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Methodology Applied to the Diagnosis and Monitoring of Dikes and Dams

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1. Introduction

The recent and dramatic floods of the last years in Europe (Windstorm Xynthia, February 2010) and United-States (Hurricane Katrina, August 2005) showed the vulnerability of flood defence systems. The first key point for avoiding these dramatic damages and the high cost of a failure and its consequences lies in the conception and construction of the dams and dikes, taking into account the past flooding events. A well-designed dike with the correct height avoids failure and overtopping.

In this chapter, a dike is defined as a flood defence system, in dry condition (no contact with water). The term "levee" is often used, specially in the USA.

Many factors introduce weaknesses in the dike. Most of them are old structures. For instance, some of the French Loire River dikes were built several centuries ago. They may have been rebuilt, modified, heightened several times, with some materials that do not necessarily match the original conception of the structure. In other aspects, trees, roots, burrows or nests could modify the structure of the dike and reduce the mechanical properties.

Particular geological formation and their evolution could also threaten the dike. This is the case in the city of Orléans, France, where levees have collapsed in karstic areas. In urban context, the dikes present many other singularities, such as networks, canalisations, human constructions like houses and walls. Due to all these factors, dikes have to be considered as heterogeneous structures. Considering the social impact of a possible breach, the stretch of hundreds of kilometres and the heterogeneity of the materials, rapid, cost-effective and reliable techniques for surveying the dike must be carried out.

This chapter presents the general approach for assessing earth embankments. The first part briefly presents a synthesis of the French approach related to dike diagnosis. The second part shows the recent improvements in this geophysical area given by current applied researches and international experiments. The third part is dedicated to the airborne LiDAR (Light Detection and Ranging) technology, which provides extremely accurate topographic

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data at a high efficient rate. The last part is a presentation of a current research work where the Electrical Resistivity Tomography (ERT) method is implemented and tested on an experimental test dam as well as real ones in order to monitor the effect of internal erosion within the structure.

2. General methodology for dike diagnosis

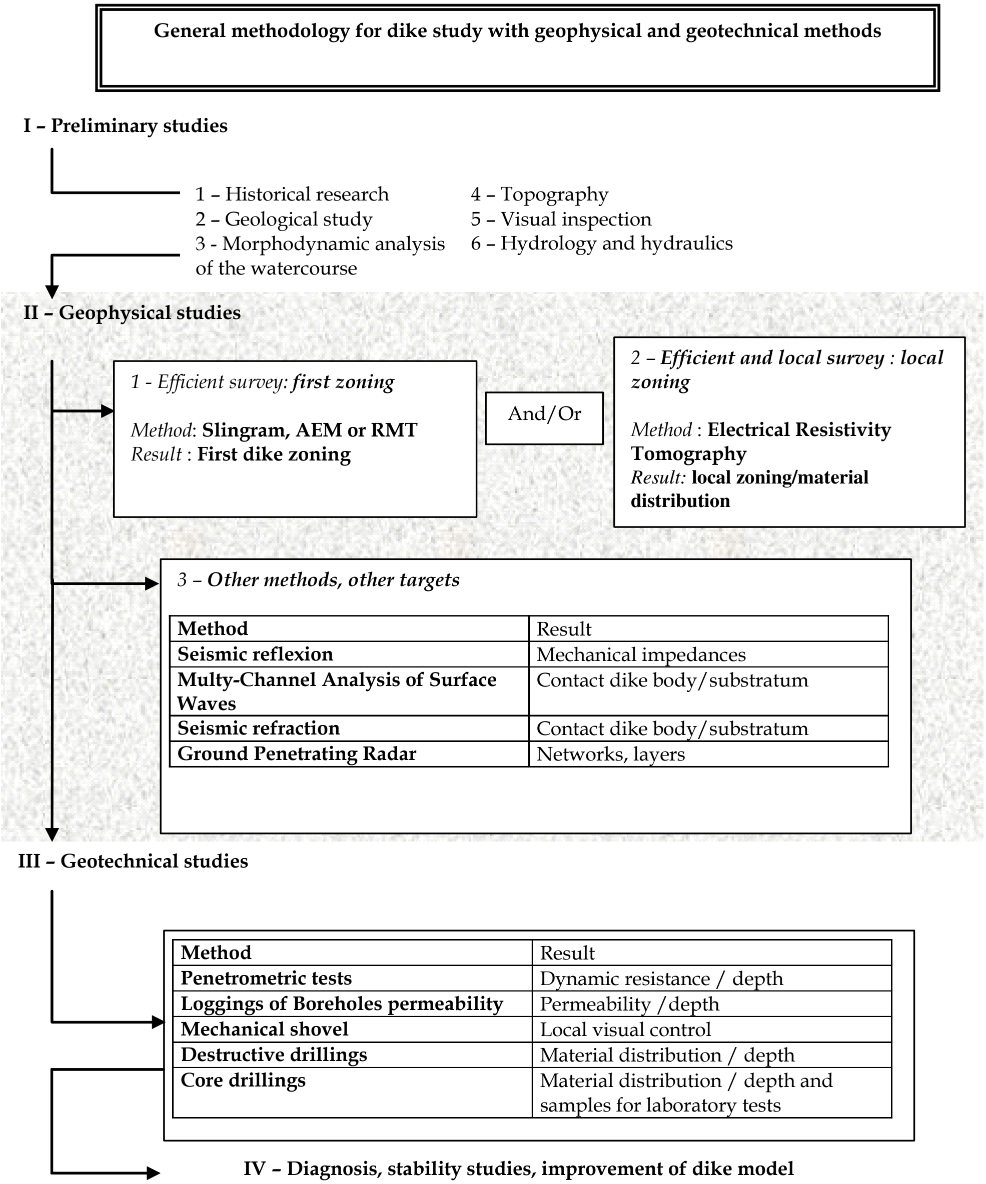
The management of a dike involves many stakeholders and consists in surveying, maintaining and making a diagnosis (Mériaux & Royet, 2001). The diagnosis should identify the weaknesses of the structure (zoning) and provide the degree of safety. Thus, a general methodology (Fig. 1) has been proposed by (Fauchard & Mériaux, 2007). It concerns the levees running alongside French rivers (Loire, Cher, Isère, Aggly), where the dikes are not in a permanent hydraulic heading. The diagnosis is performed in dry condition. The 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 dams, with slight differences during in-situ inspections.

