OWNER:

DAM NAME:

DATE OF ANALYSIS:

PROCEDURE FOR THE IDENTIFICATION AND ANALYSIS OF FAILURE MODES IN DAM-RESERVOIR SYSTEMS

Participant:	
Organization:	
Position:	

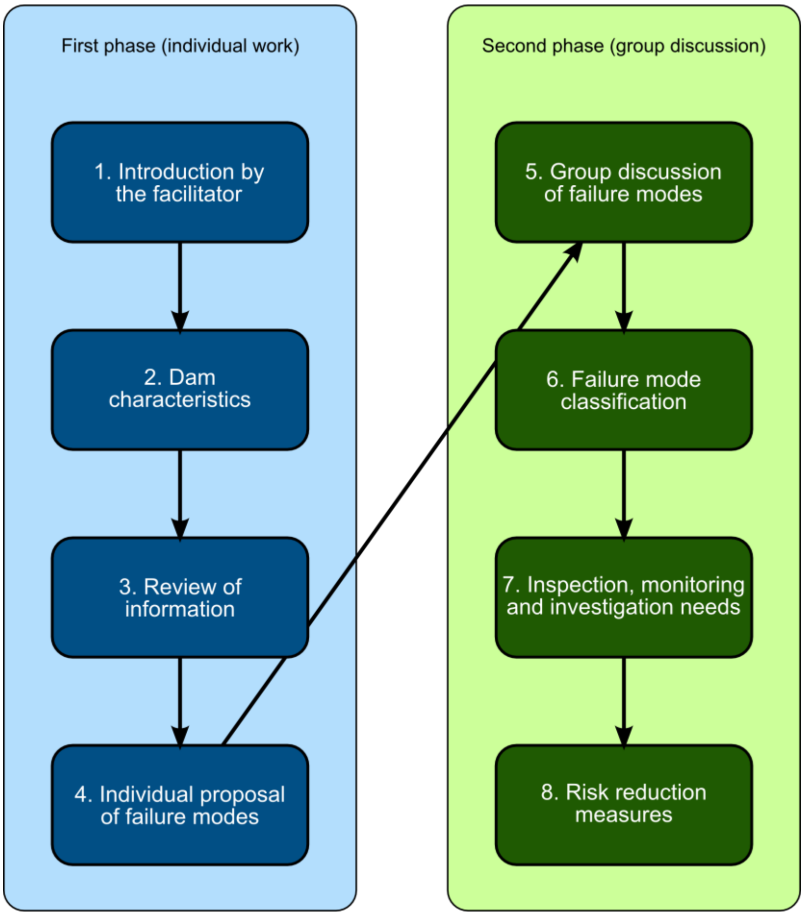
CONTENTS

1. INTRODUCTION

1.1 Foreword

The aim of this document is to be an aid in the sessions for the identification, analysis and detailed description of the failure modes of a dam-reservoir system. The procedure guides the participants of the sessions by proposing a sequence of worksheets to be filled.

The next figure presents a flowchart with the sequence of steps which must be carried out. Each of the steps has a corresponding worksheet, which should, in general, be filled out individually and then discussed with the group.



1.2 Important definitions

Some important definitions which will be used are given below.

Failure modes

A failure mode is a specific sequence of events that can lead to a dam failure. This sequence of events must be linked to a loading scenario and will have a logic sequence: starting with an *initiating event*, one or more events of *failure progression* and will end with a *dam failure*.

In general, any failure mode with the potential to produce an uncontrolled release of water, and hence with potential loss of life, is analyzed (however this can be specified further by the scope of the work). Also, this analysis is not restricted to the dam structure but can encompass any feature in the dam-reservoir system.

Loading scenarios

In order to structure the risk calculations it is common practice to break the analysis into several loading scenarios, according to the loading event which triggers the failure mode. The three most common loading scenarios are: hydrologic scenario (what can happen when a flood occurs), seismic scenario (what can happen when an earthquake occurs) and normal scenario (what can happen in an ordinary day). The combined case of flood and earthquake is not usually taken into account due to its low probability of occurrence.

Qualitative assessment of failure modes

The qualitative assessment of failure modes consists in performing an analysis to decide which failure modes are more or less likely to happen. This assesment is carried out according to the following classification.

I. **Failure is in progress or imminent.** The potential failure mode has initiated and is in progress, in which case emergency actions may be warranted, or the situation appears to be so dangerous, in terms of likelihood of failure and the resulting consequences, that increased monitoring or other interim risk reduction actions may be warranted while risk estimates and documentation are being completed.

II. **Failure mode is credible.** These potential failure modes are significant enough that they should be carried forward into a risk analysis, but do not appear to require immediate action based on the available information. Monitoring may be an appropriate risk management activity.

