on any obstructing objects on its path. Distance is calculated by measuring the time lapse from transmission to echo reception (sound propagation speed in sea water being 1,500m/s)	Boat	- Navy: submarine and mine detection - Fishery management - Sea and river navigation: watercourse longitudinal profiles or ocean floor mapping - windmillpark: forcasting of seabed changes in time		High precision			Rather cheap equipment compared to other systems, but expensive compared to low water visual inspection	Can only identify underwater objects Speed of sound is different according to depth (change in temperature and pressure)

Appendix 3.2: Cover of flight for LiDAR acquisition on Orléans pilot site the 17th and the 18th of November, 2010



Appendix 3.3: Methodology for using high resolution LiDAR data

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