UNIVERSIDAD POLITECNICA DE VALENCIA

iPresas Risk Analysis

OWNER:

DAM NAME:

DATE OF ANALYSIS:

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

Participant:	
Organization:	
Position:	

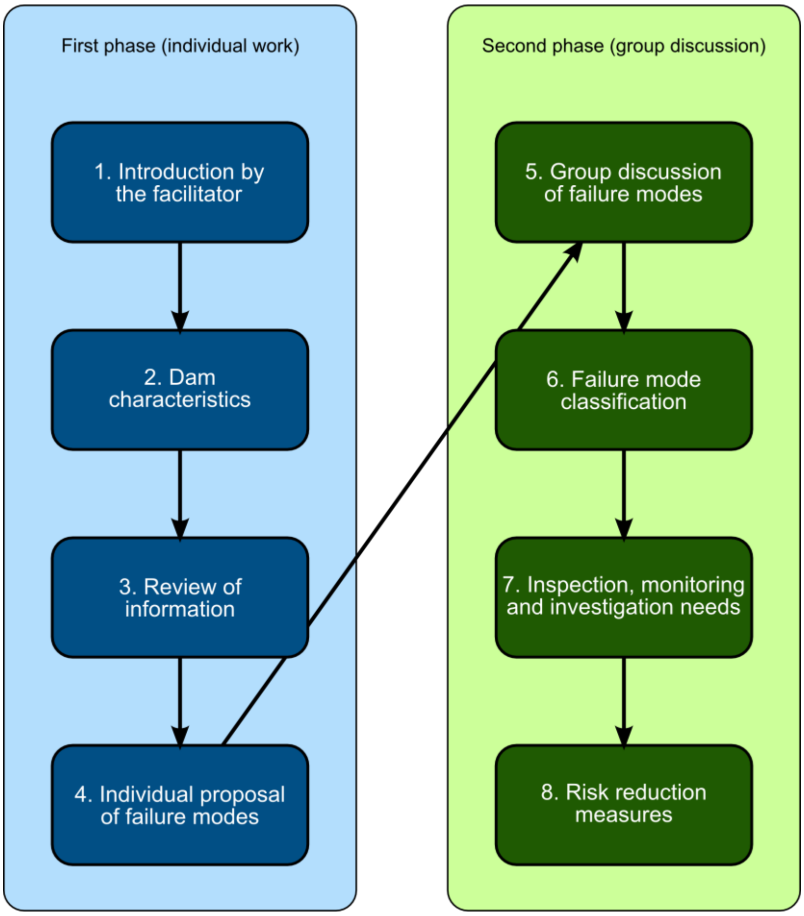
CONTENTS

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 EARTHFILL DAMS, AND LINKING THEM WITH MONITORING SYSTEM (POLITECHNICAL UNIVERSITY OF VALENCIA, 2009)

1 SCENARIOS

SCENARIOS
HYDROLOGIC -H-
1. Pool water level and water pressures increment
2. Uplift pressures increment
3. Spill increment
SEISMIC
1. Acceleration/frequency associated to shaking
2. Pore pressures increment
3. Water pressures increment
NORMAL OPERATION -N-
1. Pool water level variation
2. Operations of exploitation
3. Maintenance works
OTHERS -O-
1. Natural loads (volcanos, fires, etc.)
2. Anthropic loads

	2 RESERVOIR - DAM SYSTEM COMPONENTS		2a RESERVOIR - DAM SYSTEM SUB-COMPONENTS	3 EVENTS OCCURRING 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
				2. Movements	Movements and deformations in the foundation	Topographic methods, long extensometers, inclinometers, settlement sensors, visual inspection
				3. Liquefaction	Pore pressure in foundation	Piezometers
		-Et-	ABUTMENTS	1. Internal erosion	Leakage, uplift pressure and turbidity	Gauging elements, piezometers, turbidimeters
				2. Movements	Movements and deformations in the abutments	Topographic methods, long extensometers, inclinometers, settlement sensors, visual inspection
				3. Liquefaction	Pore pressure in abutment	Piezometers
-E-	STRUCTURES	-Cp-	DAM'S BODY*	1. Cracking	Leakage, uplift pressure and turbidity	Gauging elements, turbidimeters, piezometers, visual inspection
				2. Liquefaction	Uplift pressure	Piezometers, visual inspection
				3. Movements	Dam's body deformations and crest movements	Topographic methods, long extensometers, inclinometers, settlement sensors, visual inspection
				4. Internal erosion	Leakage, uplift pressure and turbidity	Gauging elements, turbidimeters, piezometers, visual inspection
				5. Hydraulic fracturing	Leakage, uplift pressure and turbidity	Gauging elements, turbidimeters, piezometers, visual inspection
		-Ai-	IMPERVIOUS CUTOFF LAYER	1. Cracking	Leakage, pore pressure, induced stress	Gauging elements, piezometers visual inspection, unite deformations meters
				2. Movements	Screen deflection, movement	Long extensometers, inclinometers, settlement sensors
				3. Material degradation	Leakage, uplift pressure and turbidity	Gauging elements, turbidimeters, piezometers visual inspection
		-Of-	CONCRETE WORKS IN THE DAM BODY**	1. Deformations	Joints movements, horizontal and vertical displacements, rotations	Joint movements meter, long extensometers, inclinometers, piezometers
				2. Degradation of sealing elements	Leakage	Gauging elements and 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-	SLOPES	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