This diagnosis begins with preliminary studies, before performing geophysical surveys. It goes on with geotechnical testing, before concluding on the safety level of the dike.

2.1 Preliminary study

The preliminary study consists in gathering as much information as possible concerning the dike, the near environment and its history (Lino et al., 2000).

a. **The historical research** (Fig. 2) can establish the locations of old repaired breaches, material distribution and the way the dike was built. The study of historical archives gives clues wherefrom the materials were extracted so as to build and repair the dike.
b. The **geological study** (map and in-situ observations) of the near area gives information about materials potentially used for building the dike and on the underlying substratum.
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 piping, as well as for an accurate location of any structure (walls, crest water gates, crossing networks…) that can modify the interaction between water and dike in case of flood. Finally, the topography is useful for dike 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. Longitudinal profiles are performed on the crest every 20 to 25 m and transverse profiles are realized every 50 to 200 m, depending on the context. This is a critical point 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 section 4).
d. The **visual inspection** is performed after the historical research and the topographic work. This phase confirms, completes or invalidates any information previously collected. At least three inspectors are required: one on the crest, and two at the toes dike in the riverside and landside. Any anomaly should be reported on the topographic map.



General methodology for dike study with geophysical and geotechnical methods

I – Preliminary studies

1 – Historical research
2 – Geological study
3 - Morphodynamic analysis of the watercourse
4 – Topography
5 – Visual inspection
6 – Hydrology and hydraulics

II – Geophysical studies

1 - *Efficient survey:* ***first zoning***

Method: **Slingram, AEM or RMT**
Result : **First dike zoning**

And/Or

2 – ***Efficient and local survey : local zoning***

Method : **Electrical Resistivity Tomography**
Result: **local zoning/material distribution**

3 – ***Other methods, other targets***

Method	Result
Seismic reflexion	Mechanical impedances
Multy-Channel Analysis of Surface Waves	Contact dike body/substratum
Seismic refraction	Contact dike body/substratum
Ground Penetrating Radar	Networks, layers

III – Geotechnical studies

Method	Result
Penetrometric tests	Dynamic resistance / depth
Loggings of Boreholes permeability	Permeability /depth
Mechanical shovel	Local visual control
Destructive drillings	Material distribution / depth
Core drillings	Material distribution / depth and samples for laboratory tests

IV – Diagnosis, stability studies, improvement of dike model

Fig. 1. General methodology proposed in 2007 by the French National Project CriTerre (source Fauchard & Mériaux, 2007)

e. The **morphodynamic study consists in** understanding the sedimentology, the hydrology and the morphometric characteristics of the waterway. It takes into account the temporal evolution of the watercourse channel. For instance, a sandy islet in the bed river modifies the water current: new parts of the dike could be threatened in case of flooding.

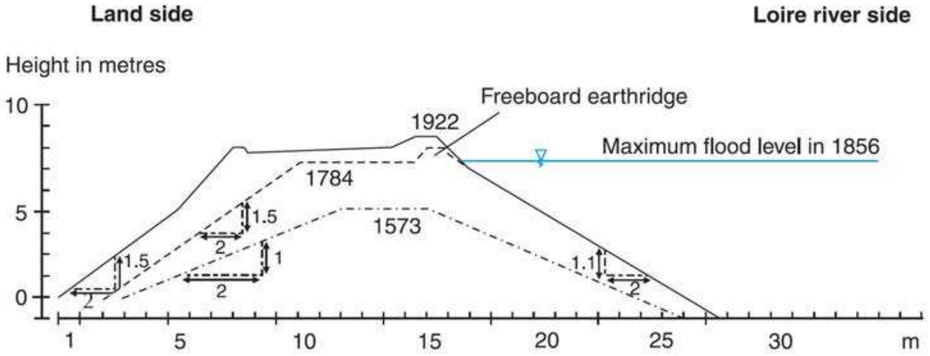


Fig. 2. Example of historical data of the dikes of the Authion river (France, Loire) (Dion, 1961)

2.2 Geophysical studies

2.2.1 Introduction

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

Considering a typical study where the dike is a long structure of several kilometres, a classical approach (Fig. 3) 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 to focus on interesting areas, which can be measured with appropriate geophysical or/and geotechnical methods. This global methodology is presented in Fig. 1.

