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KEYNOTE LECTURE
Levee failure scenarios - Complex levee failure scenarios and examples

CONFERENCIA MAGISTRAL
Escenarios de ruptura de diques: escenarios y ejemplos complejos de ruptura de diques

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I N F O R M A T I O N

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- *Levee failure*
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A B S T R A C T

Flood protection levee failures (the end result of which is a breach and the resulting flooding of protected areas) are most often the consequence not of a single deterioration mechanism but of a chain of deterioration mechanisms, some of which may, depending on the conditions, take place simultaneously. The identification of these failure scenarios is useful or even necessary to achieve different objectives:
- within the framework of carrying out structural diagnosis, safety assessment, risk analysis, hazard study, to properly assess the performance of the levee;
- in the event of a breach in the embankment or a need for reinforcement, to best adapt the work to the mechanisms that caused or might cause the breach;
- as part of the development of methods for evaluating the probabilities of rupture, to be as consistent as possible with the reality of the phenomena and their sequences.
The classic "failure modes" (external erosion, internal erosion, erosion by overflow, sliding, hydraulic uplift of the downstream toe, etc.), which are still often considered in levee assessments, are named after a single mechanism of deterioration, in general the initiating or predominant mechanism of scenarios that can lead to failure. This practice suggests that a single mechanism is at work when a levee breaks, which often leads to errors in diagnosis and/or performance evaluation during studies conducted too quickly. Furthermore, considering the possible sequences when designing a structure can lead to a safer and/or in some cases more economical design.
In this communication, the author develops the benefits of using a failure scenario approach. Contributions from several French and international bibliographic sources available on the subject are presented, as well as several examples of simple or complex scenarios. A method based on functional analysis for the identification of possible failure scenarios for a given levee is presented.

R E S U M E N

Las fallas de los diques de protección contra las inundaciones (cuyo resultado final es la ruptura y la consiguiente inundación en áreas protegidas) son en la mayoría de los casos la consecuencia no solo de un mecanismo de deterioro sino de una cadena de mecanismos de deterioro, algunos de los cuales pueden, dependiendo de la situación. condiciones, occurir simultáneamente. Identificar estos escenarios de ruptura es útil o incluso necesario para lograr diferentes objetivos:
- como parte de la realización de un diagnóstico estructural, evaluación de seguridad, análisis de riesgos, para evaluar adecuadamente el desempeño del dique;
- en caso de rotura del dique o de necesidad de refuerzo, adaptar mejor las obras a los mecanismos que provocaron o corren el riesgo de provocar la rotura;
- como parte del desarrollo de métodos para evaluar las probabilidades de ruptura, que sean más consistentes con la realidad de los fenómenos y sus secuencias.

Los "modos de ruptura" clásicos (erosión externa, erosión interna, erosión por desborde, deslizamiento, levantamiento hidráulico del pie aguas abajo, etc.), que todavía se consideran a menudo en el diagnóstico de diques, reciben su nombre de un único mecanismo de deterioro. Generalmente el mecanismo iniciador o predominante de escenarios que podrían conducir a la ruptura. Esta práctica sugiere que sólo un mecanismo está en desarollo cuando se rompe un dique, lo que a menudo conduce a errores en el diagnóstico y/o evaluación del desempeño durante estudios realizados demasiado rápido. Además, considerar posibles secuencias al diseñar una estructura puede conducir a un diseño más seguro y/o en ciertos casos, más económico.
En esta comunicación, el autor desarrolla los beneficios de utilizar un enfoque de escenario de ruptura. Se presentan contribuciones de varias fuentes bibliográficas francesas e internacionales disponibles sobre el tema, así como varios ejemplos de escenarios simples o complejos. Se presenta un método basado en el análisis funcional para la identificación de posibles escenarios de ruptura para un dique determinado.

1 INTRODUCTION

Failure of embankment or composite (embankment and rigid materials) protection levees are most often the consequence of several elementary mechanisms occurring successively and/or simultaneously. In current engineering practice, for reasons of both simplicity and availability of documentary resources, limit state equations and specific analysis methods, the different elementary mechanisms are unfortunately still often treated independently.

In this article we present an analytical approach to levee failures based on a synthesis of previous work, with the aim of promoting it so that it can be generalized in the various engineering activities relating to levees and flood protection systems: assessments, diagnostics, risk analyses, design, justification. We thus hope to formalize a set of complementary concepts, so that the profession shares a common approach and vocabulary, to also facilitate the progression of practices (works, assessments).

2 THE “FAILURE MODES” OF LEVEES

2.1 Deterioration and failure mechanisms

A failure in a levee, the result of one or more often several mechanisms of deterioration or rupture of the materials that compose it, results in a breach in the structure, that is to say an opening which can allow the passage of water through the levee into the protected area; consequently, in this case the structure no longer fulfils its protective function. The different mechanisms of deterioration or rupture of embankment materials are generally classified into three families: external erosion (by current, waves, shocks, overflow or crossing paths), internal erosion (suffusion, contact erosion, internal regressive erosion, conduit erosion) and instabilities (shear leading to sliding or collapse, liquefaction, etc.). This list is not exhaustive as many mechanisms are still poorly identified and/or need to be better analysed, like those caused by freeze-thaw or humidity-drought cycles.

