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Levee safety assessments using an index-based method

Diagnostic de digues par méthode à base d'indicateurs

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ABSTRACT: Levees can fail because of different types of mechanisms: external erosions, internal erosions, instabilities. These mechanisms can act separately or in a more complex failure scenarios, leading to a breach, a failure of the levee system, and the flooding of inhabited areas. Usually, more than one mechanism can be involved in a breach. As an example, the collapse of a protection revetment can lead to external erosion of the impervious upstream slope of a levee, which can lead to seepage and internal erosion, which can then lead to the breach. In this paper we present methods used in France for failure mode analysis and performance assessment of levees in regard to the main failure scenarios. Our failure mode analysis is briefly presented, as well as three methods for estimating the safety of levees. One of these methods, based on the use of indexes is presented in detail. This index-based method allows to use many different type of data and to combine them in different steps using expert-knowledge based rules: raw data is combined into status indicators representative of geotechnical characteristics of levee segments components, status indicators are combined into functional criteria which represent the performance of a geotechnical function, functional criteria are combined into performance indicators which represent the safety of the levee relatively to a failure scenario.

RÉSUMÉ: Les digues peuvent défaillir du fait de différents types de mécanismes : érosions externes, érosions internes, instabilités. Ces mécanismes peuvent agir séparément ou dans des scénario de défaillance plus complexe, conduisant à une brèche, une défaillance du système de digues et donc à l'inondation de zones habitées. Habituellement, plusieurs mécanismes peuvent être impliqués dans une brèche. Par exemple, l'effondrement d'une protection peut entraîner l'érosion du talus imperméable de la digue, ce qui peut entraîner des infiltrations et une érosion interne, pouvant ensuite conduire à la brèche. Dans cet article, nous présentons les méthodes utilisées en France pour l'analyse des modes de défaillance et l'évaluation de la performance des digues vis-à-vis des principaux scénarios de défaillance. Notre analyse des modes de défaillance est brièvement présentée, ainsi que trois méthodes d'estimation de la sûreté des digues. L'une de ces méthodes, basée sur l'utilisation d'indicateurs, est présentée en détail. Cette méthode à base d'indicateurs permet d'utiliser différents types de données et de les combiner au travers de différentes étapes reposant sur des règles établies de manière experte : les données brutes sont combinées dans des indicateurs d'état représentatifs des caractéristiques géotechniques des composants des tronçons de digues, les indicateurs d'état sont combinés dans des critères fonctionnels qui traduisent la performance d'une fonction géotechnique, les critères fonctionnels sont combinés dans des indicateurs de performance qui traduisent la sûreté de la digue pour un scénario de défaillance.

Keywords: Levee safety; levee assessment; failure modes

INTRODUCTION

River levees are long linear civil engineering structures. They are designed to protect an area, naturally prone to flooding, against natural river floods or sea storm surges up to a certain water level related to the height of the levee. Even this level of protection is limited, as the levee may fail (breach) before water reaches the crest of the levee system.

Since the 2000s, regulations in France and in other European countries require that levee managers should perform visual inspections and levee safety assessments at regular intervals. Levee managers may then prioritize their maintenance operations. In many cases, a French regulatory levee hazard study is also required and must be based on precise levee safety assessments.

Levee safety assessment is a complex process which aims to evaluate the probability of a levee failure, including the safety level (under which this probability is neglectible) and the danger level (above which this probability is certain). It requires as input informations of varying natures like measurements, observations, estimations, status… Designing a method applicable to most cases and computer-friendly requires uniformisation of the information format, or a specific way to make information impact coefficients or calculations in a way or another. Several levee assessment methods already exist, each with its strengths and flaws. These methods share the same pattern: First, levee system is divided in relatively short homogeneous elements, *e.g.* linear levee segments of few decameters. Then several failure scenarios (identified for example by failure modes and effects analysis), including mechanisms of deterioration, are estimated on each of these segments, for a series of loading events of different probabilty. This paper focuses on a levee assessment relying on indexes, and the failure modes and effects analysis method behind it. First, notions of failure scenario, failure modes and effects analysis, deterioration mechanisms, and safety assessment will be defined. Then we will illustrate levee assessment with three existing methods, the third being the index based one, which will be extensively described. Finally, the failure modes and effects analysis will be discussed, detailing the link bewteen physics and fonctionnality of every discertized element.