Generally stakeholders are in charge of managing permanent critical structures like dams, multifunctional dikes in urban area or dikes in heading conditions. In this case, and regarding the potential damages that a breach could generate, the choice of a more efficient, but more time and cost consuming method may be considered. Indeed, the slightest breach during a flood event, either in urban or rural areas, leads to dramatic damages. It induces costs generally higher than the diagnosis does. As a result, some **stakeholders prefer a detailed zoning whatever the stretch length of the dike** (Fig. 3).

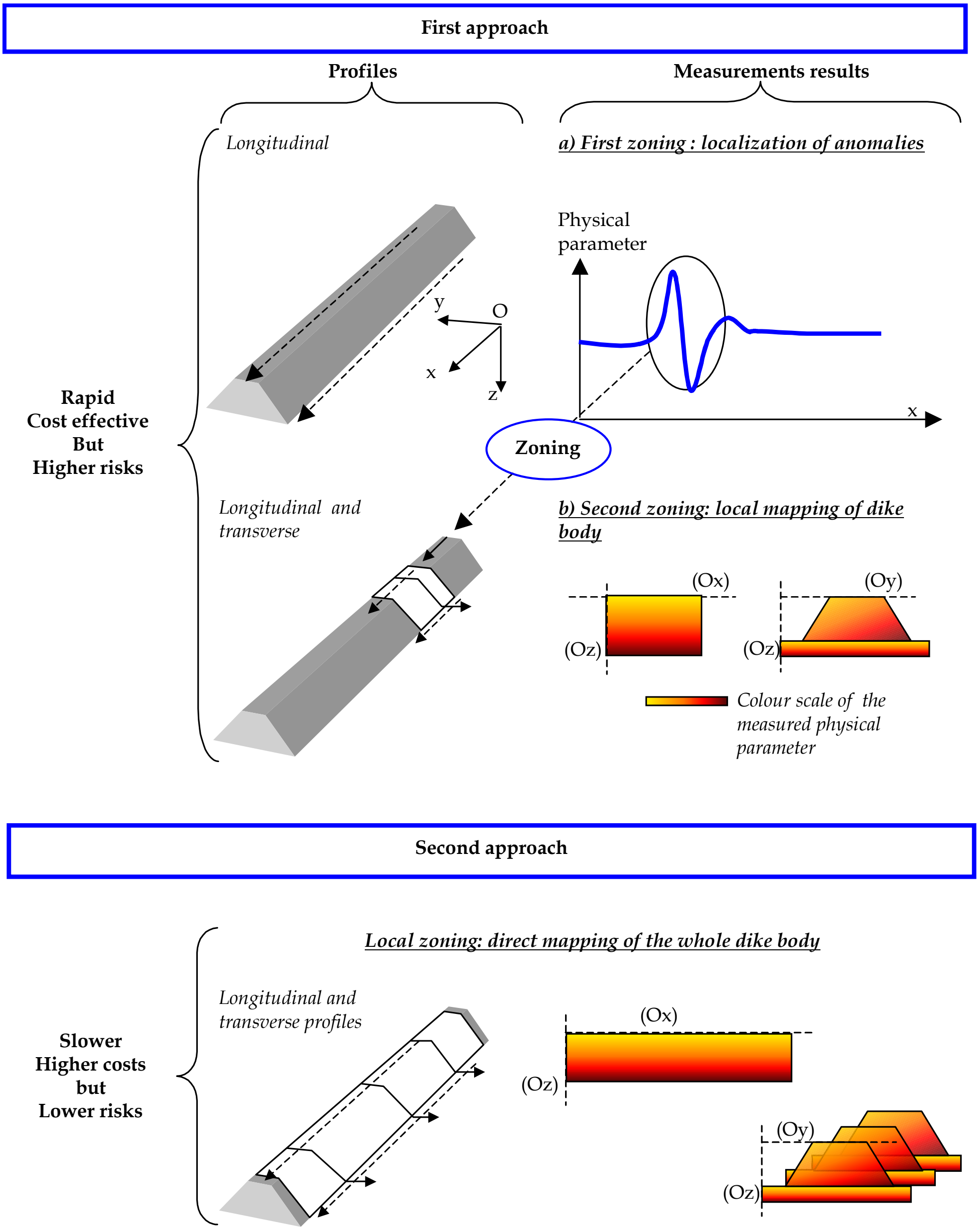


Fig. 3. Two approaches for geophysical survey on dikes

2.2.2 First zoning with geophysical methods

As discussed earlier, depending on the dike characteristics two different approaches are currently carried out. The choice is more dependent on the available time and allocated means than on the dike length.