III. **Insufficient information to determine credibility of failure mode.** There is insufficient information to make a judgment on whether these potential failure modes should be carried forward for risk analysis (in which case either, 1) risk estimates for different scenarios may help focus what information will be most valuable in estimating the risks, or 2) a decision can be made to collect and evaluate the data prior to beginning a risk analysis). Increased monitoring may be an appropriate interim risk management activity while information is being collected.

IV. **Failure mode is not credible.** These potential failure modes are clearly so remote that the likelihood of failure is negligible, and hence do not need to be carried forward for risk estimates. However, they still need to be documented along with the reasons they are considered to be negligible risk contributors. Monitoring is likely not warranted for these potential failure modes. Just because a potential failure mode was ruled out in the past does not mean it should be ruled out under each re-evaluation. Additional methods or information may have come to light since the last review that could indicate a closer look is warranted. In addition, high likelihood failure modes with minimal consequences should not be ruled out, as these should be compared

1.3 Importance of monitoring

Monitoring is a key activity in the assessment of a dam performance. Different monitoring variables can be linked to different failure modes, leading to the establishment of ranges which can help in the early detection of a progressing failure mode.

2. DAM CHARCATERISTICS

Dam characteristics			
Type		*Crest width [m]*	
Plant		*Dam volume [m³]*	
Crest level [m]		*Upstream slope [H:V]*	
Foundation level [m]		*Downstream slope [H:V]*	
River bed level [m]		*Foundation geology*	
Height (above foundation) [m]			
Height (above river bed) [m]			
Crest length [m]			

Reservoir characteristics			
Maximum operating level [m]		*Catchment surface [km²]*	
Design flood level [m]		*Reservoir capacity [hm³]*	
Extreme flood level [m]			

Spillway charateristics			
Type		*Openings*	
Location		*Energy dissipation*	
Geometry		*Capacity [m³/s]*	
Total width			

Outlet 1 characteristics			
Number of conduits		***Location***	
Valves (type and number)		***Capacity [m³/s]***	
Intake level [m]			

Outlet 2 characteristics			
Number of conduits		***Location***	
Valves (type and number)		***Capacity [m³/s]***	
Intake level [m]			

Outlet 3 characteristics			
Number of conduits		***Location***	
Valves (type and number)		***Capacity [m³/s]***	
Intake level [m]			

Other significant characteristics			

3. REVIEW OF INFORMATION

3.1.- Relevant documents

3.2.- Documentation lacks

3.3.- Key observations from the documentation review

4. INDIVIDUAL PROPOSAL OF FAILURE MODES

Definition, sketches, codification and more likely/less likely factors for each failure mode (print one table for each failure mode).

Failure mode definition
Failure mode sketch

Failure mode codification			
SCENARIO	**BEGINNING**	**DEVELOPMENT**	**FAILURE**
VARIABLES			-
INSTRUMENTS			-

Adverse or “more likely” factors	Favorable or “less likely” factors

5. GROUP DISCUSSION OF FAILURE MODES

This space is for note taking during the group discussion

6. Failure mode classification

Grade each failure mode according to the I-II-III-IV system.

Failure mode	I	II	III	IV	Group

7. Inspection, monitoring and investigation needs

Failure mode	Inspection / monitoring	Tests / investigation

8. RISK REDUCTION MEASURES

Failure mode	Possible risk reduction measures

9. Notes and comments

TOOL FOR STRUCTURING FAILURE MODES IN CONCRETE DAMS, AND LINKING THEM WITH SOUNDING SYSTEM (POLITECHNICAL UNIVERSITY OF VALENCIA, 2009)

1 SCENE/STAGE

H — HIDROLÓGICO
1. Pool water level and water pressures increment
2. Uplift pressures increment
3. Spill increment

S — SÍSMICO
1. Acceleration/frequency associated to shaking
2. Pore pressures increment
3. Water pressures increment

N — NORMAL OPERATION
1. Pool water level variation
2. Temperature variations
3. Operations of exploitation
4. Maintenance works