2.2 "Failure modes" of levees

Usually, the four classic failure modes of river levees were named after a mechanism (Mériaux et al., 2007), or even after the action which was at their origin: overflow (more precisely: erosion by overflow), external erosion, internal erosion, slope sliding.

Going into detail, external erosion by the current as well as slope sliding rarely lead to a levee breach on their own. For example, external erosion must be followed by sliding or collapse, and sliding must be followed, for example, by internal erosion. Note that even internal erosion and overflow, which can potentially lead to a breach on their own, can nevertheless be associated with other mechanisms. For example, the Saint-Laurent-de-la-Salanque breach on the Agly river, during the 1999 flood, has often been attributed to overflow, because significant erosion linked to the overflows over a very large part of the length of the levee (several kilometres). However, the breach took place precisely at the crossing of a pipe from the municipal wastewater treatment plant. If we analyse the causes of the breach by admitting that there may be several mechanisms at work, we can strongly suspect that a phenomenon of internal erosion due to the presence of crossing pipes played a preponderant role in the location of the breach (Tourment et al., 2018).

These four "failure modes" have often been supplemented by a fifth, hydraulic uplifting (or "cracking") of the downstream foot. This mechanism occurring at the level of the natural terrain at the foot of the levee on the protected zone side must also be followed by other mechanisms in order to lead to a breach, most often at least regressive internal erosion. This mechanism can be involved in the family of scenarios involving sand boils presented in 3.2.

2.3 Hydraulic failure and structural failure

In a flood protection system risk analysis framework, it is important to distinguish between hydraulic and structural failures which, although not always independent, are nevertheless clearly different (Tourment et al., 2015). In English the word "failure" is used to talk either about a material damage or about the inability to achieve a specific performance. This may have created a certain ambiguity between these two notions. Hydraulic failure of a levee concerns the flood protection function, it is therefore evaluated at the level of the levee system (which, as a whole, ensures the protection function) and corresponds to flooding before the protection level is reached, whereas structural failure (a rupture or a breach) concerns a levee section and corresponds to a rupture before reaching the safety level. A hydraulic failure scenario results in an inundation where the protected area is flooded before the nominal protection level of the levee system is reached; a structural failure scenario results in the rupture of a levee section. Structural failure can induce hydraulic failure and viceversa. The differences and links between these two types of failures is illustrated in figure 1. Hydraulic failures are not the subject of this article, so we will not go into more detail about them, but it was appropriate to present this duality and potential ambiguity that must be kept in mind.

2.4 Failure scenarios

To avoid any ambiguity, it is therefore preferable to distinguish mechanisms and scenarios by using the appropriate term, and to try to avoid the expression "failure modes". Furthermore, the failure scenarios can be relatively complex and are conditioned by the composition of the levee (components, zoning, transitions) and by the characteristics and actions of the surrounding environment, it is not desirable to try to create a generic list of all possible scenarios, given their potentially huge number.

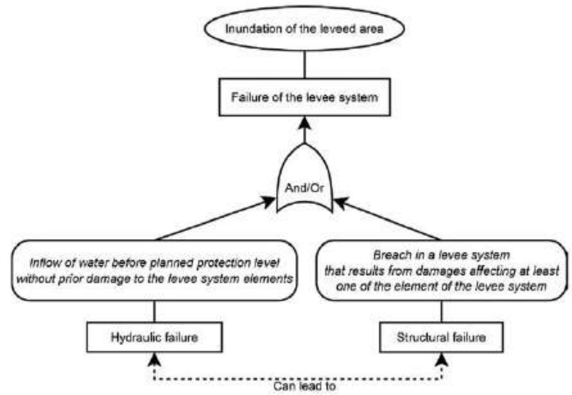


Figure 1. Hydraulic and structural levee system failures

The International Levee Handbook, or ILH in short, (CIRIA, 2013) validated this scenario-based approach in its chapter 3 devoted, among other things, to levee failures. It was also highlighted the interest to clearly distinguish, within a scenario, the stresses and actions (generally hydraulic) at the origin of mechanisms, the mechanisms themselves of deterioration or damage to components and the failures of the associated functions of components, which in turn can cause the appearance of other mechanisms (figure 2).