The first approach (Fig. 3 top) consists in measuring a **physical parameter** related to the type of material of the dike body. The **apparent resistivity** (or its inverse, the conductivity) is a common physical parameter measured for this purpose. The resistivity describes how materials resist to (or conduct) electricity. It strongly depends on the nature of the studied material, its water and clay contents. Other parameters like tortuosity or water salinity of soils are also of importance. The resistivity values of encountered materials in dikes spread in a large scale: few Ω.m (ohm meter) in clays, from few Ω.m to few hundreds Ω.m for silty soils and from few hundreds Ω.m to several thousands Ω.m in sand, gravels and limestone. Fig. 4 shows the range of resistivity values of the main materials encountered in applied geophysics.

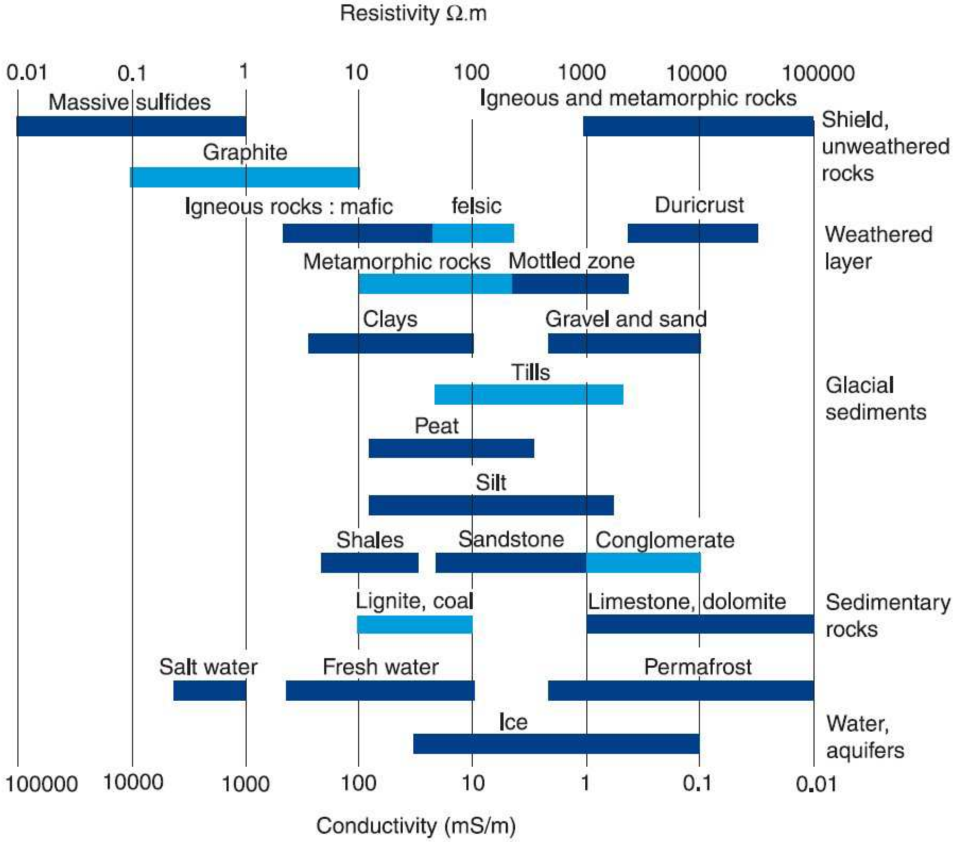


Fig. 4. Resistivity (and its inverse, conductivity) of the main earth materials (Palacky, 1991)

A rapid and cost effective technique is the electromagnetic method of **Slingram** (Mc Neill, 1980)**.** It works in low frequency domain and measures the apparent conductivity of the dike body. The depth of penetration of such a method can reach 50 m, but common devices are designed to reach a classical depth of 10 m (mean height of dikes). A car can track the device if the dike crest has a pavement structure. The measurements are represented as a curve showing the variations of the conductivity (or resistivity) with regard to the distance. A significant variation compared to an average value is interpreted as a potential variation of dike body properties: it defines the area for a more detailed survey.

Nevertheless, these methods are highly sensitive to metallic environment, and their applications are still difficult in urban areas.

Airborne Electromagnetic Method (AEM) belongs to the Slingram family methods: the survey is performed from an airborne platform. It has been widely used for the levee in the region of New Orleans (Dunbar, 2003). Other high output methods were also carried out in the French context of the Loire Rivers. The **Radio MagnetoTelluric method,** identical to the Very Low Frequency in resistivity mode, but uses higher frequencies, has been designed for first zoning with good performances in the re-localization of repaired breaches. Today, this method has been discarded by most geophysicists mainly because its technical aspect is getting older, and because of the poor quality of incoming waves.

Another popular technique is the **Spectral Analysis of Surface Waves (SASW)** initially developed for marine seismic exploration (Gimble sensors). It is implemented for studying the contact surface between the dike body and its substratum. It evaluates the shear modulus. This method was described and implemented on the Loire levees (Samyn et al., 2009) for the detection of sinkhole in karstic substratum in the region of Orléans, France.

