Risk analysis of dams: French practice through Safety Review Risk Assessment

Methods For Dam Failure Modes

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1-Introduction

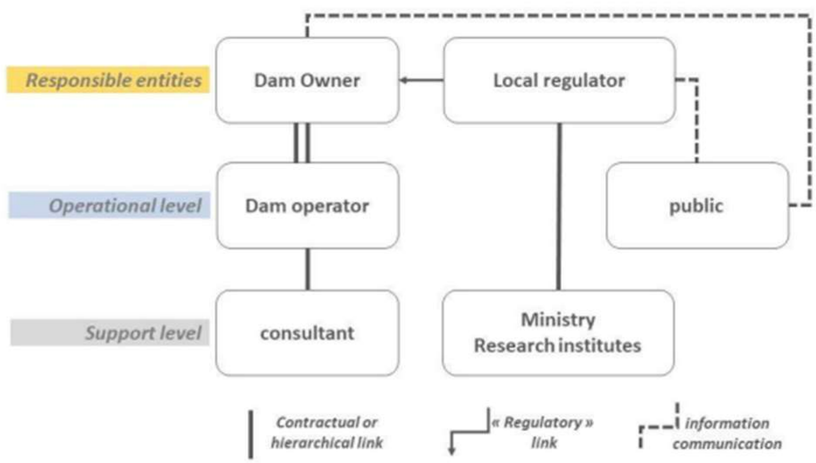
ICOLD Bulletin 130 “Risk assessment in dam safety management” sets the principles of risk management for dams, where the main objectives are:

- ✓ to identify all the configurations likely to jeopardize a structure’s safety and integrity and therefore the safety of the human, economic and environmental issues located upstream or downstream of the structure;
- ✓ to analyze the performance of the technical, human and organizational provisions made by the operator to maintain an acceptable level of safety relative to the risk.

1-Introduction

Carried out under the responsibility of the entity responsible of the dam, Safety Review Risk Assessments (SaRRA) are :

- ✓ carried out by analysis managers - consultants or technical services of the owner;
- ✓ subject to examination by the State supervisory authority.

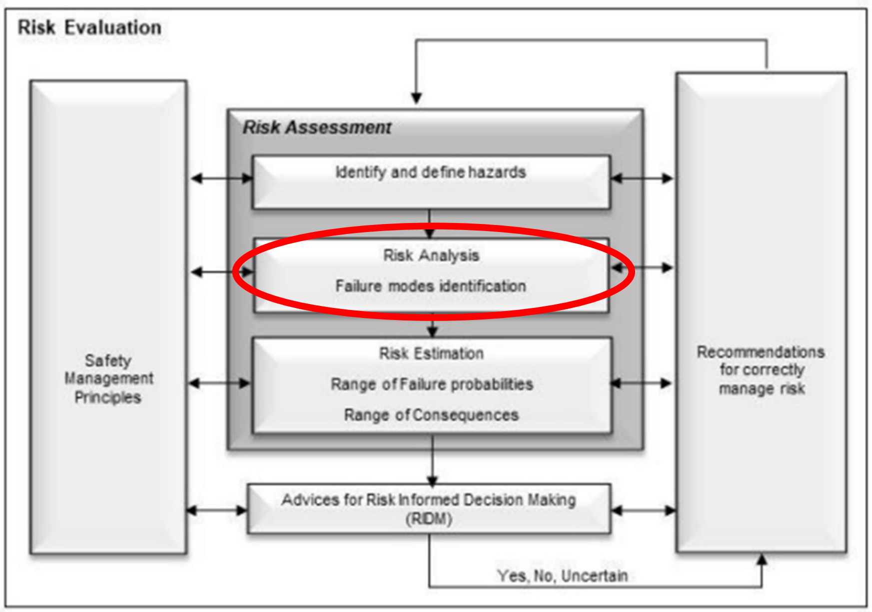


1-Introduction

The management and assessment of risks therefore constitutes an iterative process aimed at reducing risks to an acceptable level.