1 FAILURE MODES AND SAFETY ASSESSMENTS

1.1 Structural failure scenarios of levees

A levee segment is made up of components (main body, drain, filter, erosion protection, sealing element, etc.) whose structural properties combine to ensure its sustainability under loading situation. Levee components are characterized by their functions: stability, impermeability, drainage, filtration, etc. Failure of a component occurs when one or more of its functions are no longer effective, which mostly results from the effect of deterioration mechanisms (see 1.2).

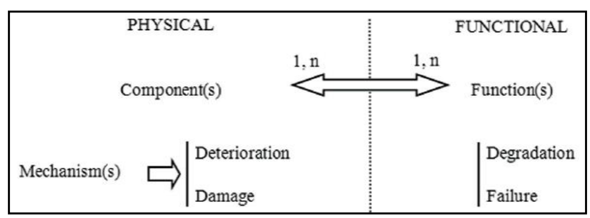

Figure 1: Structural failure involves both physical and functional phenomena. (Ciria et al., 2013)

A structural failure scenario leads to a breach and consists in a process which involves both physical and functional phenomenon (see figure 1). The initial deterioration mechanisms in structural failure scenarios are triggered by external loads on the levee. They may cause damage to or destroy one or several components and lead to degradation or failure of one or more associated functions. The operational degradation or failure can then trigger or aggravate mechanisms (see figure 4, section 3).

Based on fonctional analysis principle, failure modes and effects analysis (FMEA) methods, such as the one proposed in section 3, organize the analysis of structural failure scenarios and permit to identify them exhaustively.

1.2 Mechanisms of deterioration of levees

Deterioration mechanisms can be grouped into three main categories: external erosion, internal erosion and instabilities (CFBR, 2016).

External erosion groups all mechanisms that cause separation of materials under the influence of loads that are applied to the external surface of the levee. This takes place when surface materials do not have enough resistance to these loads. The separation of materials can alter the geometry of defense systems and contribute to their reduced resistance.

Internal erosion processes are caused by the flow of water through the embankment structure or its foundation. They include the migration or separation of the soil grains, at material or interface level, as the hydraulic gradient reaches a threshold referred to as the critical hydraulic gradient. These processes are particularly sensitive to heterogeneity, with more permeable areas concentrating flows and increasing flow constraints. Four types of internal erosion can be identified: suffusion, contact erosion, backward erosion and concentrated leak erosion (in holes) (Morris, 2012).

Instability can be divided into two main groups: localized instability (such as sliding or collapse) and mass instability leading to diffuse failure (such as liquefaction). Instabilities are primarily linked to: the increase in bank slopes, increased hydraulic pressures within the structure, increased loads on the structure or the foundations, and the unfavorable evolution of component materials or foundation characteristics over time. The main instability mechanisms of earth structures are: superficial sliding, rotational sliding, translational sliding, collapse, liquefaction, subsidence, and cracking.

1.3 Safety assessment of levees

A safety 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 reliability to achieve its flood protection function (Ciria et al., 2013).

For each levee segments, the assessment process must provide an estimation of the potentiality of failure for each potential failure scenarios, for relevent loading events.

There are different assessment methods, all based on a combination of data, using expert judgment, index based methods, empirical models - physical and/or mathematical models.

2 LEVEE ASSESSMENT METHODS

Different methods have been created for levee assessment, in order to provide managers with scientific methods and technical tools for levees management. Levees can be divided in segments of constant or varying length, where levee profile is supposed constant. Probability of the first breach is then calculated for every failure mechanism, for every flood type, and for every segment. These values are finally used to calculate a global annual failure probability for each segment. Here are given representative examples of methodologies using this segmentation.