Ground Penetrating Radar is sometimes used on particular studies – on paved dikes for instance, or on very resistive dike bodies. This electromagnetic method is based on the radiation of electromagnetic waves in time domain and the reception of waves reflecting on dielectric contrasts encountered in the soil. Most of dike bodies absorb this kind of waves, and the provided information is often useless for a diagnosis.

2.2.3 Local zoning with geophysical methods

The local zoning consists in carrying out directly a more precise geophysical method. It is for instance an internal map (or tomography) of the dike body and of the top of its substratum. The best-suited method for this approach is the **Electrical Resistivity Tomography (ERT).** This approach takes more time and is more expensive than the others. However, it provides more accurate data entailing a better detection of potentially weak areas and therefore a better understanding of the structure stability.

In case of heading conditions (for dams or earthen embankments), the ERT can be applied for mapping internal structure and can be implemented for a time lapse monitoring. But here, the most important is to detect seepages and/or leakages, through or under the dike body. For that purpose **the self potential** is more appropriate. It can be implemented directly on the top of the structure, or could be carried out on river, along the dike. This method also leads to the estimation of the seepage flow through the structure (Bolève et al., 2007). In that case, ERT provides additional measurements for processing the data. Some temperature probes could also be buried in the dike and the temperature variation could be correlated to the presence of water in the dike body (Radzicki & Bonelli, 2010).

2.3 Geotechnical testing

Geotechnical testing are 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 dike.

Geotechnical testing locally provide physical parameters of the dike 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 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 permeability 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 an helicoidal cutting tool (auger). If percussion or rotopercussion 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 to take some material samples for lab-test analysis (water content, Atterberg limit, …). 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 more 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).

3. The airborne LiDAR as an efficient tool for topographical survey and detection of surface anomalies on dikes

3.1 Backgound on LiDAR systems

Airborne laser scanning (also called ALS) or LiDAR (Light Detection And Ranging) is an active remote sensing technique that provides georeferenced distance measurements between an airborne platform and the surface. It measures the time-of flight of a short laser pulse once reflected on the Earth surface. Strips of several kilometres, with a high overlapping ratio, provide the surveyed topography. The attitude of the airborne platform is acquired by both a GPS and an inertial measurement system. Distance measurements are then transformed into georeferenced 3D points. A detailed description of the processing chain can be found in (Mallet & Bretar, 2008) and (Shan & Toth, 2009).

The height accuracy (resp. horizontal accuracy), at the top end process, is less than 0.05 m (resp. about 0.40 m) or less depending on the flying conditions as well as on the surveyed topography.

Moreover, such active systems, called multiple echo LiDAR, allow detecting several return signals for a single laser shot. It is particularly relevant in case of vegetation areas since a single LiDAR pulse allows acquiring not only the canopy, but also points inside the vegetation layer and on the ground underneath.

In recent years this technique has been applied over natural landscapes to extract terrain elevation (Kraus & Pfeifer, 1998; Bretar & Chehata, 2010) or to classify land cover (Antonarakis et al., 2008; Yoon et al., 2008, Bretar et al, 2009).

In the particular case of dike monitoring, we need a high flexibility in the flight planning in terms of altitude (100-300 m) and heading, and also a high accuracy because dikes are civil engineering structures with a relative low height (less than 7 m) and with a lot of small surface singularities. As a result, it is advised to use a corridor mapping system like FLI-MAP (Fast Laser Imaging and Mapping Airborne Platform) developed by Fugro-Geoid (Gomes Pereira & Wicherson, 1999).

Embedded in an helicopter, FLI-MAP can provide[†], over a 105 m wide corridor at a fly height of 150 m, a point density of 80 pts/m2, with an absolute height accuracy (Z) of 0.03 m. The Pulse Frequency Rate (PRF) of the latest version can reach 250 kHz with a field of view of 60 ° in the cross track direction. The survey is done following three scan plans in the flight direction (vertical for 50% of the points, front 7 ° and rear 7 ° for 2 x 25%), which reduce the effects of shadows.

The trajectory of the helicopter is recorded by two dual frequency GPS and an inertial measurement unit. A digital camera in nadiral position, synchronised with the LiDAR system, records the surveyed landscape and is used both to build a mosaic of georeferenced images and to colorize in real time the 3D point cloud so that a user should have a better understanding of the scene (Fig. 5). The system also includes two frontal and oblique cameras (photo and video). These data are particularly popular for dike managers who use

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[†] Example based on a recent application of the FLI-MAP technique on the Loire levees near Orléans, in the context of the FloodProBE European research project.

the images for later processing and for marketing/communication actions towards the public or financial sponsors.

3.2 Surveying a dike with LiDAR data

A LiDAR system is able to acquire data on a dike structure of up to 80 km per day, which makes the use of this technique valuable in case of emergency situations (after a major flood, for example). Provided that it exceeds a length of up to 60 - 80 km (corresponding to a day of helicopter), the costs are competitive with regard to conventional field topographic techniques (in the order 2000 euros / km) and provide additional valuable products like precious information on dike slopes and crest or their near environment (river banks, etc.). The high-resolution digital images allow to measure with accuracy visible objects. Figure 6 shows the identification of a pump line through the base of a dike.

