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Thibault Balouin, Anabel Lahoz, Christophe Bolvin, Yann Flauw. Risk assessment required in the framework of new french regulation on dams. Methodology developped by INERIS. 24. ICOLD Congress & International Symposium on Dams for a Changing World, Jun 2012, Kyoto, Japan. <ineris-00973668>

HAL Id: ineris-00973668

https://hal-ineris.ccsd.cnrs.fr/ineris-00973668

Submitted on 4 Apr 2014

Risk Assessment Required In The Framework Of New French Regulation On Dams
Methodology Developed By INERIS

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ABSTRACT:
The new French dam safety regulation classifies each dam in 4 classes depending on its height and the volume of water it stores. The first two classes require each owner to establish a safety report for an authority review. A main objective of this report is to demonstrate that all hazardous scenarios have been taken into account by the dam owner in assessing the risk level and also that sufficient safety measures have been specified to reach a global risk as low as reasonably possible. First, considering all existing data and characteristics of the dam, the owner has to carry out a risk analysis to identify all failure modes that may occur on dam structure and hydraulic equipment. Every potential accident is then characterised in terms of severity of consequences and annual occurrence probability. The severity level is assessed quantitatively or qualitatively, using a combination of maps representing the effects of the flood waves and the Population At Risks. The probability is assessed using a semi-quantitative method analyzing all scenarios and safety measures involved in prevention and protection: the bow-tie approach. This cross analysis implements an iterative approach to highlight complementary measures and recommendations and therefore enhance global safety level.

Keywords: Major accident, Risk Analysis, Severity, Probability, Risk Acceptability

1. INTRODUCTION

1.1. Dam Safety Regulation

French regulation on hydraulic structures changed in 2007 with the publication of a decree (n°2077-1735, 11th December 2007) that sets new requirements in terms of dam and dike safety. Hydraulic structures are classified into four classes (A, B, C and D) according to their characteristics. Concerning dams, the considered parameters are the height (H in meters) above the ground surface and the volume (V in cubic meters) of the reservoir.

Table 1. Classification of Dams in French Regulation

Categories	Threshold parameters
A	$H \geq 20$
B	No A class $H^2 \times \sqrt{V} \geq 200$ and $H \geq 10$
C	No A & B classes $H^2 \times \sqrt{V} \geq 20$ and $H \geq 5$
D	No A, B & C classes $H \geq 2$

The previously referenced decree, among other mandatory measures, requires the realization by the owner of a safety report for classes A and B dams. This safety report is then analysed by the Authorities who decide if the report is admissible. If it is not, Authorities can ask for supplementary information.

1.2. Objectives of a Safety Report

One of the safety report's objectives is to demonstrate that all risks that may occur on the single dam are identified and managed. The risk of a dam failure must be studied, for example during a flood event or an earthquake, but so must all the events (accidents or incidents) related to current operations be. The safety report also presents the safety measures implemented to avoid or limit the accidents and possible additional measures to reach a level As Low As Reasonably Practicable (ALARP).

The Ministerial decree of June 12th, 2008 presents the standard timetable and content of such a safety report, organized into eleven sections:

0. Non-technical summary of the safety report;
1. Administrative Information;
2. Purpose of the Study;
3. Functional analysis of the structure and its environment;
4. Presentation of the Preventing Major Accidents Policy and the Safety Management System;
5. Identification and characterization of potential

hazards;
6. Characterization of natural hazards;
7. Field experience and feedback;
8. Identification and characterization of risk in terms of probability of occurrence, intensity and kinetics of the effects, and severity;
9. Risk reduction;
10. Mapping.

Chapters 3 to 7 represent input data needed to lead to the assessment and characterisation in terms of severity and annual probability developed in chapters 8 and 9. The Figure 1 below shows the process of a study focused on risk assessment (chapter 8) to determine all the hazards that may be encountered.

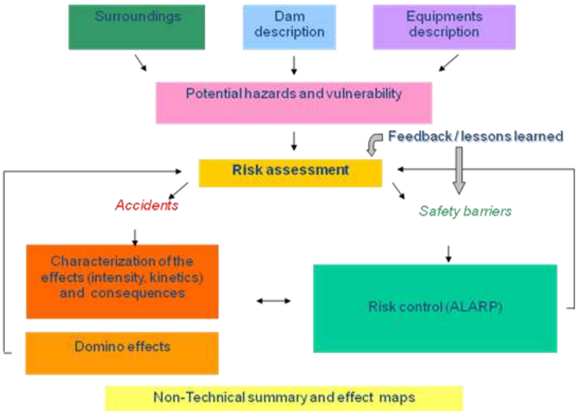

Figure 1. Structure of the Safety Report

This article describes the methodology developed by INERIS (from the risk assessment step to the risk reduction phase) to identify and quantify all the accidents. It is divided into 4 parts:

- Risk analysis,
- Consequences assessment,
- Probability assessment,
- Risk acceptability criteria and risk reduction.

