Geophysical and geotechnical methods for diagnosing flood protection dikes

Guide for implementation and interpretation

Cyrille Fauchard, Patrice Mériaux

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1 Introduction

The flood protection dikes that run alongside many French rivers have been modified and upgraded many times over the years. Often very old, these works are mostly made of earth and have been built in stages. Details of their structure are not generally known, and they are usually heterogeneous, either in transverse section through the dike (*e.g.* a weighted zone in one of the slopes) or in the longitudinal profile (*e.g.* a repaired breach).

The spectacular and occasionally dramatic floods of the last decade both in Europe and in the United States have confirmed the chronic vulnerability of these dikes and the need for their diagnostic analysis. Moreover, review of breach repair work (in some cases of recent repairs) clearly shows that this work has often been conducted in haste, with insufficient control of the filler materials and using materials that do not match the original construction materials. Details of the repair work tend to fade quickly from archived records, with the result that heterogeneities lay hidden within the body of the dike – potential points of weakness for the structure that must first be detected using reliable methods, and then characterised during a subsequent diagnosis.

In this context, the investigative work conducted to diagnose dikes now tends to combine geophysical methods with more traditional geotechnical methods (test drills, *in situ tests*, etc.). Compared with geotechnical methods, geophysical methods generally offer the advantage of very short exploration increments (that only slightly, if at all, affect the efficiency); however, they only produce "apparent" and overall values of a particular soil property.

As a general rule, difficulties can arise when applying geophysical or geotechnical methods to dikes:

– they are "dry" (no hydraulic head) for most of the time and the critical element in their vulnerability at times of flood, *i.e.* seepage, is absent at the time of the investigation;

– their great length poses a crucial problem in finding a balance between cost and technical performance when conducting investigative work.

To address these and other issues, the LCPC (French Public Works Research Laboratory) in Nantes and Cemagref in Aix-en-Provence, France, conducted experimental research from 1998 to 2004 within the framework of the "CriTerre" National research Project ("Improvement of soils and control of reinforced soils" – theme "Detection of soil anomalies"), coordinated by the IREX (French Institute for applied Research and Experimentation in Civil Engineering). The aim of this research was to test and evaluate, for two French dike systems (one on the Cher river in the "Indre-et-Loire" department and the other on the Agly coastal river in the "Pyrénées-Orientales" department), the high-efficiency geophysical and geotechnical surveying methods applicable to dikes, and to draw from this experimental work the methodological elements required for the optimal utilisation of these tools.

This experimental research work forms the basis for this guide, which describes a general, three-phase approach to the high-efficiency diagnosis of "dry dikes"[1].

The first phase of the diagnosis, the "preliminary studies", is an essential prerequisite for the study. It involves collecting as much information as possible about the history of the dike (construction, breach history), its external characteristics (topography, how it is maintained, signs of deterioration), and its role in the local system (local geology and river dynamics). This information is collated in various ways – searching through archives and analysing them, interviews with the manager responsible for the various structures and a visual inspection. This study must determine the nature of the component materials of the dike, the nature of the foundation on which it rests and the hydraulic and morphodynamic conditions that it must

1. Synonymous with: "flood protection dikes" that do not have to resist a permanent hydraulic head; these dikes are generally built above the normal water level of the river and are "dry" when the diagnostic survey is performed.

resist. The quality of the final diagnosis is dependent on the thorough and rigorous execution of this phase of the study.

The main aim of **the second phase** of the study – the geophysical survey – is to isolate heterogeneous portions of the dike, and to determine those sections of the structure which, due to their differing physical characteristics, may be the point of initiation of irreversible damage (particularly breaches) during a flood. The geophysical methods used must satisfy, as a minimum, the following two main requirements: firstly the need to survey over long distances and secondly the need to identify the degree of heterogeneity of the structure over its entire height (including its foundation). The information collected, following correlation with the preliminary studies, is then used firstly to define specific zones that are the focus for localised investigation methods to determine, in detail, the geometry across a horizontal or transverse section of the dike, and secondly to set up the geotechnical surveys that constitute phase three.

This third phase comprises various geotechnical tests and drillings that ascertain *in situ* the principal mechanical characteristics of the materials that make up the structure. The results obtained are used to calibrate the geophysical measurements, and can lead to the deployment of further localised geophysical investigations.