Fig. 5. Colored 3D point cloud over a dike (source FloodProBE - FUGRO)

Moreover, in case of vegetation, LiDAR data makes possible to study invisible structures from images. Fig. 7 illustrates the way the erosion of riverbanks under vegetation can be quantitatively analysed with laser profiles.

The field visit (Fig. 8) confirmed this erosion process. The possibility of studying the vegetation is also of high importance: the development of woody vegetation near or onto the dike is a major risk factor (Mériaux et al., 2006).

Surface singularities are often signs of disorder or suspected disorder in the dike itself: for example a subsidence or a sinkhole on a ridge may result from internal erosion or karst collapse. Such singularities, once pre-identified on the images are, of course, to be confirmed by field visits, but the contribution of high resolution LiDAR data is to improve the completeness of these visual clues (Clement & Mériaux, 2007). Geophysical survey or geotechnical testing will then characterize possible extension of surface singularities in the dike body or in the foundation.

Fig. 6. 0.02 m resolution digital image acquired during the LiDAR survey. It shows a pump line through the base of a dike (source Cemagref -FUGRO)

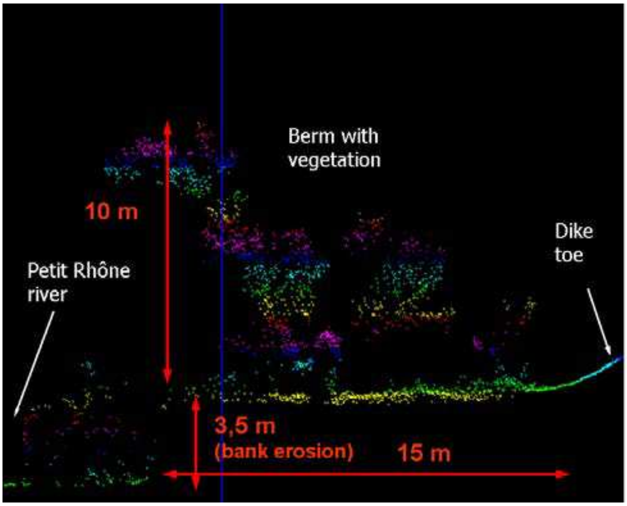

Fig. 7. Laser profile of a bank under the vegetation (source Cemagref-FUGRO)

Finally, high resolution topographic data contribute to build specific geomechanical model of the dike that, after incorporating data provided by geophysical and geotechnical surveys, are integrated in the calculations of the structure stability. The quality of the geomechanical model also depends on the accurate location of in situ geophysical and geotechnical surveys so that one should interpret the results with relevance. In this regard, a decimeter resolution DTM acquired with a LiDAR system or derived topographic plans at 1: 100 is of high interest for people in charge of operating field measurements.

Fig. 8. Bank erosion. The red arrow represents the 3.5 m elevation gap seen on Fig. 7 (source Cemagref)

4. Investigation and monitoring of dikes and dams with Electrical Resistivity Tomography

4.1 Quest for complementarity

Internal erosion processes and overtopping phenomenon represent more than 90% of dike failure (Foster et al., 2000; Fell & Fry, 2007). This section focuses on internal erosion processes which are more complex, and above all, should be detected by geophysical methods before the rupture of the earthwork.

Among them, the **DC-Electrical Resistivity Tomography (ERT)** is of particular interest (Johansson, 1997) for dike monitoring in heading condition. This technique is considered highly sensitive to the induced physical phenomenon such as changes in clay or water content, temperature and porosity. Fig. 9 presents the main interactions regarding the effects of internal erosion on electrical resistivity.

The main purpose of ERT campaigns is an insight of the subsurface via 1D, 2D, or 3D representations of the spatial and/or temporal variations of the electrical resistivity. One of the advantages of the method is its double resolution capacity:

- Low resolution imaging for high outputs with fast zoning techniques,
- High resolution imaging for selected short stretch

This double resolution capacity can be exploited in two ways:

- Instant survey for imaging the apparent resistivity distribution of the observed medium,
- Temporal monitoring to follow the evolution of the electrical resistivity of the earthwork.

For cost effectiveness purposes, in the case of dike survey, ERT is usually applied in a "classical" way (2D): a set of equidistant electrodes is aligned along the longitudinal direction on the dike crest, slope, or toe. Whereas the geo-electrical behaviour of dikes evolves in 3D, recorded and processed data are based on a two dimensional measurements and interpretation - 2D inversion software like Res2dinv® (Loke & Barker, 1996).