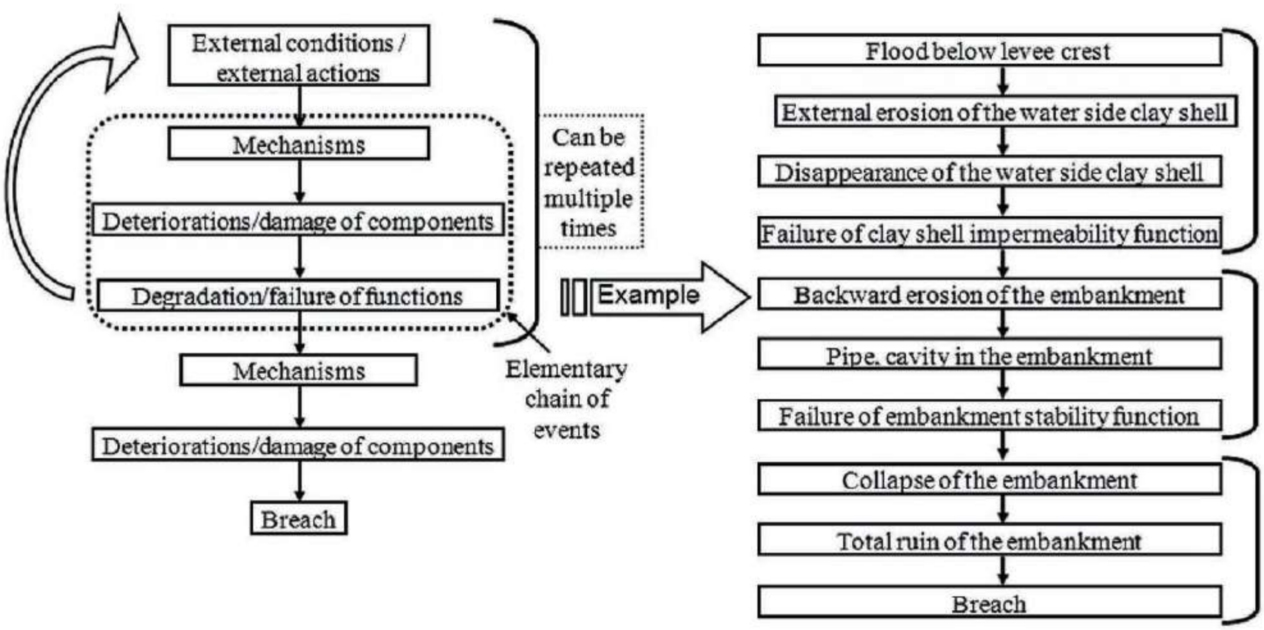


Figure 2. Scenarios leading to a levee breach (R. Tourment, from the ILH)

The Technical Committee on Levees of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE TC201) recently published a report focused on this levee failure scenarios approach that combine several mechanisms (Van et al., 2022). A “generic” flowchart was proposed (figure 3) presenting the possible sequence of multiple mechanisms and especially the way in which they can interact; the most common mechanisms are there. This flowchart is probably not the most complete possible, but it is possible to include a large number of failure scenarios ("failure paths" in the original version); it was also used in the report to represent nine cases of levee failures, which made it possible to verify its applicability.