These three steps, if conducted correctly, provide all the elements required for a thorough investigation of a dry dike. Since methodological tools have been in short supply in the field of <u>geophysical surveying</u>, (but not for the first and the third phases mentioned above, that are already covered in various French guides: cf. bibliography), the methodology proposed in this guide includes a comprehensive description of the principles underpinning the geophysical methods, their implementation and interpretation. The aim of this guide is to provide owners, project managers, contractors or others with all the elements they require to assess the strengths and weaknesses of the dikes diagnosed. This work can then serve as the basis for reinforcement work or for more in-depth studies.

Although the principles of the method described herein were developed on dikes in France, they may be applied with confidence to flood protection dikes and levees in other countries around the world. For this reason, the original French version of this guide (written in 2004) has been translated into English for this edition.

2

Background to the civil engineering diagnosis of flood protection dikes

2.1 Nature, functions and composition of dikes

This section is a summary of chapter 1 of the guide produced by Mériaux *et al.* (2001).

2.1.1 Definition

A dike (or levee, in the context of this guide) is a linear structure that protects against flooding, with at least some of the structure rising above the flood plain. Its main function is to contain high water levels during floods and thus protect areas that are naturally prone to flooding. A typical cross-section through a dike is a berm of earth built up from the original ground with the protected zone[2] on one side and the river bed on the other. Depending on the circumstances, the dike is built either alongside the main channel, or set back from the river on the flood plain (figure 1).

2. Also called: [protected] valley.

Dikes are usually “dry” structures, insofar as hydraulic head is only a factor at times of flood; this is an important point when considering how they work and in selecting appropriate investigative techniques.

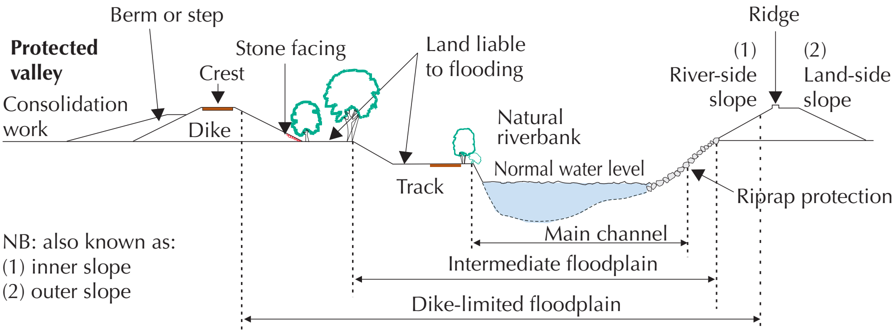

Figure 1 – Typical cross-section across a dike-protected valley (Mériaux *et al.*, 2001)

2.1.2 How dike systems work

Dike systems work as follows:

1. Rising water levels cause the river to break out of its main channel (figure 2) and spill out over the flood plain. The dike stops the flooding spreading to the protected valley.

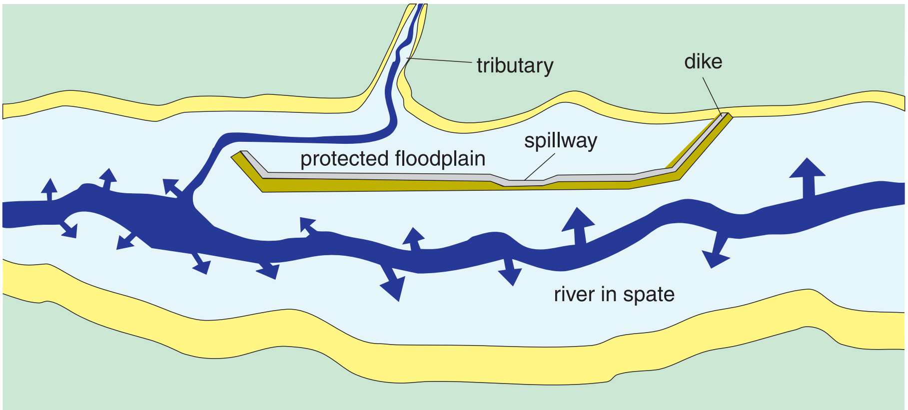

Figure 2 – Flood waters spreading into a dike-protected flood plain (Mériaux *et al.*, 2001)

2. The dike system is designed to limit the impact of low- and medium-severity floods on the valley that it protects. Inevitably, however, compared to the situation with no dikes, the contained water rises to a higher level, and especially if the diked channel is narrow (a common feature in urban areas).