This process is based on a risk analysis that consists of:

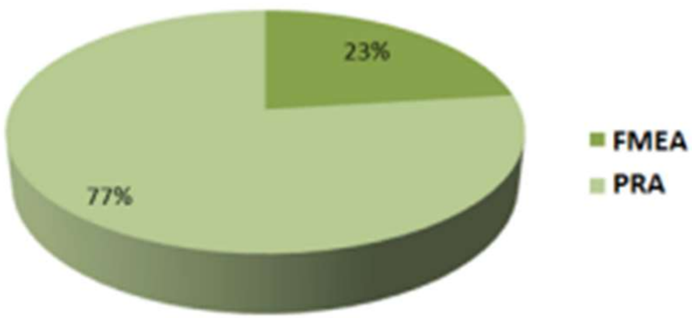
- ✓ Identifying the sources of hazards, i.e. the elements that are likely to cause significant damage in their environment;
- ✓ Identifying in detail the different conditions in which the hazards identified may materialize through failure modes;
- ✓ Offering a quantitative, semi-quantitative or qualitative characterization of the risks according to several criteria such as the severity of the consequences and the probability of occurrence;
- ✓ Proposing measures of control and/or risk reduction by prioritizing them, particularly if the risk is deemed to be uncontrolled. The risk reduction process then continues until it reaches a level that is as low as reasonably practicable (ALARP).



1-Introduction

2 main methods in France :

1. Preliminary Risk Analysis (PRA)
2. Failure Modes and Effects Analysis (FMEA)



2-Preliminary Risk Analysis (PRA)

Context:

The **Preliminary Risk Analysis** draws up an inventory that is as complete as possible of the failure modes of the dam and its safety equipment, for all conditions of operation.

It is **not a standardized method**

The PRA approach occurs prior to the construction of failure scenarios and is used as their input data.

It constitutes a macroscopic analysis of the structure's risk situations and makes it possible to detect the feared events to be studied and the associated risks to be assessed.

It also includes an initial assessment of the severity of the identified failures .

2-Preliminary Risk Analysis (PRA)

Principles :

The aim of the PRA is to identify all the dangerous phenomena likely to harm third parties

The PRA therefore supplies the input data for the detailed modeling of failure scenarios but is not a substitute for that.

Indeed, elements that are not identified in the PRA can be added during the construction of failure scenarios, which is a more detailed phase of the risk analysis.

2-Preliminary Risk Analysis (PRA)

4 stages :

1. An expert identification of the failure modes of each element in the perimeter of the structure, in various given conditions of operation. This identification is based on the functional analysis of the perimeter elements;

2. An estimation of the consequences of these failures, characterized by the kinetics and the extent of the effects of this failure. This estimation is qualitative. It is based on the experts' functional analysis of the structure;

3. The choice of the failure modes to retain, regarding the severity of their consequences;

4. An initial identification of the causes of the retained failure modes and the existing methods of prevention.

What does a PRA look like ?

2-Preliminary Risk Analysis (PRA)

Example 1 : Arch dam with gated spillway

(1) Structure element concerned	(2) Operating conditions, condition, corresponding position	(3) Failure mode	(4) Dam function affected	(5) Consequences	(6) Post-accident kinetics	(7) Severity only for CFE minor, severe	(8) Type CFE= Central Feared Event IE= Initiating Event for a CFE	(9) Pre-accident kinetics	(10) Remarks and justification for not taking CFE or EI into account
Dam	All conditions	Failure	Water retention	Dam break wave downstream. Sudden emptying of reservoir.	Rapid	Severe	CFE 1		Earthquake has not been retained as a cause of dam failure. The dam is situated in a low seismic hazard zone (level 1) and feedback on the behavior of arch dams in earthquakes is overall very favorable. This element has therefore not been retained for the rest of the analysis. The failure of a penstock has not been selected either. The leak would be collected in the dam's drains and would be visible: • via the piezometers (inspected every two weeks, a sufficient period with the kinetics of the phenomenon of introduction of uplift following the loss of containment of one of the penstocks, which can lead to a dam failure); • visually at the power station at the start of flooding. Also, 2 power station water level switches at the pump shaft generating an urgent alarm to bring down the head gate. This element has therefore not been retained for the rest of the analysis.
Tainter gate, spillway	Normal / unsolicited closed	Failure	Water retention	550m³/s wave downstream. Lowering of the reservoir level	Rapid	Severe	CFE 2		Flow of 550 m³/s (equivalent to the biggest known flood – before construction of the structure). Failure of the links (bearing support): inspections of the bearing supports are carried out every 10 years. The last technical inspection reports very good behavior (excellent condition).
		Unintentional opening	Control of flow variations downstream						Not selected because of the gate technology (tendency to close), power blocked (breaker open) (Inappropriate action: not retained because gate not solicited in normal operation).
		~~Failure to close~~	Control of flow variations downstream						Incoherent (gate already closed).
		~~Failure to open~~	Control of level variations in upstream reservoir						Incoherent (unsolicited gate).
		~~Unintentional closing~~	Control of level variations in upstream reservoir						Incoherent (gate already closed).