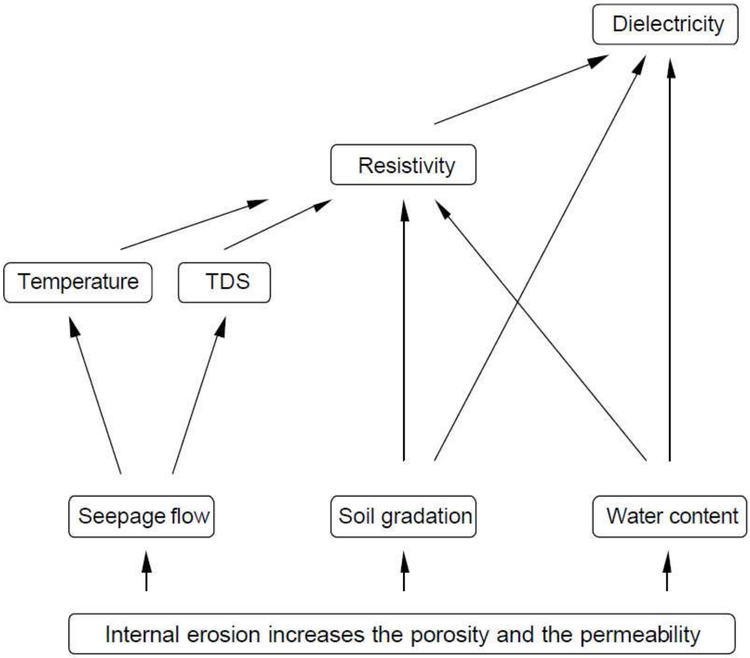

Fig. 9. Major influences of internal erosion processes on selected parameters (Johansson, 1997).

The principle of an inversion process is to find a model that best explains measurements obtained on the field plus other constraints. Consequently, in the case of a 2D inversion realized on a 3D medium the 2D inversion process inevitably leads to 3D artefacts. They are mainly due to the topographic effects, the siltation of the reservoir, the water reservoir effect, and the clay core effect.

However, external information collected from preliminary studies Fig. 1 can help to reduce these effects as presented in Table 1. Indeed, the location or depth of the anomaly can be given by a visual inspection or a morphodynamic study of the river to focus ERT acquisitions. The knowledge of the geomaterial of the dike and/or the foundation can be supply by a geological study to constrain the inversion. Then, the depth of the foundation or the thickness of a repaired breach can be available after historical investigations and can also constrain the inversion. Finally, the topography of the dike can be available (e.g. from LiDAR data or in situ measurements).

Here, we aim to illustrate pitfalls and misinterpretations of 2D-ERT inversion, before presenting methodological improvements without acquiring full 3D data.

	Explicit constrain on the model	**Explicit constrain during the inversion**
Topography	geometry	-
Geological study	substratum depth	material variation
Hydrogeological study	water table depth	roughness
visual inspection	focused measurement	-
Historical research	internal composition	smoothness

Table 1. External information gathered form preliminary studies.

4.2 Background on inversion artefacts

In case of ill-posed problem, the inversion process can become unstable and generate artefacts. Moreover, it is well known that the potential of inversion methods depends on the amount of information contained in the data (Tarantola, 1982). Therefore, the concepts of model resolution matrix or Region Of Investigation (Oldenburg & Li, 1999; Marescot et al., 2006) were introduced to assess the robustness of geophysical imaging methods. Neglecting 3D effects decreases the model resolution matrix or values of the region of investigation. This matrix represents a direct link between measurements and robustness of the result. Thus, this information can be used to enhance the method by:

- Allowing **image appraisal** (Stummer et al., 2004; Oldenburg & Li, 1999) by compensating the loss of spatial resolution and the topographic effects. This technique allows a quality control of the image and a better interpretation of the result;
- Creating optimized sequences of measurements to increase the quality of the information contained in the data (Tsourlos et al., 1999; Stummer et al., 2004; Sjödahl et al., 2006; Hennig et al., 2005);
- Finding an optimized design of electrode location to focus the survey and increase the reliability of the inversion result (Fargier et al., 2010).

4.3 Normalisation technique

The **normalisation technique** makes use of the original definition of apparent resistivity (Kunetz, 1966; Marescot et al., 2006). It indicates that the topography effects can be normalized and partly accounted during the inversion. This first technique is based on the definition of a general geometrical factor which is a generalisation of the conventional geometrical factor. This method requires an approximate knowledge of the topography (digital terrain model) as well as the resistivity of the media. As a result, this normalisation partly decreases 3D effects. However, in theory, the diffusion of an electrical field is a highly non-linear problem and the normalisation technique cannot completely take into account this non-linearity. This limitation can cause the formation of artefacts and can lead to misinterpretation.

4.4 2D$^+$ inversion strategy

Contrary to relevant works of Fox et al. (1980), Tong & Yang (1990) showed that previous normalisation techniques cannot completely take into account all non-linear effects. They showed also that the best way to remove non linear effects is to integrate explicitly the topography in the model. This principle is not only dedicated to the topography but can be extended to all finite media inside the observed domain.

Therefore, it is necessary to develop inversion methods capable of taking this non-linearity into account. To limit the financial cost of the acquisition and the computational cost of inversion, new inversion codes specifically dedicated to the dike and dam context have been developed (Fargier et al., 2011). The code InGEOTH-2D+ proposes a 2D inversion that integrates part of the full 3D geo-electrical behaviour of a dam (topography and water reservoir are included). The purpose of this code is twofold. The first purpose is to provide new discretization capabilities to better state the problem. The second purpose is to allow the inclusion of any explicit prior information that the geophysicist provides.