2.1 The "crible" method

After the major flood of 2003 in the south of France, 15 km of Petit-Rhône levee needed to be reinforced. In order to run a safety assessment if these levees, a spreadsheet based method named “crible” has been developped and described in Soulat et al. (2013).

Levee is divided in 20 m long segments which are attributed the following characteristics:
-Profile geometry, extracted from the digital terrain model, resulting in several points which

give dimensions needed for calculations (e.g. levee height, flood channel length, ...).
-Geotechnics and geophysics, simplified in 4 embankment-foundation configurations, chosen by the operator.
-Water height.

On every segment, defined by the previous characteristics, the probability of breach Pb is calculated for several failure mechanisms. The corresponding hazards are as follow:
-Overflowing, which is considered to always lead to breachPb is a function of probability of flood, freeboard, fetch, hydraulic model accuracy and sensibility.
-Internal erosion. Pb is here estimated by a security factor, related to the critical height expressed by the Seillmeijer method.
-Slope stability. Here, Pb is estimated using simplified Fellenius method.
-Scour, where Pb is a fonction of the distance between levee and minor bed, adjusted by two factors: Nsol representing the influence of the ground composition, and Nsit representing the existing erosion witnessed on site.

2.2 The CARDigues method

A spreadsheet based method has been developped in 2008 for the assessment of 40 Loire levee systems (600 km), divided in 50 m segments (Durand et al., 2016; Maurin et al., 2013). This method allows the integration of information which were not usually used in computer based safety assessments: structural data and disorders (e.g. presence of burrows, pipes, …), reinforcement data and management data (i.e. the ability of the levee manager to anticipate or repair a deterioration or failure of the levee components). In each segment, embankment and ground components are supposed constant: an embankment made of sandy silt, a foundation of optional clayey silt oversand and gravel, lying on an impervious substratum.

Erosion by overflowing and internal erosion are considered as the only mechanisms directly leading to breach.
-Overflowing is a function of freeboard, the presence and defined efficient height of berm.
-Internal erosion is calculated using the Blight method.

The other hazards are considered as triggers of internal erosion, which then leads to breach:
-Slope instability is estimated by a security factor derived from the ultimate limit state described by the Bishop method. This factor can also be manually input by the operator if relevant events have been observed (e.g. a building included in the levee, slope protection, …). If this hazard is considered happening, internal erosion probability is multiplied by 1.1.
-Scour occurrence probability is here a function of the width of river bank, eventually refined by aggravating (e.g. scour ditch, obstacles at levee toe, …) or favorable factors (e.g. rock berm, soft protection, …). Scour occurrence multiplies slope instability probability by 4.
-Uplift probability is given by a safety factor describe by the USACE method (. It affects the Blight coefficient used in internal erosion probability.

2.3 The Digsure method

Digsure is a levee performance assessment method based on indicators. It produces probabilistic distributions for levee performance indicators related to failure scenarios (Peyras et al., 2015).

Each failure scenario is identified through a FMEA process based on a functional model (see 1.1 and 3). Then, in cooperation with a group of experts in hydraulic structures, each failure scenario is modelled through 3 groups of variables (see figure 2):
-Status indicators: these indexes are fundamentals that detail the information to be considered for determining each functional criterion. These result from raw data or information interpreted or inferred from

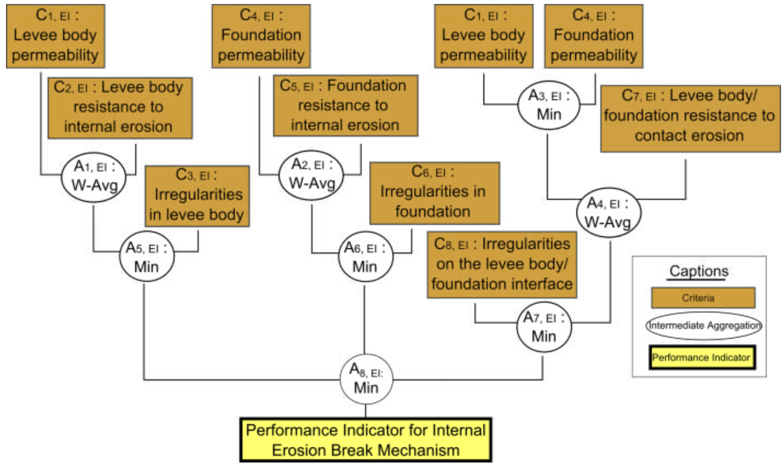

Figure 2: Calculation rule for internal erosion performance indicator. Min = minimum; W-Avg = weighed average. (Vuillet et al. 2012)

measures, observations, computations or material.