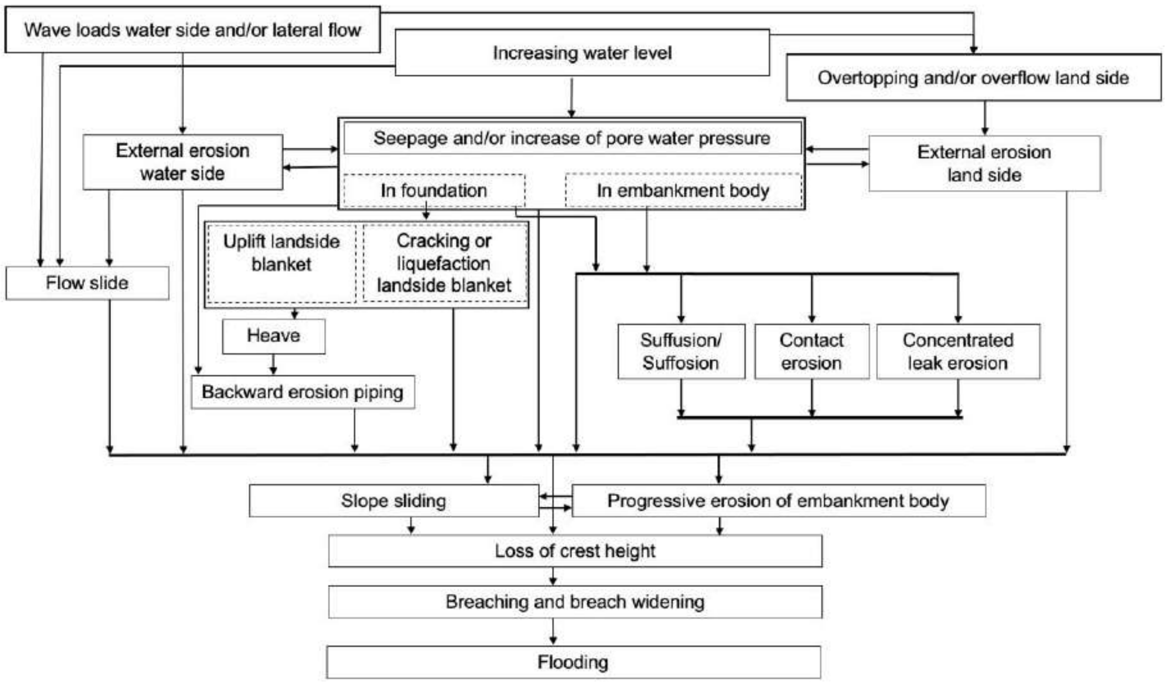


Figure 3. Flowchart presenting the main mechanisms in embankments and how they can interact within a levee failure scenario (from Van et al., 2022)

At the French level, the levee failure scenario approach is part of the method proposed by INRAE for the risk analysis of flood protection systems (Tourment & Beullac, 2019) which will be mentioned later in section 4.3. This method has been used in several regulatory hazard studies of levee systems in France (hazard studies are based on a safety assessment, a risk analysis and follow a specific outline, defined by regulation). Figure 4 presents the case of a levee with three components: the main body which function is stability, a clay layer which function is imperviousness, and a masonry revetment which function is protection against external erosion, and the successive damage of the three components and failure of their associated function.

2.5 Gradation of phenomena

In the post-event forensic analysis or in the case of justification of resistance to a levee failure scenario during design, we can often be led to distinguish a gradation between different levels of deterioration of a structure or one of its components (Simm, 2013), from least serious to most serious: a deterioration (which does not necessarily have any other consequence), a damage (which can initiate a breach process), a breach initiation (the breach process has begun) , a partial breach (opening which allows water to pass towards the protected area), a total breach (the levee, or even including its foundation, has completely disappeared).

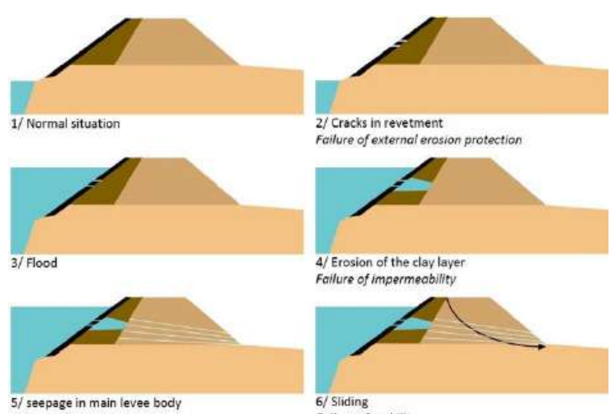


Figure 4. Levee failure and damage of components and failure of their main functions

2.6 *Kinetics of mechanisms*

It is also useful to take into account a difference in kinetics between the different mechanisms, as illustrated in figure 5, those producing progressive deterioration, such as erosion, or sudden ruptures, such as sliding.

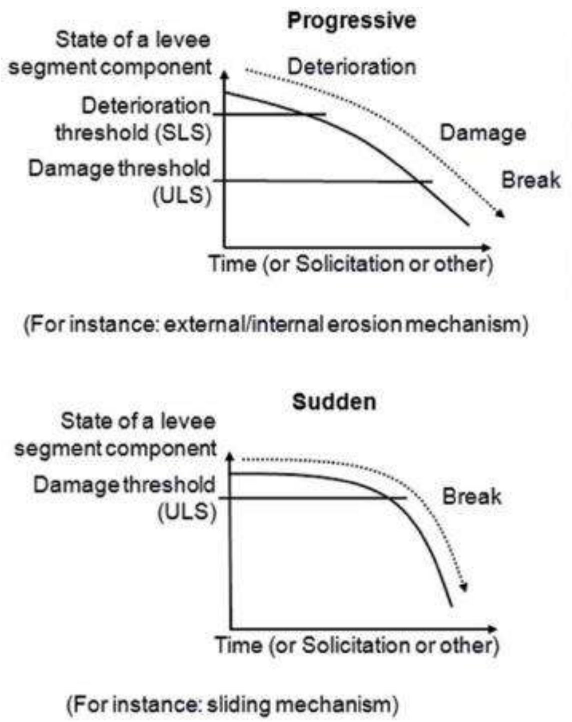


Figure 5. Kinematics of mechanisms (R. Tourment and Y. Deniaud, from the ILH)

Once a breach has formed, it will enlarge, deepen and widen, it is therefore important to understand and analyse its kinetics and dimensions to assess the hydrograph of the flood going through the breach and consequences in terms of flooding, but this does not pose any particular question in terms of the overall analysis of the failure scenario. Development of the preach is the final process in the scenario.