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2-Preliminary Risk Analysis (PRA)

Example 1 : Arch dam with gated spillway

(1) Element of the structure concerned	(2) Conditions of operation, condition, corresponding position	(3) Failure mode	(4) Dam function affected	(5) Consequences	(6) Post-accident kinetic	(7) Severity Only for CFE minor, severe	(8) Type CFE= Central Feared Event IE= Initiating Event for a CFE	(9) Pre-accident kinetic	(10) Remarks and justification for not taking CFE or EI into account
Tainter gate, Spillway	Flood / open on demand	Failure	Water retention	550 m³/s wave downstream. Lowering of reservoir level.	Rapid	Severe	CFE 2		(Flow: between 10 year flood and 100 year flood) Impacts from floating objects: presence of pontoons, leisure base, boats… which in flood could be carried rapidly with the flow to the gate and cause its failure.
		Unintentional opening	Control of flow variations downstream	Maximum wave downstream of 550 m³/s. Lowering of reservoir level.	Slow	Severe	CFE 3		The loss of the power supply (opening of the breaker – for the failure of the automatic control system) has not been retained since, as the gate operation is done preferentially from the power station control room, the Operator would not be on site and the gate operation would be done with fast kinetics (also, as the lifts are not used during flooding it would take a very long time to reach the gallery at the crest).
		Failure to close	Control of flow variations downstream	Upstream: lowering of the reservoir level. Downstream: no consequences (flow in river already established)			Not retained		
		Failure to open	Control of the upstream reservoir level	Heading up of reservoir level			IE2 of CFE 1 and CFE 2 (through heading up of reservoir (IE1))	Slow	IE that could, through rise of the water level of the reservoir, lead to failure of one of the gates or the dam by exceeding the gate's design levels or the dam's failure threshold water level.
		Unintentional closing	Control of the upstream reservoir level	Heading up of reservoir level			IE3 of CFE1 and CFE 2 (through heading up of reservoir (IE1))	Fast	IE that could, through rise of the water level of the reservoir, lead to failure of one of the gates or the dam by exceeding the gate's design levels or the dam's failure threshold water level. Human error possible (error of interpretation). The failure of both chains has not been studied (double failure) and the failure of a single chain would only cause the jamming of the gate. The loss of the power supply (opening of the breaker) has not been retained since, as the gate operation is done preferentially from the power station control room, the Operator would not be on site and the gate operation would be done with fast kinetics (also, as the lifts are not used during flooding it would take a very long time to reach the gallery at the crest).

2-Preliminary Risk Analysis (PRA)