4.5 Results

To test the relevance of the presented techniques a measurement campaign has been carried out at the crest of a dam. An historical research, a topographic survey, a geological study, and a visual inspection were realized before the geo-electrical survey.

A dense Wenner-Schlumberger protocol was used because of its spatial resolution and robustness. Fig. 10 a) shows one electrical resistivity section obtained after inversion of the raw data without any external information. Fig. 10 b) represents the same section after normalization of the water reservoir effect and the topography. Fig. 10 c) shows the final result of the inversion obtained with InGEOHT - 2D+. Fig. 10 d) illustrates the inverse model used for the inversion shown in Fig 10 c). For all three results, and after four iterations, the convergence data criterion is less than 1%.

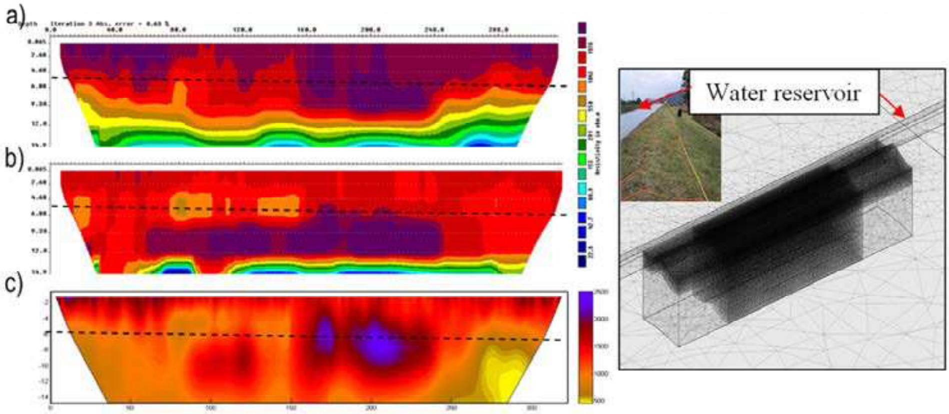

Fig. 10. Results of the the inversion process obtained a) without any correction procedure (Res2dinv®), b) with normalization of water reservoir effect and topography effect (Res2dinv®), c) with the InGEOHT - 2D+ inversion code. d) presents a view of the measurement campaign and The 2D+ inversion model used to inverse the result.

A first interpretation of the inverted section in Fig. 10 a) indicates that the medium is quite regular in the longitudinal direction and composed by two layers. The upper layer whose wall varies between 9 m and 12 m has a resistivity oscillating between 500 Ω.m and 2500 Ω.m. The resistivity of the lower layer decreases to 40 Ω.m. In Fig. 10 b) the electrical resistivity of the water reservoir was integrated in the inversion process (81 Ω.m). The effect of the normalization indicates that the influence of the lower layer decreases. This result suggests that the lower layer is in fact an artefact due to the presence of the water reservoir.

Figure 10.c), after applying InGEOHT - 2D+, shows that the effects of the water reservoir has been entirely removed (the lower conductive layer disappeared). The resistivity section is smoother than the two previous calculations except for three resistive anomalies between 9m and 12m depth. In conclusion, we think that this last result provide a better insight of the true behaviour of the dike and the detection of some suspicious zones will be further investigated by high resolution geophysical and geotechnical methods to validate this result.

5. Conclusion

In many countries, the regulation of hydraulic structures has recently been enhanced and is declined in classes depending on the issues in case of breakage. It stresses the need to know the level of safety of the structures, through in-depth diagnosis and analysis of risks, and to strengthen the surveillance. In France, these regulations now apply to 700 large dams, tens of thousands of small dams, and about 10 000 km of linear dikes.

We have presented in this chapter on going improvements in the global methodology of dike diagnosis in Europe. The stakeholders involved in the management of dikes must continue to integrate these improvements in their practices so that an efficient diagnosis should be drawn over time for a sustainable maintenance of the earthworks and dams.

Nowadays, the ERT method becomes the reference one for dike and dam geophysical investigations. Coupled with accurate 3D topographic data acquired with a LiDAR system, the 3D effects should be better integrated when interpreting the data. Those improvements will be all the more interesting for stakeholders (e.g. multi temporal analysis of long stretch dikes) as repetitive survey will be performed.

Phenomena like leakage or seepage are still difficult to detect and future research works on streaming potential (Bolève et al., 2007) and optic fibres (Khan et al., 2010) methods should supplement the available tools of stakeholders.

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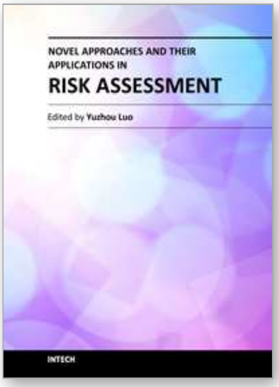

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