O — OTHERS
1. Natural loads (volcanos, fires, etc.)
2. Anthropic loads

2 RESERVOIR - DAM SYSTEM COMPONENTS	2a RESERVOIR - DAM SYSTEM SUB-COMPONENTS	3 EVENTS OCCURING AT THE BEGINNING OR DURING THE DEVELOPMENT	3a MOST INFLUENCIAL MONITORING VARIABLES	3b INSTRUMENTS
C FOUNDATION (including abutments)	Ci *FOUNDATION*	1. Internal erosion	Leakage, uplift pressure and turbidity	Gauging elements, piezometers, turbidimeters, visual inspection
		2. Tensile cracks	Tensile stress	Electric extensometers, pressure cells, visual inspection
		3. Liquefaction	Pore pressure in foundation	Piezometers
		4. Movements	Movements and deformations in the foundation	Topographic methods, long extensometers, inclinometers, settlement sensors, visual inspection
	Es *ABUNTMENTS*	1. Internal erosion	Leakage, uplift pressure and turbidity	Gauging elements, piezometers, turbidimeters, visual inspection
		2. Tensile cracks	Tensile stress	Electric extensometers, pressure cells, visual inspection
		3. Liquefaction	Pore pressure in foundation	Piezometers
		4. Movements	Movements and deformations in the foundation	Topographic methods, long extensometers, inclinometers, settlement sensors, visual inspection
E STRUCTURES	Cp *DAM'S BODY*	1. Cracking	Stress in concrete structure	Electrical extensometers, pressure cells, rigid inclusions, electrical thermometers (embedded), sonoscope, visual inspection
		2. Internal degradation of concrete	Variation in concrete characteristics	Samples extraction and lab analysis, visual inspection, electrical thermometers (embedded)
		3. Concrete weathering	Variation in concrete characteristics	Samples extraction and lab analysis, visual inspection
		4. Alkali aggregate reaction (AAR)	Variation in the volume and characteristics of the concrete	Thermometers, extensometers, samples extraction and lab analysis, visual inspection
		5. Degradation of sealing elements	Leakage	Gauging elements, visual inspection
		6. Movements	Joints movements, horizontal and vertical displacements, rotations	Joint meters, plumb line and inverted pendulum, geodesic triangulation, topographic collimation, wire in the dam foundation, optical plumb leveller, inclinometer, visual inspection
	Si *IMPERVIOUS CUTOFF WALL*	1. Cutoff wall misfunction	Uplift pressure and leakage in galleries	Piezometer, gauging elements
	Sd *DRAINAGE SYSTEM*	1. Drains siltation	Uplift pressure and leakage in galleries	Piezometer, gauging elements, visual inspection
D OUTLET WORKS AND INTAKES	Oc *CIVIL WORK*	1. Overcoming erosion at the foot of the dam	Socavation at the foot of the dam	Visual inspection
		2. Overtopping in spillway walls	Water depth in spillway	Visual inspection
		3. Crest overtopping	Pool water level	(*) Water level meter, pneumatic scales, visual inspection
		4. Material degradation	Variation of the concrete characteristics	Samples extraction and lab analysis, visual inspection
		5. Degradation of sealing elements	Leakage	Gauging elements, visual inspection
	Eo *ELECTROMECHANICAL EQUIPMENT*	1. Loss of gate functionality	-	Sensors, visual inspection
		2. Collapse of gate	-	Visual inspection
		3. Loss of electrical generation	-	Sensors
		4. Operation mistake	-	Sensors
V RESERVOIR BASIN	La *HILLSIDE*	1. Land slide	Deformations, horizontal and vertical movements	Topographic methods, long extensometers, inclinometers, visual inspection
		2. Creep	Deformations, horizontal and vertical movements	Topographic methods, long extensometers, inclinometers, visual inspection

4

ULTIMATE FAILURE MECHANISM	MECHANISM DEFINITION
I. SLIDING	Failure of a dam due to the movement of one of its structural monoliths over a surface, produced by the hydrostatic load and the uplift pressure.
II. SUBSIDENCE	Vertical movement of the dam produced by the foundation due to its high deformability or its discontinuities and cavities.
III. CRACKING	Failure in concrete resistance produced by fissures and cracks.
IV. OTROS	Any other failure mechanism, including mechanisms that don't produce dam collapse, but produce important damages downstream or economical losses due to the loss of function.

GUIDE FOR USING THE TOOL

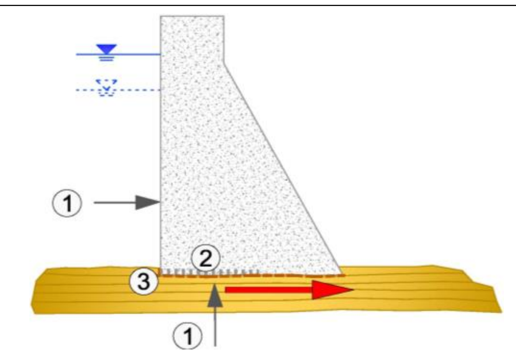
In order to use this tool, the next steps must be followed:

1. Identification of the load scenario and the location of the failure mode.
2. Specification of the Components and Subcomponents in the dam-reservoir system where the initial or development process occur.
3. Description of the initial mechanism, linked and coded following the Events occurring at the beginning or during the development category.
3.a. Association of this mechanism with the Most influential monitoring variables category.
3.b. Association of this mechanism with the Instruments.
4. Repetition of the steps 2 and 3, depending on how the failure events are produced or propagated until the Ultimate Failure Mechanism is defined.