Example 2 : Embankment dam

Index des situations dangereuses sur un barrage en remblais				Estimation de la probabilité des scénarios							
	Organes / Éléments importants pour la sécurité	Situation dangereuse	Cause potentielle	Probabilité initiale		Justification	Barrières de sécurité existantes			Probabilité avec barrières	
				Fréquence	Niveau		N°	Intitulé	NC	Fréquence	Niveau
BARRAGE EN REMBLAI	Cavalier	Rupture du cavalier par surverse	Tassement point bas	x	x	**Sans objet** : le profil en long du barrage fait l'objet d'un suivi et d'un entretien régulier pour le rendre conforme au cahier des charges	x	x	x	x	x
	Talus amont	Rupture de l'ouvrage suite à un glissement du talus amont	Erosion du talus amont suite à une protection du talus insuffisante par rapport aux crues (blocométrie insuffisante suite au gel ou au vent - phénomène	$P=10^{-2}$	3	Probabilité de la crue à l'origine de l'accident potentiel	232	Surveillance courante et adaptée, analyse et actions	2	$P=10^{-5}$	0
							202	Mise en œuvre d'une parade	1		
	Corps du barrage	Rupture par érosion interne	Formation de renards (anomalie géologique) (phénomène lent)	P=10-2	3	Probabilité de rupture en section courante sans les barrières de sécurité, Cf. calculs érosion interne	232	Surveillance courante et adaptée, analyse et actions	2	P=10-5	0
							202	Mise en œuvre d'une parade	1		
		Rupture par charge hydraulique excessive	Décolmatage du barrage lié à un entrainement de fines (suite à une onde de disjonction par ex.), associé à un mauvais drainage	x	x	**Sans effet :** Le barrage est stable y compris quand le parement amont n'est pas colmaté et donc pas étanche. Cf. calculs de stabilité	x	x	x	x	x
		Rupture suite à une agression externe	Animaux fouisseurs	x	x	**Sans objet** : Le barrage, par construction et par les matériaux présents, n'est pas sensible à ce genre d'agression	x	x	x	x	x
	Talus aval	Rupture par érosion externe	Endommagement du parement aval suite à la présence de végétation	x	x	**Sans objet** : pas de végétation dans la partie inférieure du talus aval	x	x	x	x	x
		Rupture par perte de stabilité	Glissement du talus aval suite à un mauvais drainage	x	x	**Sans objet :** l'étude de stabilité des endiguements montre que le talus aval n'est pas sensible au glissement même en cas de drainage défavorable	x	x	x	x	x
		Rupture par surcharge physique combinée à un défaut de drainage	Passage sur le barrage d'engins de transport trop lourd sur la piste de risberme	$P=10^{-2}$	3	Probabilité de rupture du barrage en section courante sans les barriéres de sécurité	232	Surveillance courante et adaptée, analyse et actions	2	$P=10^{-5}$	0
							202	Mise en œuvre d'une parade	1		

2-Preliminary Risk Analysis (PRA)

Conclusion :

The PRA table can have different forms and levels of detail,

But, if the information shown and the level of detail can vary, the PRA always includes, for each component identified, the dangerous situations or consequences and their potential cause or failure mode, as well as the argument on whether or not to retain these initiating events for the rest of the study.

3-Failure Modes and Effects Analysis (FMEA)

Context :

The **FMEA method (Failure modes and Effects Analysis)** constitutes a detailed method of analyzing the failure modes of a system's components.

It is sometimes carried out in the form of a FMECA analysis which consists of a FMEA analysis to which a specific analysis of the criticality is added.

The FMEA method is widely used in the mechanical industry (spatial, nuclear, automobile, etc.). It is the subject of several standards in France, Europe and worldwide (NF X 60-510, CEI 812-1985, MIL-STD-1269 A).

3-Failure Modes and Effects Analysis (FMEA)

Principles :

The FMEA method consists of a systematic analysis of a system's components in the form of a table, to research the failure modes and their causes and effects.

The failure modes constitute the failure of the system's components to carry out their functions or their degraded or partial realizations, and the search for them is based on the results of the functional analysis carried out prior to implementing the FMEA.

Through its systematic character, **the FMEA guarantees the completeness of the analysis** of the failure modes, as long as the functional analysis has been carried out fully

3-Failure Modes and Effects Analysis (FMEA)

Principles :

The implementation of the FMEA is produced in the form of a table showing :

- ✓ The system's components;
- ✓ The components' main and technical functions;

Functional analysis

- ✓ The failure modes : non-realization or partial realization of function;
- ✓ The possible causes of the failure modes :
  - Linked to the contacts between the environment and the components,
  - Linked to the hydraulic interactions or constraints with the environment and the components,
  - Linked to the component's intrinsic condition.

Failure modes

- ✓ The possible effects of the failure modes :
  - On the contacts between the environment and the components,
  - On the hydraulic interactions or constraints with the environment and the components,
  - On the component's intrinsic condition.