3 IDENTIFICATION OF FAILURE SCENARIOS AND EXAMPLES

As part of a risk analysis, the design of a new structure or the rehabilitation of an existing structure, it is necessary to be able to rely on an analysis of potential failure scenarios on the structure in question. We have proposed methods for analysing hydraulic and structural failure modes (analysis of failure modes, identification of failure scenarios) for flood protection systems and structures, based on functional analyses of hydraulic and structural functions (Tourment et al. 2015, Tourment & Beullac, 2019).

3.1 *Link between functions and their failures and deterioration/damage/rupture of levee components*

The main structural functions of a levee's components are waterproofing, drainage, sliding stability, resistance to external erosion, filtration (at interfaces) and self-filtration (within a material), these last two functions being linked to resistance to different internal erosion mechanisms.

The different components of a levee carry one or more of these functions. Deterioration, disorder or even ruin or disappearance of a component leads to a degradation in the performance of one (or more) of the functions it carries, or even to its complete failure. This function(s) failure leads to unforeseen stresses on other components which can in turn lead to the appearance of deterioration or breakage mechanisms.

The structural decomposition associated with the functional analysis of a levee section, followed by an analysis of the corresponding failures, therefore allows the identification of different failure scenarios.

The technical handbook "Methods and techniques for reinforcing and repairing protection levees" published by the French national dams committee (CFBR, 2021) uses, in its first part "General Framework", these functions as an entry point for the definition of reinforcement or repair measures, on the basis of a diagnosis identifying the mechanisms causing or potentially leading to disorders.

3.2 *Examples of failure scenarios*

Levee failure scenarios can be more or less complex, include only one mechanism, or a few as in the examples described above, or on the contrary a large number. They can be described in different forms, in text of course, or in the form of trees or flowcharts. A tree or a flowchart can represent a single scenario or even a family of scenarios, a scenario being in this case one of the possible paths on this tree. We present below two examples, figure 6 which presents two partial (not going up to a breach) rupture scenarios initiated by scour, and figure 7 which represents a family of scenarios centred on the presence of sand boils.

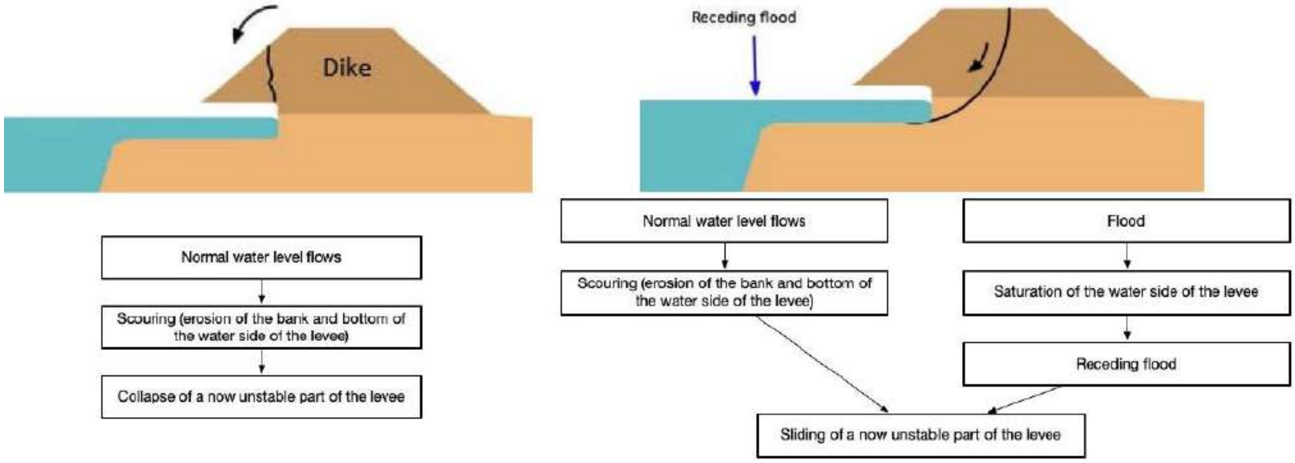


Figure 6. Beginning of two scenarios initiated by scouring (R. Tourment, from Van et al., 2022)