-Functional criteria: decision-making indexes used to assess levee component performance. They help to determine how well the levee component functions are performed. A number of status indicators must be reviewed before a criterion can be determined.

-Performance indicators: these indexes determine levee performance against levee failure scenarios by combining several functional criteria.

Based on these indexes, the functional model provides a representation of levee failure senarios as sequences of successive failures of technical functions according to functional criteria and their related status indicators (Vuillet et al. 2012 ; Serre et al. 2007).

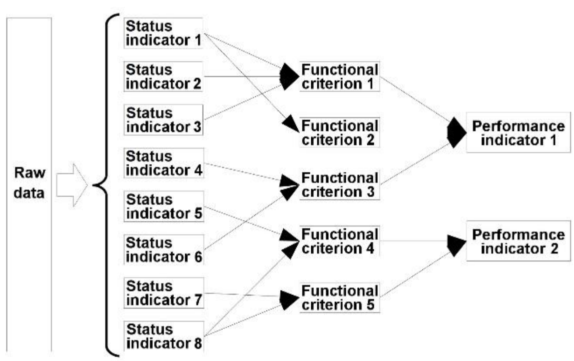

Figure 3: Generic structure and variables of the assessment model. (Vuillet et al. 2012)

Digsure method models levees as continuous linear objects divided by dynamic segmentation. The linear levee structure is split into homogenous levee segments, according to changes in the spatially referenced data used to assess status indicator values.

For each homogeneous levee segment, a multi-criteria method is implemented to calculate performance indicators by combining functional criteria values according to rules (see figure 3) specific to each levee failure scenario (Vuillet et al., 2012). Values for functional criteria and performance indicators are estimated and harmonized through a continuous preference scale between [0 and 10].

Many imperfections may characterize the data used to determine the status indicators: uncertainties on the representativeness of a local investigation, incomplete data due to the absence of levee monitoring during floods, etc. Such imperfections are traducted in terms of probabilistic distributions for functional criteria values and propagated, through calculation rules, to performance indicators values.

As shown in the example of table 1, functional criteria values are estimated according to associated status indicators, themselves estimated according to specific data (Serre et al. 2008).

Table 1. Status indicators and associated data for the "Levee body permeability criterion" (adapted from Vuillet et al. 2012).

Functional criteria	Status indicators	Data
$C_{1,EI}$ – Levee body permeability	Material permeability	Permeability measurement Granulometry Compaction Material variability Hydraulic loading duration
	Geometry	Geometry taking into account included singularities
	Seepage	Rate of flow Location (top, mid height, base) Presence of material in the water

To use the model of safety assessment previously established by the experts, the user of the method must implement each status indicators. Some indicators require only one data (direct indicators) while others require several data of different natures (visual data, historical data, geotechnical tests, modelling, etc.) and some expertise from the user.

3 A METHODOLOGY FOR STRUCTURAL FAILURE ANALYSIS

Failure is the inability for a system to achieve a defined performance threshold for a given function (Ciria et al., 2013 ; Morris, 2008).

For a levee system, failure can be defined as a situation for which an unintentional inundation of the protected area becomes possible. Such a situation results from a hydraulic failure for one or several levee segments (Simm et al. 2012). The most damaging cause of hydraulique failure is a breach in a levee segment which results from a 'structural failure' scenario (Ciria et al., 2013).