2. RISK ANALYSIS

2.1. General Framework

Risk analysis is the first step of risk assessment. Under the new French regulation, owners have to identify all possible major accident scenarios that could occur on the dam, along with the implemented safety measures that could stop them or limit their consequences. Scenarios leading to a dam failure have to be considered, but not only: all failure modes have to be identified, including emptying valve failure or spillgate rupture. This identification is based on dam characteristics and includes dam environment, as a potential extern aggressor. This identification also integrates field experience.

The French regulation does not make compulsory a specific methodology of risk assessment. The owner is free to use FMEA, Preliminary Hazard Analysis or any other methodology to his or her convenience, as long as this choice is justified and leads to an exhaustive list of dam failure modes and associated scenarios.

2.2. INERIS Methodology for Scenarios Identification

Risk estimation is supported by a dedicated working group. This group is composed of experts and operators who have a good knowledge of the dam and the risk analysis methodology. The working group fills up a table in which each line represents a scenario, as presented on Table 2.

Table 2. Example of table used for scenarios identification

N°	Central event	Failure mode	Cause	Safety barriers	Kinetic and flow	Impacted people

During this analysis, all using modes of the dam have to be considered, such as usual operation mode, maintenance, emptying and filling of the reservoir, operation in times of floods... The flood following the failure of an upstream dam is also considered. The summary of this table leads to an exhaustive list of accidents, with their kinetics and estimated flow straight to the dam.

This list can now be reduced. As an example, a flood event can lead to a failure mode that would not have stronger effects than those already waited downstream because of the flood event itself. Then, this failure mode is not considered as a potential major accident. Therefore, after this selection, the residual list consists of all major accidents identified for the dam, with estimated flow and kinetics associated. Some of them, at least the dam failure, need modelling to obtain data on their consequences. Major accident implying lower flows may be studied qualitatively, without modelling.

A cross analysis between the consequences of the effects of these major accidents and their annual probability must be done in order to demonstrate the control of dam risks by the owner.

3. CONSEQUENCES ASSESSMENT

The consequences assessment of a dam major accident by INERIS is based on the superposition of a mapping of the flood wave effects and a mapping of the identified people exposed to these effects.

3.1. Effects Evaluation

The effects of major accident consequences are characterised in terms of local kinetics and intensity. Local kinetics is about the time between the arrival of the first effects of the wave and its top flow. It can be gradual or sudden, depending if the population will be able to be evacuated after the arrival of the first effects or not.

3.1.1. Local kinetics

Local kinetics is assessed for each impacted person according to two parameters: the flow speed, and the flow height, leading to the speed of the rise of water level. The French Prevention of Flood Guidelines indicates that a water height of 0.5 meters makes a man unable to move freely in the flow. It also indicates that a flow speed of 0.5 meters per second is a line above which a man could be hurt by objects carried along the flow or could be carried himself.

If the local flow speed and local speed of the rise of the water are both under the speed lines, local kinetics is gradual, as an evacuation is considered as possible. If not, kinetics is sudden. If speed data are not available, for example if there is no modelling and the accident is studied qualitatively, kinetics are considered as sudden, in a conservative approach.

3.1.2. Local intensity

The intensity level is assessed for each person by comparing local flood flows to reference local return flows, as presented by Table 3.

Table 3. Intensity levels used by INERIS

Intensity level	Local flow
Very strong	$Q \geq Q_{1000\text{-year}}$
Strong	$Q_{100\text{-year}} \leq Q < Q_{1000\text{-year}}$
Moderate	$Q_{10\text{-year}} \leq Q < Q_{100\text{-year}}$
Weak	$Q < Q_{10\text{-year}}$

If local flow data are not available, a conservative approach is used, depending on the wave flow at the level of the dam. If this flow is inferior to the ten-yearly flood flow straight to the dam, INERIS considers that the accident wave will deaden very quickly downstream and be contained in the river bed. If this flow is superior to the ten-yearly flood flow, INERIS considers that the flow remains constant along its travel, and this travel stops when the flow becomes inferior to the local ten-yearly flood flow. The flow is supposed to be contained in the river bed, except in some critic points (bridges, roads...) where this containment should be confirmed. A special attention should be paid for this confirmation, as the considered flow should be the wave flow added to the natural river flow.