Possible effects

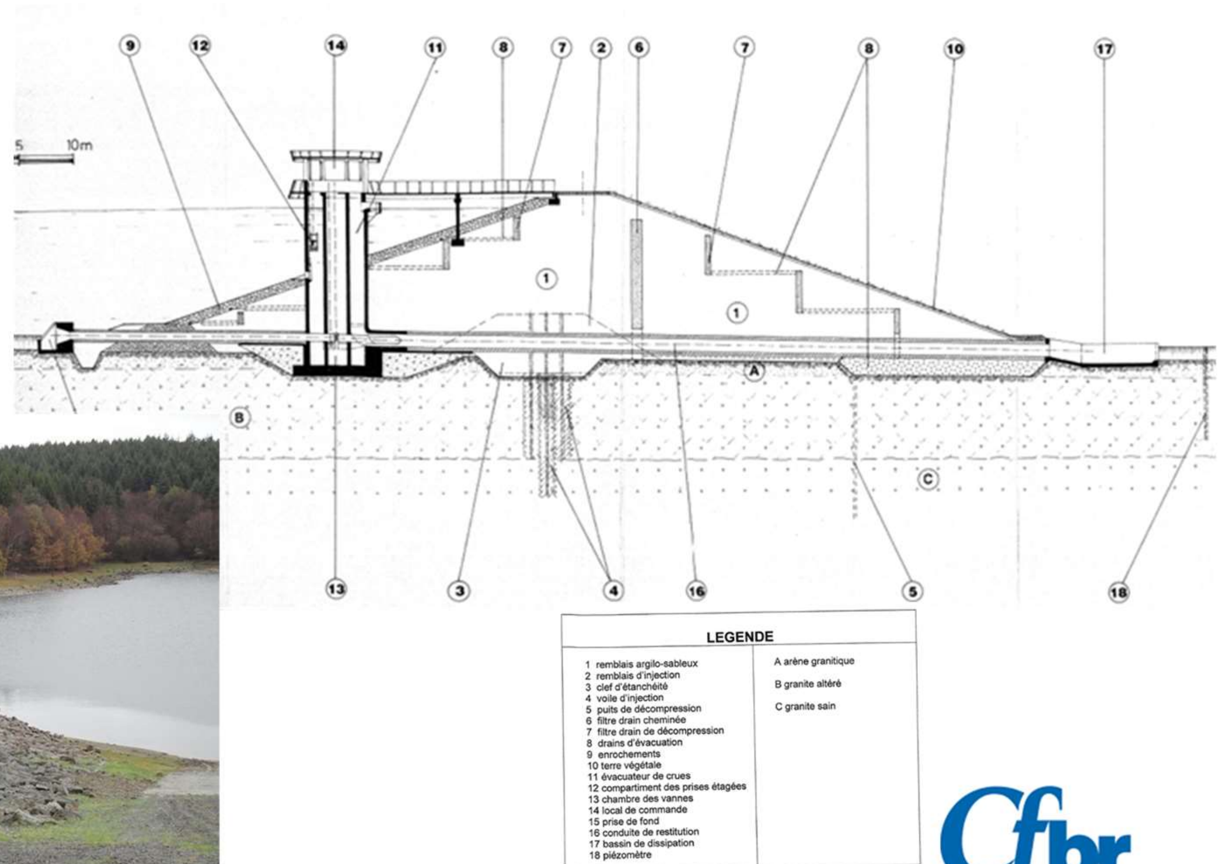
3-Failure Modes and Effects Analysis (FMEA)

Example 1 : Rockfill dam with clay core

N°	Functional analysis (rank 1)			FMEA (rank 1)		
	Component rank 1	Main functions	Technical functions	Failure modes	Causes	Effects
1	Upstream shoulder	Ensuring upstream and core stability. Resisting mechanical stresses. Not sliding.	Resisting the hydrodynamic stresses (waves).	Sliding of the upstream shoulder – Overall failure.	Excessive seismic stresses, excessive horizontal or vertical displacement of the foundation and / or the interface.	Sliding of the upstream slope and the core.
				Erosion of the upstream slope.	Excessive wave action, excessive degradation of the rip rap on the tidal zone, loss of materials.	Erosion in the tidal zone.
2	Upstream drain-filter	Draining the water that has come through the core.	Ensuring the transition between the upstream shoulder and the core. Filtering the fines from the core.	Defective filtration (insufficient filtration).	Insufficient filtration.	Erosion or suffusion of the core.
				Failure of the drainage system (excessive filtration).	Clogging of the drain. Excessive water circulation, exceeding the drainage capacity of the upstream drain-filter	Reduction of the core's capacity to lower its interstitial pressures on emptying the reservoir.