As levee systems are rarely uniform in materials, methods of construction, geometry or reliability, the process of failure analysis usually starts with a functions analysis which identifies the components of the levee system, the functions of these components', and the functionally homogenous lengths of the levee (Ciria et al., 2013). The process then continues with a failure analysis of functions which aims to identify levee systems failure scenarios to facilitate the analysis of levee system safety (Ciria et al., 2013).

The French Research Institute Irstea has developed methods for functional analysis and FMEA of levee systems (Tourment et al., 2013, 2015, Tourment et al., 2018). Together, these methods, which are well adapted to study hydraulic works (Modarres, 1993 ; Peyras, 2006), can be used to analyze, identify and represent failure scenarios, in order to select those that are most representative to study further, and to conduct efficient and well-structured levee performance assessments.

The structural functional analysis is conducted at the scale of the structural components (e.g. erosion protection, levee bodies, filters, drains) that form structurally homogeneous levee segments (see 1.1). These ones are studied and analyzed to determine and characterize their technical functions, considering the protection function of each levee segment.

The main functions of structural components for earth levees are: stability, impermeability, drainage, filtration, auto-filtration, and protection against erosion. According to its specificities and to the nature of the other components, a same component can support several functions.

Based on the results of the functional analysis, Irstea FMEA method formalize the definition of functions failure modes of levee system components, and of their causes and their effects. Then, by identifying the cause-and-effect relationships existing between failures of levee

Table 2. Example of FMEA analysis result for a revetment levee component (Tourment et al., 2015).

Components	**Functions**	**Degradations of functions**	**Failure of functions**	**Possible mechanisms**	**Causes of degradations or failures of functions (deterioration/damage of components)**	**Consequences of degradations or failures of functions (mechanisms)**
Revetment	Protection against external erosion	Deteriorated protection	No more protection	Overflowing Erosion	Partial disappearance	- Overflowing erosion of revetment
					Total disappearance	- Overflowing erosion of levee body
				External erosion	Partial disappearance	- External erosion of revetment
					Total disappearance	- External erosion of levee body

components functions, the method make it possible to define every failure scenario of levee segments (see section 1.1 and figure 4).

Table 2 shows an extract of a FMEA analysis result through the example of a revetment levee component. First, the analysis identify the function of the component and characterizes its degradation and failure states. Then, mechanisms for which the component is vulnerable are identified, as well as causes of degradations or failures of functions due to mechanisms actions and consequences in terms of mechanisms impacting the same (here the revetment) or other (here the levee body) components.

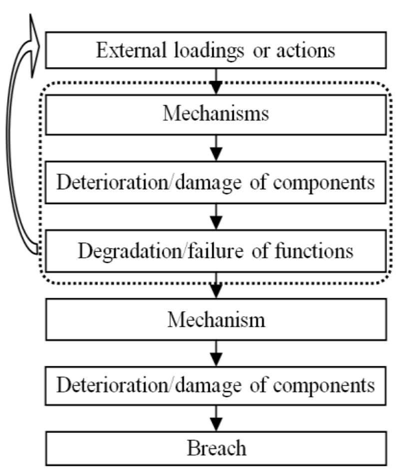

Figure 4: Process of structurel failure scenario (*Ciria et al., 2013; Tourment et al., 2013)*

Such scenarios can stop when external loadings or actions cease. The state of the levee is then deteriorated (which means that the functions of some of its components are degraded or failed) but not necessarily ruined (meaning that there is a breach). The scenario can then start again when a new loading/action occurs.

4 PROSPECT AND CONCLUSION

The three different assessment methods are all based on failure modes involving different mechanisms and the failure of multiple functions. We present a structural failure mode analysis which can help determine the different failure scenarios for any specific levee cross section, and an index based method which can be used to assess these scenarios using potentially all available data, whatever its form and nature. At the moment this assessment method has been developed and validated through different research projects and PhDs works, each working on a specific stage of the method, but it still has to be developed as an operational tool. It is planned to develop a specific module of SIRS Digues (Tourment, 2004), the data management system for levee managers, to implement this method, which will help its practical use. SIRS data model has been since its initial conception designed to be used for this type of assessment.

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