3.1.3. Zoning

The characterisation in local kinetics and intensity leads to a zoning of the effects map: INERIS chose to define 3 zones, based on a methodology already used for the establishment of French emergency plans. This zoning is presented by Table 4.

Table 4. Zoning based on intensity and kinetics levels

	Sudden kinetics	Gradual kinetics
Very strong	A	A
Strong	A	B
Moderate	B	C
Weak	B	C

A zone is attributed to each person, and so the mapping can be zoned as shows the figure below.

Figure 2. Simplified representation of a zoned effects map

3.2. Impacted People Census

Once the effects are characterised, an identification of the impacted people is necessary to assess the severity level. INERIS methodology is based on the Population At Risk (PAR) parameter.

According to the wave modelling maps, the number of people likely to be impacted by the accident flood wave is counted. The regulation does not require a precise number, but asks for the counting mesh to be fine enough to obtain a good estimation of this maximal PAR. The census can be based on the Corine Land Cover database, which shows land cover mapping. It can also be done by adapting the counting methodology used for critical industrial infrastructures presented in the section “Elements for severity level assessment in safety reports” of the circular of May 10th, 2010 which summarizes the methodological rules applicable to safety reports, the approach of risk reduction at source and plans for prevention of technological risks. This methodology recommends for example to count 2.5 persons for each house, the whole capacity for buildings receiving public, etc.

Once the max PAR is determined, global kinetics of the accident can justify the use of reduction factors. Global kinetics can be of two types: pre-accidental kinetics and post-accidental kinetics. Pre-accidental kinetics is the time for the accident to occur once pre-incidental drifts have been detected. If a pre-incidental drift can be detected and therefore the accident predicted soon enough to allow an evacuation before the accident actually occurs, a reduction factor may be applied to the whole max PAR. Post-accidental kinetics is the time of the arrival of the wave first effects straight to the impacted people. A reduction factor may be applied to the part of the max PAR located far enough from the dam to be impacted by the first effects of the wave in a time longer than the time needed for evacuation.

However, the evaluation of a emergency evacuation plan is not easy and reduction factors have to be assessed carefully. If this evaluation cannot be done, or if the available data cannot be trusted because of too many uncertainties, it is safer to consider the max PAR in a conservative approach.

3.3. Severity Levels

Once zoning and PAR are available, the severity level can be assessed, using the scale as shown in Table 5.

Table 5. Severity Levels scale used by INERIS (unit: people exposed)

	Zone A	Zone B	Zone C
SL5	≥ 1,000	≥ 10,000	≥ 100,000
SL4	≥ 100 and < 1,000	≥ 1,000 and < 10,000	≥ 10,000 and < 100,000
SL3	≥ 10 and < 100	≥ 100 and < 1,000	≥ 1,000 and < 10,000
SL2	< 10	≥ 10 and < 100	≥ 100 and < 1,000
SL1		< 10	< 100

To each zone is given a Severity Level (SL) depending on its PAR. The global severity level of the accident is the maxima of the severity levels of each zone. As a result, the Severity Level of an accident whose zoning and PAR would be as shown on Fig. 3 is SL3.

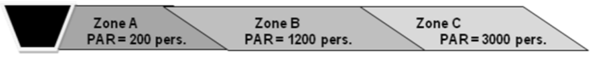

Figure 3. Example of a simplified zoning and PAR associated

4. PROBABILITY ASSESSMENT

The risk analysis usually identifies the possible central events (example: loss of containment) and their consequences (dangerous phenomena), but also, the initiating events leading to them. In order to present the results of this identification process, INERIS uses bow-tie diagrams.

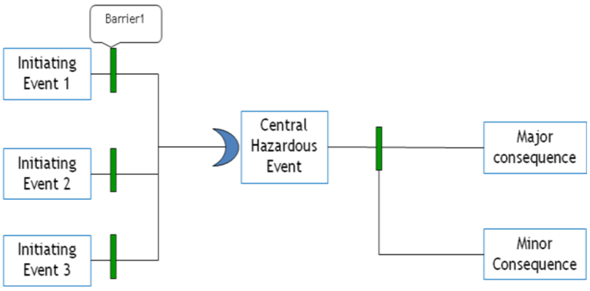

Figure 4. Example of a bow-tie diagram

The bow-tie diagram is a combination of a simplified failure tree and an event tree. It is composed of initiating events in the left side of the diagram. Examples of initiating events could be a human error in a filling procedure, an impact resulting of a vehicle collision, etc. These initiating events lead to a central hazardous event which is often a loss of containment. Then, the central event leads to several dangerous phenomena.