3. In this scenario, the potential for flood peak reduction (relieving maximum downstream flow rates by inundating the flood plain) is limited.

4. Even so, the protected zones may be flooded by a rise in the water table (figure 3), by runoff from a catchment basin, or even by the river backing up into a tributary.

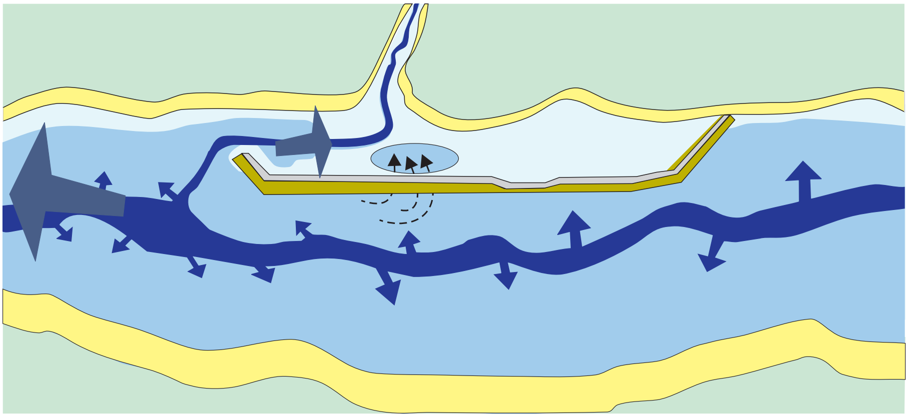

Figure 3 – Flooding of a valley by backing up, by runoff from a catchment basin or a rise in the water table (Mériaux *et al.*, 2001)

5. To reduce the risk of uncontrolled overtopping in cases of severe flooding, spillways (figure 4) are sometimes built into the dikes. These spillways can also be used to reduce downstream flow rates by flooding less critical valleys upstream.

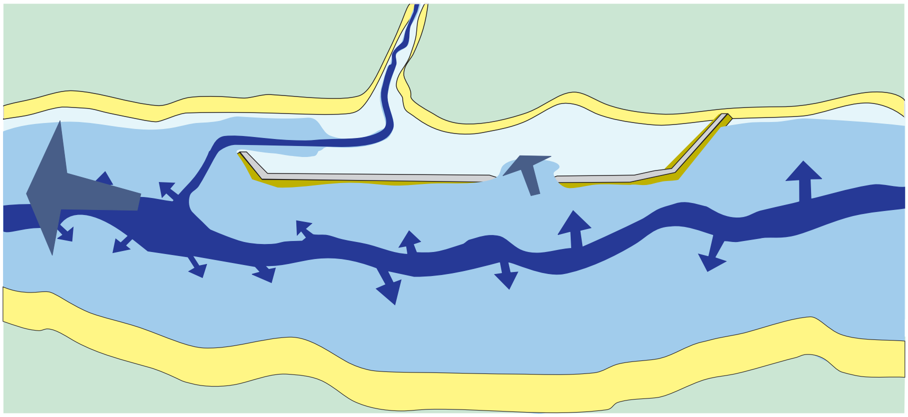

Figure 4 – Operation of a spillway (Mériaux *et al.*, 2001)

6. When river levels are exceptionally high the entire valley will flood, due either to the operation of a spillway, or to the effect of one or more breaches opening in the dike.

2.1.3 Composition of a dike

a) Earthfill dike

A dike is generally made of loose materials (sand, silt-loam, clay). Its morphological and mechanical characteristics vary greatly, depending on its geographical location, history, the water courses that it borders and on the floods that it is designed to contain.

Most French dikes were first constructed many years ago, and built using the resources and techniques available at the time. Consequently, the materials that make up the body of the dike were generally sourced from close to the structure and tend to be sandy in the middle reaches of rivers, and loamy nearer to the mouth. This approach produced poorly-compacted structures, insufficiently pervious and with no cut-off trench into the foundation. Moreover, they have been strengthened and/or raised over the years in response to the damage caused by historical floods (figure 5). Their heterogeneity is even greater, either through a transverse section (due to raising or broadening) or in the longitudinal profile (*e.g.* post-breach repair work).