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ULTIMATE FAILURE MECHANISM	MECHANISM DEFINITION
I. EROSION	**a) Overtopping:** Produced when the pool water level gets too high and goes over the top of the dam, scouring the dam body and producing the structural failure of the dam.
	b) Internal: Flow through the dam's body, with significant loss of constituent material, that results in an instability and a structural collapse.
II. SLIDING	Movement of an important part of the dam over a surface, located only in the dam's body or including the foundation, produced by the hydrostatic load and the uplift pressure.
III. OTHERS	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

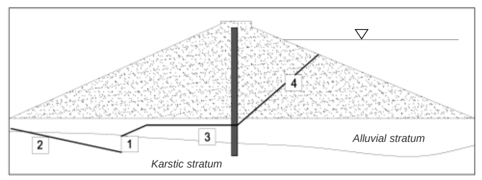
In order to use this tool, the next steps must be followed:

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.

EXAMPLE OF USE OF THE TOOL FOR STRUCTURING A FAILURE MODE

In normal operation, a collapse of a karstic cavity occurs **(1),** the alluvial material is eroded through this cavity **(2)** and is sweepped along the foundation downstream. Backward erosion through the alluvial material **(3)**, being propagated through cracks in the impervious layer and producing the propagation of the erosion towards the crest wall **(4)**. This conduct reaches the reservoir and gets larger quickly, producing the definitive failure of the dam due to internal erosion.

GRAPHICAL SCHEME OF FAILURE MODE



FAILURE MODE CODE

SCENARIO	BEGININNG	DEVELOPMENT	FAILURE
1 N	2 2a 3 *C - Ci (1)*	2 2a 3 *C - Ci (1)* *E - Ai (1)* *E - Cp (4)*	4 I
3a VARIABLES	Leakage, turbidity and pore pressures	Leakage, turbidity, uplift pressures and induced stress	-
3b INSTRUMENTS	Gauging elements, turbidimeters, piezometers, visual inspection	Gauging elements, turbidimeters, piezometers, extensometers, unite deformations meters, visual inspection	-

***** *it is only referred to the elements of natural origin in the dam's body (crest walls, , filters and drains).*

****** *like tunnels, galleries and all the works with a different stiffness that the dam's body (excluding outlet works).*

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

MONITORING IN EMBANKMENT DAMS

CATEGORY	PARAMETERS	EQUIPMENT	PURPOSE
Deformation or movements (structure)	Displacements (Horizontal)	Topographic triangulation	Measurement of horizontal displacements of characteristic points of the dam by obtaining data from, at least, three different reference points
		Distance meters	Measurement of horizontal displacements of characteristic points of the dam
		Topographic collimation	Measurement of horizontal displacements of characteristic points of the dam
		Inclinometer	Monitoring horizontal deformations in a vertical axis of the dam (if they are deeply anchored through the foundation, they can be assumed as absolute movements)
		Horizontal telescopic pipes with frames or crossheads	Monitoring relative horizontal deformations between elements of different rigidity (core-abutment interfaces, steep slope, etc.)
	Displacements (Vertical)	Topographic levelling	Vertical displacements of the dam crest, berms and abutments by topographic levelling of high precision.
		Telescopic pipes	Fast and efficient control of deformations along a vertical line at the dam and its foundation.
		Settlement cells (hydraulic or pneumatic)	Measurement of vertical displacements at the dam body (settlement monitoring)
	Rotation	Inclinometer	Measurement of rotation in several points of a single line.
Deformation or movements (foundation)	Displacements or movements in geological faults	Extensometers (single-point or multi-point)	Monitoring of soil deformations (faults, landslides, etc.)
	Deformations at the foundation	Long extensometers	Monitoring of vertical deformation at the foundation (specially, if the river bed is located above a very compressible layer)
Deformations (impervious material)	Transverse movement (joints)	Groups of three sensors.	Monitoring of joints between slabs of the concrete screen.
	Modulus of deformation (vertical and horizontal)	Total pressure cells or extensometers	Estimation of the horizontal modulus of deformation.
		Settlement cells (hydraulic or pneumatic)	Estimation of the vertical modulus of deformation.
	Rotation	Inclinometer	Angle of rotation between two orthogonal planes with measurements in different dates.
Hydraulics	Pore water pressures	Closed piezometers (electrical, pneumatic or hydraulic)	Monitoring of pore water pressures in saturated zones of low permeability (saturation curve).
		Open piezometers	Monitoring of pore water pressures in saturated zones of high permeability (saturation curve).
	Turbidity	Turbidimiter	Determine if there are dragging processes through the dam body
	Leakage	Weir at the downstream toe of the dam	Determine leakage outflow and control its evolution in important sectors of the dam (foundation, abutments, galleries, etc.)
		Drainage system with manometer	Monitoring of uplifts and reduction
Loads	Pressure	Total pressure cells (electrical or vibrating wire, hydraulic system)	Monitoring of total tensile stresses at the core and interfaces between foundation, blankets and other zones.
Tensional (impervious material)	Induced tensional forces	Extensometer or unit deformation sensor (vibrating wire or ohmic resistance)	Measurement of unit strains related to induced tensile stresses.
Volumetric and chemical	Concrete volumetric variations	Thermometer and extensometer	Measurement of temperatures and unit strains not related to tensile forces.
	Concrete characteristics	Sampling and laboratory tests	Characterization of the concrete state