The qualitative identification of initiating events, central hazardous events, prevention and protection safety barriers and possible consequences realized through the implementation of the bow-tie diagram has to be considered as a major step of the safety report, leading to a probabilistic quantification of the scenarios.

To realize this quantification, when the identification step is achieved, the ability of the barriers to prevent the occurrence of scenario or to limit the consequences has to be evaluated.

4.1. Safety Barriers Evaluation

The barrier analysis is a main issue for the demonstration of the risk control, as they usually bring the proof that the safety system meets the ALARP requirements. Three kinds of safety barriers have been identified: technical barriers, human barriers and barriers which gather both technical and human elements, as shown on Fig. 5.

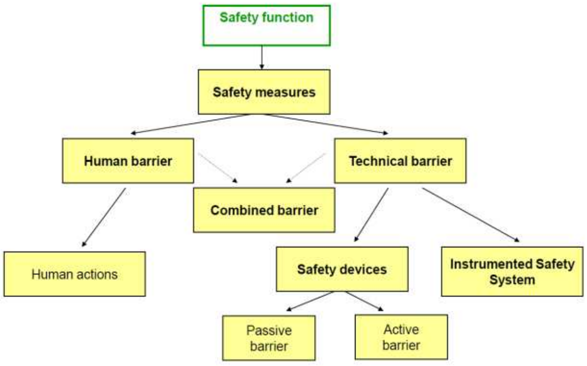

Figure 5. Safety barrier typology as developed in the INERIS methodology

In order to be considered in the French regulatory framework, a safety barrier has to meet the following requirements. It has to be:

- Independent: the safety barrier must be independent of the cause of the scenario or of the scenario itself;
- Effective: able to fulfil the safety function that it was chosen for, in its usage context, for a period of operation process independent and independent of other safety barriers;
- With a response time in accordance with the kinetics of the scenario;
- Testable;
- Covered by preventive maintenance designed to guarantee that performance levels are maintained over time.

If these requirements are met, the safety barrier can be taken into account in the probabilistic quantification of a dangerous phenomenon, as it reduces the occurrence frequency of a given scenario. The point is then to assess the failure probability of a barrier, and so the impact of the barrier on the occurrence frequency of an accident. There are few data about the failure probability on-demand of a specific barrier. Moreover, the available data are generally an average of failure rates and are not applicable for a specific facility, in a specific environment.

The INERIS methodology is based on the “level of confidence”. The risk reduction factor of an active barrier is calculated using an extrapolation of SIL (Safety Integrity level) defined in the norms NF EN 61 508 and NF EN 61 511. The approach described in these norms has been extended to all active barriers. Concerning passive barriers and human barriers, a maximum level of confidence has been defined through literature researches. The level of confidence is then reduced on the basis of different criteria (for more details, see Ω10 and Ω20 reports, INERIS 2008 and 2009, available on INERIS website www.ineris.fr).

When all identified barriers are evaluated, the frequency of major accident can be assessed.

4.2. Dangerous Phenomena Probability

As owners are free to choose the methodology to be used in the safety report for assessing the occurrence probability of a dangerous phenomenon, the methodologies can significantly vary. Since 2005, INERIS uses the quantitative evaluation “from initiating events to dangerous phenomena”, based on the bow-tie representation. Two main approaches are used in order to estimate the frequency of initiating events.

A first one uses reliability data, or generic frequencies obtained by using reliability data. These data can be available for failure related to equipment. However, data related to human and organizational failures are very limited. A second one, used by INERIS, is the assessment of the frequencies through a questioning process applied to a working group (which could gather for example the risk manager of the facility, people from the maintenance, operators, etc.). Each initiating event is studied by the working group, using frequency classes. Table 6 presents the scale of frequency classes usually used.

Table 6. Frequency classes used by INERIS to quantify initiating events

Frequency class	Failure frequency
F-1	Between 1 and 10 per year
F0	Between 10^{-1} and 1 per year
F1	Between 10^{-2} and 10^{-1} per year
F2	Between 10^{-3} and 10^{-2} per year
F3	Between 10^{-4} and 10^{-3} per year

Frequencies of initiating events leading to a common central event are combined using AND and OR gates:

- If any of the initiating event can cause the central hazardous event, an OR gate is used. In that case, the frequency class of the central event is equal to the minimum frequency class of the initiating event;
- If multiple initiating events (and the frequency of these events are below 10-1) are required for the occurrence of the central hazardous event, an AND gate is used. In this case, the frequency class of the central event is equal to the sum of the frequency classes of the required initiating event;
- If a prevention barrier exists, the risk reduction factor of the barrier is added to the frequency class of the cause, which gives the frequency class of the intermediate event.