3-Failure Modes and Effects Analysis (FMEA)

Example 2 : Embankment dam - Training



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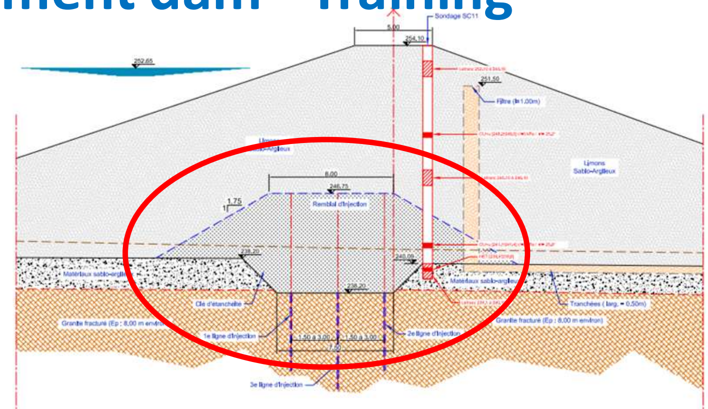
3-Failure Modes and Effects Analysis (FMEA)

Example 2 : Embankment dam - Training



N°	Component	Main function	Technological function / Constraint	Failure mode	Cause	Effect
3	**Dam foundations**					
3.1	*Dam foundations*	Transferring stresses to the ground Limiting water infiltration	Resisting mechanical stresses (deformation, punching, liquefaction) Resisting hydraulic stresses (internal erosion, infiltrations)	Deformation/Failure	Differential settlement Internal erosion Seismic stresses (liquefaction)	Loss of capacity to take up the mechanical stresses of the dam
3.2	*Sealing works (grout curtain)*	Improving watertightness in the foundation	Resisting hydraulic stresses	Excessive water infiltration	Displacement or deformation of foundations Dissolution, degradation of grout curtain	Infiltration towards downstream foundation

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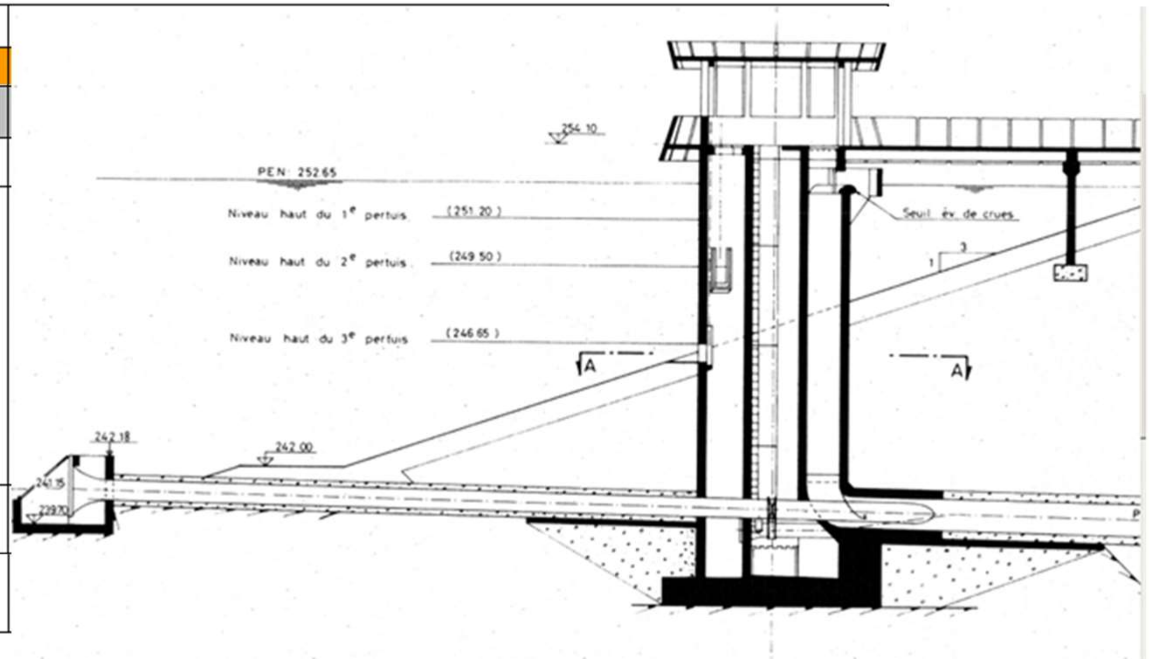
3-Failure Modes and Effects Analysis (FMEA)