EJEMPLO DE ESTRUCTURACIÓN DETALLADA DE UN MODO DE FALLO UTILIZANDO LA HERRAMIENTA

In ***hydrological situation,*** there is an ***increase on the water loads and uplift pressure (1)*** that produces ***a tensile crack (2)*** at the foot of the dam-foundation interface, and produces an increment in the hydraulic gradient in the foundation joints close to the dam-foundation interface, what produce ***an erosion in the foundation material (3)*** resulting in the ***sliding*** of one monolith of the dam along a failure surface.

GRAPHICAL ESCHEMA OF FAILURE MODE



FAILURE MODE CODE

SCENARIO	BEGINNING	DEVELOPMENT	FAILURE
1 H	2 2a 3 C - Ci (2)	2 2a 3 C - Ci (2)	4 I
3a VARIABLES	Stress	Leakeage, uplift pressure, turbidity	-
3b INSTRUMENTS	Electrical extensometers, pressure cells, rigid inclusions, visual inspection	Piezometer, gauging elements, turbidimeter, visual inspection	-

Note: (*) In general, the sound system related with external variables is linked to the load scenario

Category	Parameter	Instrumentation	Purpose
Deformation or movement (structure)	Horizontal movements	Plumb line and inverted pendulum	Registration of horizontal displacements (tangencial and radial) by comparing with a vertical axis for different elevations.
		Geodesic triangulation (topographic piles, sights and theodolites)	Registration of horizontal displacements (tangencial and radial) in main points of the downstream face and dam crest using high quality geodesic triangulation.
		Topographic collimation (total stations, sights and theodolites)	Registration of dam crest horizontal displacements.
		Wire in the dam foundation	Registration of horizontal displacements [(1)]
		Optical plumb leveler	Registration of horizontal displacements [(2)]
	Vertical movements	Topographic leveling (total stations, sights and theodolites)	Registration of vertical displacements (settlement or sliding) at the dam crest by using topographic leveling of high precision.
		Invar rod pendulum	Registration of vertical displacements by means of aluminium discs which register position with respect to a sensor located at the level of measurement.
	Rotation	Inclinometers	Angle of rotation between two orthogonal planes with measurements in different dates.
	Movements - construction joints	Joint meters	Registration of transverse movements along a joint with imbibed extensometers between adjacent blocks.
	Movements - construction joints or cracking	Crack monitors	Registration of transverse movements along construction joints or cracks by using deformeters, with two (2D) o a group of three (3D) deformeters.
	Cracking	Sonoscope	Detection of cracks in the dam body when it is suspected[(3)]
Deformation or movement (foundation)	Deformations or settlement in foundation, and movements in geological fault	Rod extensometers	To obtain, approximately, vertical or horizontal movements (depending on its installation) according to different points established at the foundation and a reference station. It is possible to determine the resulting thrust forces and the modulus of global deformability of the controlled zone.
Hydraulics	Leakage	Weirs	To determine the outflow, analysing its evolution in important sectors (leakage through abutments, in the downstream toe of the dam, galleries, etc. including the water flow from the drainage system and seepage through the dam body).
	Turbidity	Turbidimeter	To measure turbidity of the seepage outflow with material in suspension, by comparing with photoelectric cells.
	Uplift and pore water pressures	Open-system piezometers, conventional (pneumatic or twin-tube) and closed (vibrating wire piezometers)	To register uplift distributions and pore water pressures.
Chemical and volumetric	Volumetric variations of concrete characteristics (shrinkage and deflection)	Thermometers and extensometers	Measurement of temperatures and unit strains not related to tensile forces.
	Variation on concrete characteristics	Sampling and laboratory tests (mineralogical analysis, etc.)	Characterization of variations in material properties.
Thermal monitoring	Temperatures at the dam body	Electrical thermometers (embedded)	Analysis of the evolution in temperature and thermal behaviour of the structure, in general, with the aim of determining thermal gradients and maximum levels during cement hydration, deformations at the dam due to thermal variations, idoneous moment for injecting joints, etc.
Tensile monitoring	Tensional forces in dam body or transmitted to the foundation. Indirect method [(4)]	Electrical or rosette extensometers (vibrating wire or ohmic resistance).	Application of the Theory of Elasticity to determine tensile forces from unit deformations in different directions and mechanical properties of the medium (Young's modulus, Poisson's ratio, etc.)
	Tensional forces in dam body or transmitted to the foundation. Direct method	Pressure cells (vibrating wire or pneumatic piezometer) and rigid inclusions.	Direct registration of tensional forces at the dam body, it enables fast decision making, but up to now this equipment has resulted in some problems.

Note:

(1). Method not commonly used at present

(2). Plays an important role in case of dams with high vertical curvarture (without galleries)

(3). Method used occasionally

(4) This method is more reliable than the direct method, but it requires laboratory experiments in order to determine material properties.