One of the more obvious advantages of this methodology is that it results from a deep analysis of the safety and of accident scenarios that could occur, their causes and barriers that prevent their occurrence. Therefore, dam specific aspects (example: domino effects) and risk prevention issues are explicitly taken into account in probabilistic calculations. In this framework, operator’s safety efforts are well promoted and their effectiveness is demonstrated qualitatively and quantitatively. The main possible causes of an accident are identified and graded in function of their frequency. The operator can, on this basis, target the future implementation of its prevention system.

As frequency classes are used, this method has several limits: the assessment does not aim to be as accurate as an assessment using frequency values. This implies an increase of uncertainties when there is a need for aggregating the probabilities of different dangerous phenomena. Besides, some initiating events are difficult to assess. This refers mainly to rare events that the working group have not observed in their facility or in similar facilities. In these cases, generic data on initiating events and reliability data can be used, although it also implies uncertainties due to the use of generic data on a specific situation. An alternative way to assess the frequency of these events can also be the use of expert judgements.

5. RISK ACCEPTABILITY CRITERIA AND RISK REDUCTION

Once severity of consequences and probability of each accident determined, the last step of the methodology is to assess the risk acceptability for the studied dam.

First, each accident is positioned in a matrix corresponding to its severity level (5 levels) and its annual probability of occurrence class (5 classes).

Table 7. Risk Matrix

	Annual Probability of Occurrence (E = Very Low ; A = Very High)				
	10^{-5}	10^{-4}	10^{-3}	10^{-2}	
Severity	**E**	**D**	**C**	**B**	**A**
5					
4					
3					
2					
1					

Then, the dam owner defined criteria of acceptability in order to support the discussions in terms of reducing risk following the positioning of the various consequences of hazards in the matrix. Since there is no compulsory matrix yet, owners generally decide to consider the risk acceptance matrix indicated in another French circular (circular of May 10th, 2010 which summarizes the methodological rules applicable to safety reports, the approach of risk reduction at source and plans for prevention of technological risks) in which explicit classes or additional compensatory measures are implemented. This matrix is given below, as an example:

Table 8. Example of Risk Acceptability Matrix

	Probability (E = Very Low ; A = Very High)				
Severity	**E**	**D**	**C**	**B**	**A**
5	🟧	🟥	🟥	🟥	🟥
4	🟧	🟧	🟥	🟥	🟥
3	🟧	🟧	🟧	🟥	🟥
2	🟩	🟩	🟧	🟧	🟥
1	🟩	🟩	🟩	🟩	🟧

Three classes are defined:

- Zone at high risk (red);
- Zone at intermediate risk (orange);
- Zone at low risk (green).

This gradation corresponds to the priority that can be given to risk reduction, focusing first on reducing the greatest risks:

- High risk: Additional Measures to reduce risk at source to emerge from the class "High".
- Intermediate risk: Measures to control the risk and possible implementation of those whose cost is not disproportionate to the expected benefits,
- Low risk: Given the measures to control the risk, no obligation to further reduction, but recommendations can be made.

For any accident located in "High Risk" or “Intermediate Risk”, the owner has to propose a list of recommendations to improve existing safety barriers and to identify additional measures if necessary. The aim is to reduce the probability and/or the severity level and slide the accident to a safer zone. This residual risk level is compared with the risk acceptability criteria. Additional measures could be established with the aim of reducing risk (damages and/or probability) and make if As Low As Reasonably Possible.

6. CONCLUSION

To produce dam safety report according to the new French regulation, INERIS has developed a methodology responding to all required criteria. This methodology has been tested on several case studies and it proved efficient. However, there is still work to do relative to global kinetics to help reduce the max PAR and obtain a better approximation of impacted people. This supposes to define criteria relative to flow speed and flow height, and to be able to assess the time needed to alert and evacuate the population. Furthermore, this assessment done, reduction factors have still to be decided. Besides, another field of study is the probabilistic assessment of initiating events, which remains complicated for natural hazards and human factors.

It is important to note that the French dam regulation is relatively recent and does not define severity level scale, probability scale or risk acceptability matrix yet. To be able to compare several safety reports, these scales could be regulated in the future. The regulation is expected to evolve and therefore INERIS methodology may be adapted in the years to come.

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