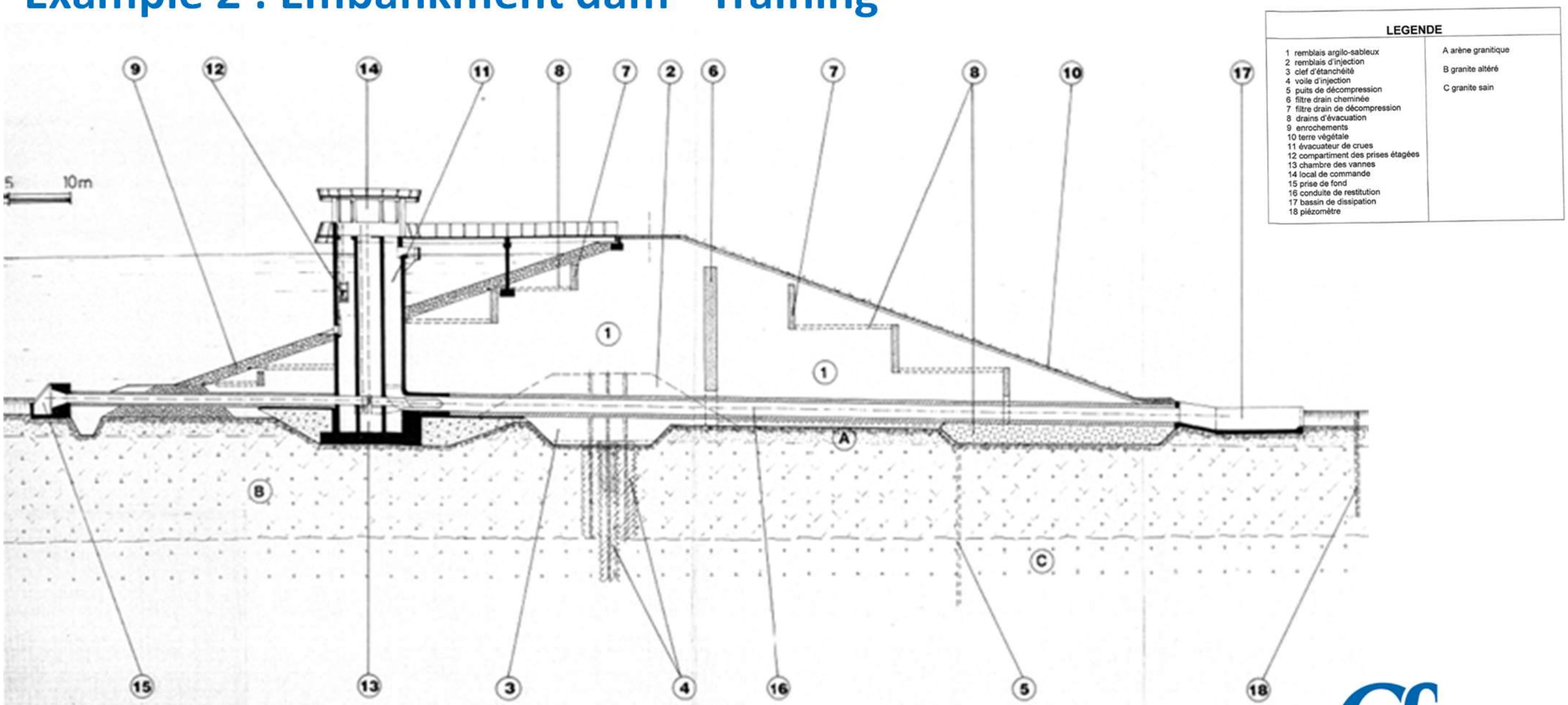
Example 2 : Embankment dam

		Functional Analysis	
N°	**Component**	**Main function**	**Technological function / Constraint**
4	**Water intake and outlet system**		
4.1	*Upstream water intake structure*	Taking water from the bottom of the reservoir	Resisting the risk of obstruction
4.2	*Upstream cofferdam*	Ensuring cutoff of the release flow Allowing passage of intake, outlet and emptying water	Resisting hydraulic and mechanical stresses
4.3	*Intake and outlet tower*	Houses the hydraulic equipment and the gate operating components	Resisting the mechanical constraints (deformation, failure)
4.4	*DN700 butterfly valve*	Allows passage of outlet water	Resisting hydraulic and mechanical stresses



3-Failure Modes and Effects Analysis (FMEA)

Example 2 : Embankment dam - Training



3-Failure Modes and Effects Analysis (FMEA)