Clearly dikes are highly heterogeneous structures, both in type and composition (figures 6 and 7).

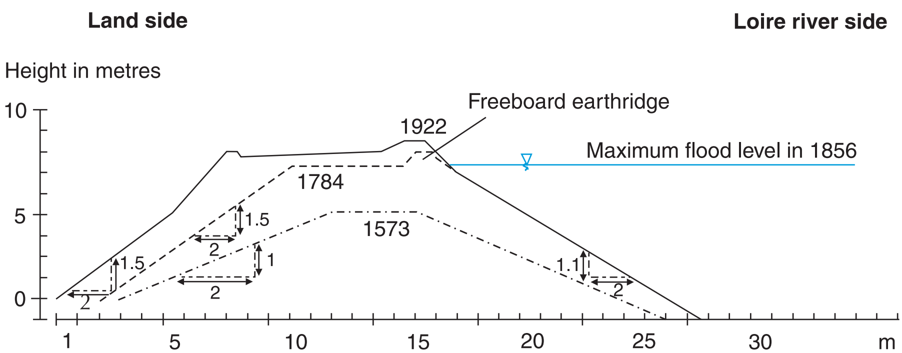

Figure 5 – Typical cross-section of a Loire river levee before recent strengthening work, showing the work conducted after historical floods (Dion, 1934)

b) The immediate environment

The sloping surfaces of dikes are generally protected by grassing. On the river side, sections in contact with the main channel are often protected by a masonry pitching, in some cases covered by a natural deposit of silt or by vegetation.

In zones exposed to scouring, linear protective features, generally made from secant wood piles, have sometimes been used at the toe of the river-side slope of the dike.

Finally, in order to provide a freeboard that can let the dike resist a maximum design flood, the crest of the structure is often topped with a ridge of earth or a small masonry wall, called a “banquette” in French.

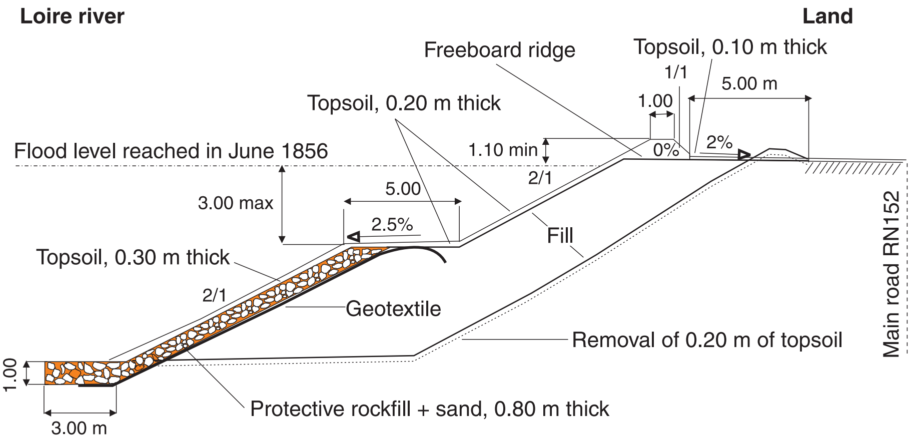

Figure 6 – Typical cross-section showing reinforcement on the Loire river side of the Fondettes-Luynes dike – DDE Project Indre-et-Loire (1997)