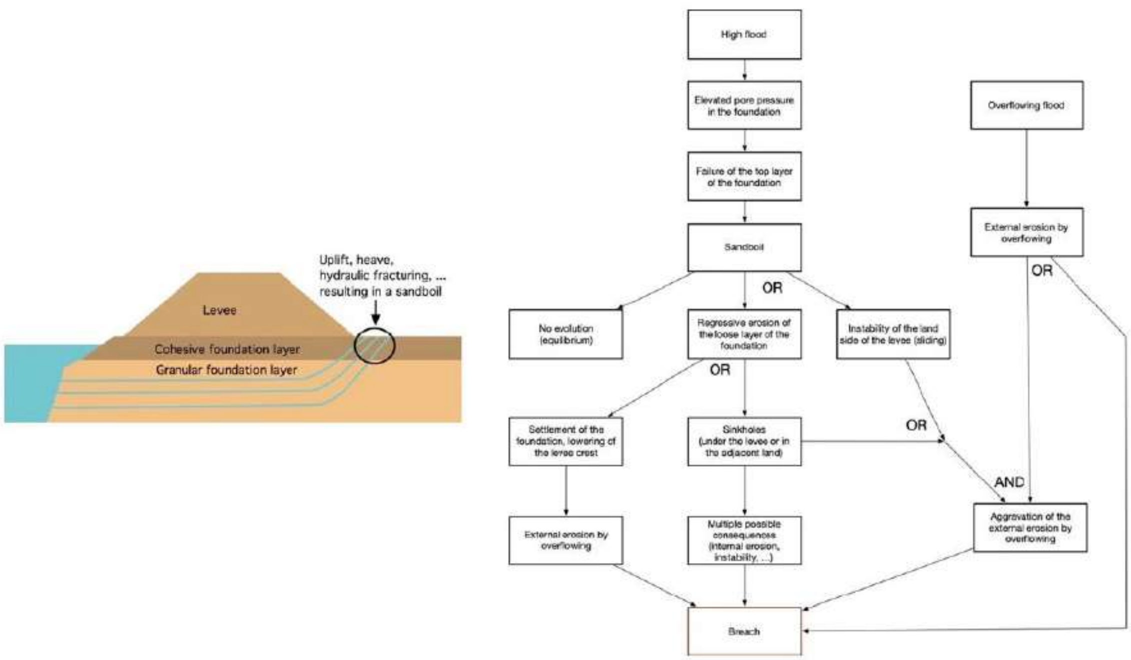


Figure 7. Family of scenarios centred on the presence of sand boils (R. Tourment, from Van et al., 2022)

3.3 The case of internal erosion

Internal erosion is a family of mechanisms, which historically were confused in view of their consequence (a "pipe" / "piping" - in French : "renard hydraulique" = "hydraulic fox"). We could analyse a failure scenario by considering internal erosion globally as a single mechanism but this would in many cases be an excessive simplification, as they have different criteria and limit equations.

Within the same scenario it is possible for several mechanisms to occur simultaneously at different points of the structure and successively at the same point, as illustrated with two examples of scenarios in figure 8: internal erosion in the levee body and internal erosion at the contact between levee and foundation. The cross section on the left illustrates the different mechanisms occurring at different places and the flowcharts on the right illustrate the temporal sequences at a specific place.

The European research project FloodProBE analysed the possible links and sequences between the four internal erosion mechanisms (Morris et al., 2012). Based on the FloodProBE "matrix", figure 9 represents a set of possible scenarios involving the different internal erosion mechanisms. This flowchart includes all possible links between internal erosion mechanisms, but not all other possible mechanisms (external erosion, instability, …).

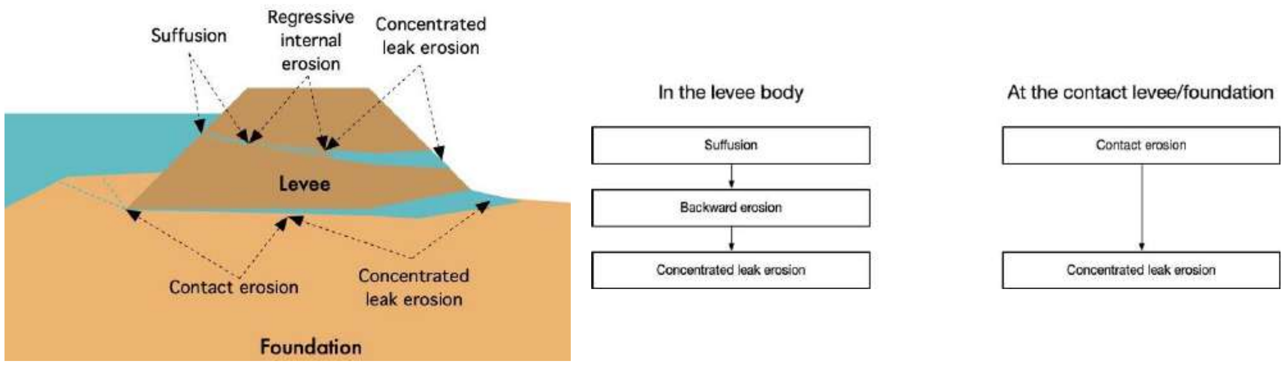


Figure 8. Two partial scenarios, before the development of a breach, involving several internal erosion mechanisms (R. Tourment, from Van et al., 2022)