Example 2 : Embankment dam - Training

		Analyse Fonctionnelle		AMDE		
N°	Composant	Fonction principale	Fonction technologique / Contrainte	Mode de défaillance	Cause	Effet
1	**Corps du barrage**	Contenir les eaux de la retenue	Contenir les eaux jusqu'à la cote de dangers			
1,1	*Corps de remblai*	Assurer la stabilité mécanique du barrage	Résister à l'érosion interne	Rupture par érosion interne	Gradient hydraulique élevé, infiltrations excessives dans le corps du barrage Matériaux et mise en œuvre non adaptés (sensibilité à l'érosion interne)	Rupture du barrage avec libération non-maîtrisée d'eau vers l'aval
			Résister aux contraintes de cisaillement	Rupture par glissement	Piézométrie élevée dans le remblai aval du barrage Géométrie défavorable du barrage (largeur, inclinaison talus) Propriétés mécaniques des matériaux défavorables Sollicitations sismiques excessives	Rupture du barrage avec libération non-maîtrisée d'eau vers l'aval
				Rupture par déformation excessive de la fondation ou du corps du barrage	Perte des capacités de reprise des efforts mécaniques du barrage Effondrement de la galerie de vidange ou de la tour de prise d'eau	
			Résister à l'érosion externe	Rupture par surverse	Augmentation du niveau d'eau dans la retenue Perte de revanche (tassement de la crête)	Rupture du barrage avec libération non-maîtrisée d'eau vers l'aval
		Assurer l'étanchéité du barrage	Présenter une perméabilité homogène suffisamment faible	Perte de capacité à assurer l'étanchéité du barrage	Matériaux non adaptés (sensibilité à l'érosion interne) Compactage des matériaux insuffisant	Infiltrations, Erosion interne
1,2	*Parement amont*	Protéger le corps du barrage de l'action de l'eau	Résister à l'érosion externe	Erosion	Courant d'eau / Marnage / Batillage	Erosion superficielle du corps du barrage
1,3	*Parement aval*	Protéger le corps du barrage de l'érosion externe	Résister à l'érosion externe	Erosion	Ruisselement	Erosion superficielle du corps du barrage
1,4	*Crête*	Permettre la circulation des véhicules	Résister à l'érosion externe et aux contraintes d'exploitation	Dégradations, obstruction	Erosion (ruissellement, passage véhicules)	Passage délicat, difficultés de surveillance ou d'intervention en cas d'urgence
		Assurer une revanche	Résister aux phénomènes de tassement	Revanche insuffisante	Tassement	Surverse potentielle

4-Conclusion

The two main methods applied in Safety Review Risk Assessments on dams in France are:

1. **the PRA method (Preliminary Risk Analysis)** which is based on a simple risk analysis based on expertise,

2. **the FMEA method (Failure Modes and Effects Analysis)** which constitutes a more complete analysis of the failure modes.

4-Conclusion

The application of the PRA method is largely based on **an expert assessment** : the identification of the hazards is carried out using the experience and knowledge of a panel of Experts.

PRAs are generally based on a summary internal functional analysis and they then expose a first order of magnitude analysis by highlighting only the major failure modes likely to be encountered on the dams.

The method is pertinent for dams, insofar as the expert's judgement remains highly significant in determining a certain number of degradations and failures.

As there is no standardization of the method, PRA practices in Safety Review Risk Assessments in France show a great variability.

4-Conclusion

In a standardized context, **the FMEA method** constitutes a complete analysis of the failure modes of the dam's components after a quality functional analysis.

It is therefore well adapted to a later complete or even quantitative analysis.

The expertise serves during the implementation of the FMEA method, when simplifying unrealistic causes and effects for the dam studied.

Its application is conditioned by the structural and functional knowledge of the dam and therefore depends on the quality of the functional analysis.

Other similar methods are used (Potential Failure Mode Analysis [PFMA] reviews the chain of events leading to unsatisfactory performance and failure of the dam (*see TN for Potential Failure Mode Analysis - World Bank 2020k*)

4-Conclusion

The failure mode analysis methods described in this session (PRA and FMEA(C)) **consider simple and independent failures** of an element or a component of the system analyzed.

Their implementation is based on tables identifying accidental sequences based on the causes.

These methods are not adapted to taking combinations of several components or events in a failure scenario into account (technical, human or organizational).

Other methods are available for taking these different types of failures and their combinations into account

Next session