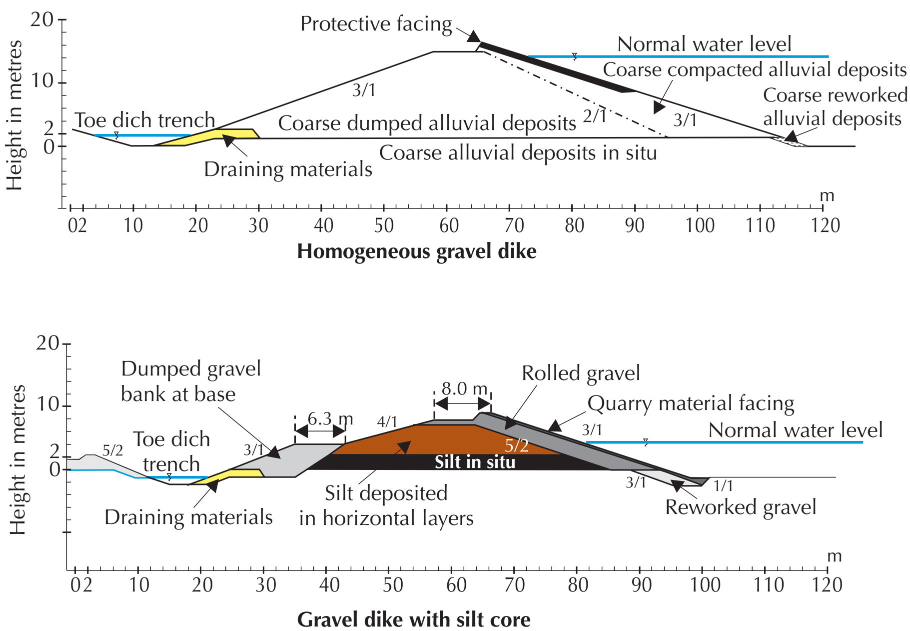

Figure 7 – Typical cross-sections of a dike for a hydroelectric development on the Rhone river (Mériaux *et al.*, 2001, taken from a CNR diagram)

Currently, the design of this type of structure is very similar to that of small earthfill dams or of embankments for hydroelectric developments (figure 7). A soil mechanics study must be performed to determine the mechanical and sealing characteristics of the materials. The dike may be divided up into zones to separate the sealing function from the mechanical stability function. Particular attention must be paid to the problem of draining seepage water away from the dike, which may involve the use of draining materials. The reader may wish to refer to Degoutte (1997) for a description of construction principles for small dams.

This guide will not dwell on the design of new dikes, since its primary focus is on existing dikes and their diagnosis.

c) Quay walls made from masonry

When the available width for a structure is limited, which is often the case when a river passes through an urban area – "gravity retaining wall" type dikes are built. Older dikes are made from cut stone, whereas more recent examples are made of concrete. Their foundations may be on piles. On the land side, they may be supported by a shoulder of earth or rock, and in some cases are topped with a road.

d) Spillways

Spillways (figure 8) are designed to come into operation only during rare floods (typically to cope with hundred-year floods). They are normally a few dozen centimetres (typically 1 metre) lower than the crest of the dike. They spill water as the flood peaks into a less critical zone such as a flood meadow and thus prevent or delay an overtopping-type failure of the dike. Spillways are low points built into the longitudinal section of the dike. They usually consist of a weir, with a chute and then a stilling basin on the land side slope to control and dissipate the energy of the flowing water. The concrete or masonry sill is topped in some cases by a sand ridge (also called "banquette"), which is slightly lower than the crest of the dike. This "banquette" is a deliberate point of weakness that is eroded rapidly in the event of overtopping, and its function is to delay the operation of the spillway, so as to optimise its effect on peak water levels.

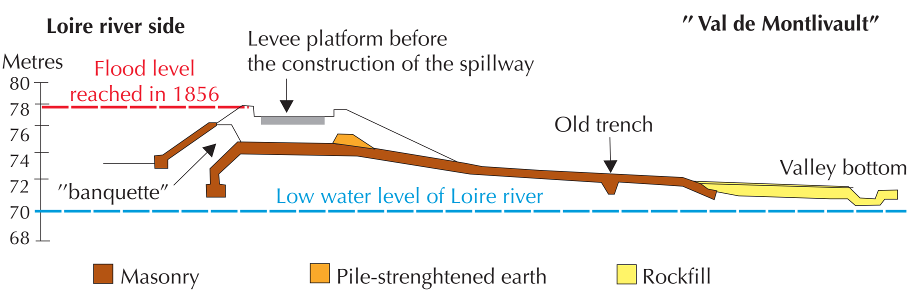

Figure 8 – Typical cross-section of an overflow weir in the Montlivault dike (Loir-et-Cher) (1890) (Lino *et al.*, 2000)

e) Particular structures

It is not unusual to find a variety of structures in dikes, often traversing and in many cases difficult to spot: buried channels, tunnels, aqueducts, various pipes and cables (hydraulics, electrical, telephone, etc.) travelling along or through the dike,