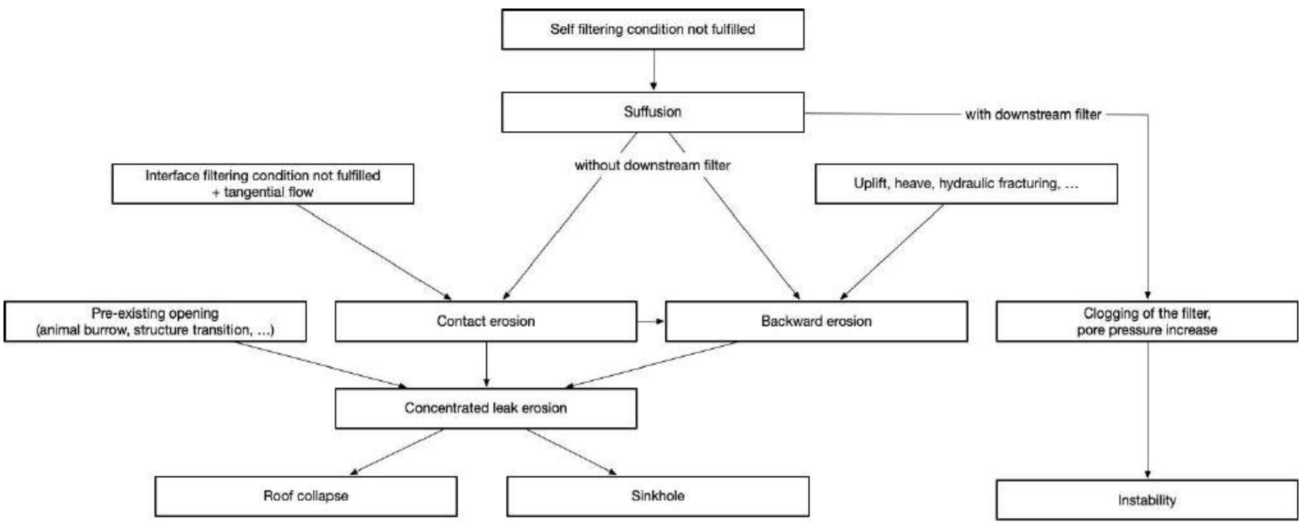


Figure 9. The different possible interactions between internal erosion mechanisms, according to FloodProBE (R. Tourment, from Van et al., 2022)

4 INTEREST OF AN ANALYTICAL APPROACH TO FAILURE SCENARIOS – CONCLUSION AND PERSPECTIVES

Taking into account all the mechanisms involved in a failure scenario instead of, as has often been the case in the past, considering "failure modes " designated and evaluated on the basis of a single mechanism, allows more precise assessments, diagnostics, risk analyses and justifications. The fact that it is necessary to focus on scenarios involving various elementary mechanisms is now recognized, both at national and international levels, although it is unfortunately not common practice yet.

4.1 Interest for assessments, diagnostics and risk analyses

In the context of an assessment, a diagnosis or a risk analysis, the recognition of the existence of scenarios that combine various mechanisms and the case-by-case identification of possible scenarios allows to aim at exhaustiveness in terms of identification of scenarios, especially if we use a rigorous method, as previously mentioned in 2.4 and detailed in 4.3. If these scenarios are potentially over-numbered to be all evaluated, we need to choose which ones will be, but we will avoid not having considered an uncommon but potentially very dangerous and/or very probable scenario.

The estimation of the rupture probabilities by a given failure scenario is therefore more precise, but it is also made easier by first evaluating the probabilities of each mechanism independently, to then combine them.

Finally, the detailed representation in the form of a tree of a scenario with the different mechanisms which participate in it and, if possible, the deterioration of components and associated function failures, makes it possible to easily identify safety barriers and measures to reduce risks to be put in place to reduce the probability of the scenario and/or its consequences.

4.2 Interest for design and justification of levees

Whether in the case of the construction of new levees or the reinforcement of existing ones, we can carry out an analysis of potential failure scenarios on the planned levee and its environment, which makes it possible to adapt its design: failures of the main function of a component can be relayed by another component ensuring it as a secondary function. For instance, in a levee with occasional loading, we can allow a degradation of the performance of the imperviousness of the component primarily in charge of this function if another component remains impervious enough to withstand a flood episode without leading to the levee failure. In the example of figure 4, if the levee body permeability is low enough to avoid saturation during a flood episode, the vee will not breach and it will be possible to repair it after the flood. According to the probability of this event it will be during design acceptable or not to reinforce revetment resistance or clay layer thickness by comparing the life cycle costs of the different alternatives.

In terms of justification, taking into account the different components of the structure, their functions, main ones and secondary ones, and their performance with respect to each function, instead of evaluating the resistance of the structure (often of a single component) to each mechanism, allows more precision and therefore potentially cost reduction.

4.3 Failure modes analysis: a proposed method for levees

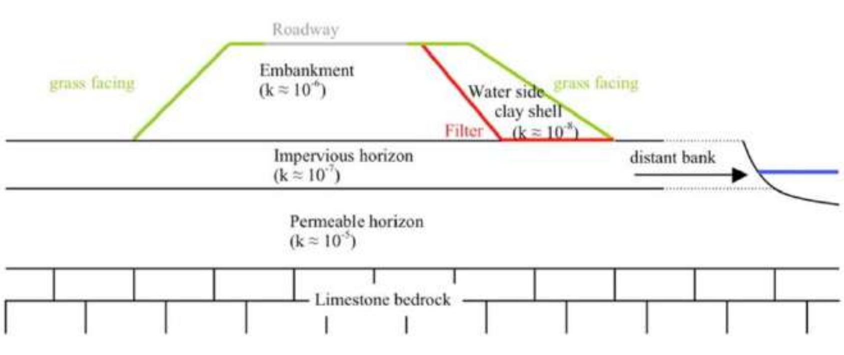
In a scenarios-based approach, failure modes analysis aims at identifying for each specific levee which failure scenarios may occur (potential failure modes analysis - PFMA) or which scenarios may have been the cause of a failure that occurred (forensic failure modes analysis). PFMA is an almost essential step of a risk analysis. It is possible to conduct a failure modes analysis using expert opinion and based on literature review, but a more structured method generally leads to the identification of more possible scenarios, if not all. Different methods exist to conduct a failure modes analysis. We proposed (Tourment et al. 2015, Tourment & Beullac 2019) a method for failure modes analysis of embankment levees based on a structural decomposition, which is generally conducted based on a cross section of the levee, and a functional analysis. In this method we defined generic functions of levee components :

- stability,
- impermeability,
- filtration,
- self-filtration,
- drainage,
- protection against external erosion.

These generic functions can be supplemented by others in specific cases.

According to its specificities and to the nature of the other components, a same component can support several functions.

Figure 10 presents an example of such a structural decomposition and functional analysis.



Component	Function
Roadway	Protection against external erosion
Grass facing	Protection against external erosion
Water side clay shell	Imperviousness Global mechanical stability Auto-filtration
Filter	Filtration
Embankment	Global mechanical stability Auto-filtration Drainage (relative)
Surface foundation layer	Global mechanical stability Imperviousness Auto-filtration
Permeable foundation layer	Global mechanical stability Auto-filtration
Limestone	Global mechanical stability

Figure 10. Example of a structural decomposition and functional analysis of an embankment levee

The result of this analysis also contains not only a list of the components and their functions but also the list of physical contacts between components, which is essential to analysing the chain of failures of the basic functions and the consequences they have in terms of actions, mechanisms and deterioration/damage.

Based on these results, our method formalizes the identification of failure modes of the levee components functions, of their causes and their effects. Table 1 shows an extract of a failure mode and effects analysis (FMEA) result, through the example of a levee revetment component.

Then, by identifying the cause-and-effect relationships existing between failures of levee components functions, the method makes it possible to define every failure scenario of levee segments. First, the analysis identifies 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 component (here the revetment) or other ones (here the levee body).

Failure modes anaysis and identification of failure scenarios link the material scale (mechanisms affecting components) to the structural scale (levee breach scenario).

4.4 Perspectives and complements

It is currently envisaged to develop tools which make it possible to automate the construction of potential failure scenarios based on the structural decomposition and functional analysis of a structure.

Table 1. extract of a FMEA analysis result.

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 (deterioration /damage mechanisms)
Revetment	Protection against external erosion	Deteriorated protection	No more protection	Overflowing erosion	Partial disappearance of revetment	- Overflowing erosion of revetment
					Total disappearance of revetment	- Overflowing erosion of levee body
				External erosion (by lateral flow)	Partial disappearance of revetment	- External erosion of revetment
					Total disappearance of revetment	- External erosion of levee body

Of course, a better knowledge of elementary mechanisms is desirable, with if possible in the long term a coherent mode of evaluation for all mechanisms on the basis of behavior laws of materials and limit state equations. Currently, the evaluation of many mechanisms still requires a large dose of expertise, and certain mechanisms are evaluated on the basis of empirical laws that are not always appropriate (use of a law for a similar but different mechanism, or outside its limits of application).

Finally, it is also desirable to be able to probabilize the appearance of the different mechanisms and/or their development up to a limit value, to facilitate the probabilization of the scenarios where they intervene.

4.5 General conclusion: necessary generalization of a scenario approach

This explicit and analytical approach by scenarios is still relatively little applied, probably because at first it can be seen as more complex. As we have tried to demonstrate in this article, it nevertheless has many advantages, mainly because it is closer to reality. But it still can benefit from some development in several areas. Its practice will become easier and more precise on the basis of feedback from its application and exchanges within the profession, in addition to research.

Like the "risk" approach which has gradually been integrated into the engineering practices of hydraulic structures, we believe that it is inevitable in the long term to integrate this approach by scenarios into the current practice of assessments, diagnostics, risk analysis, design and justification of hydraulic structures and more particularly flood protection levees.

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