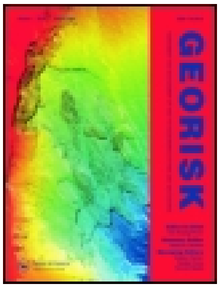

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FMEA of a tailings dam

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FMEA of a tailings dam

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The concepts, principles, assumptions and fundamental rules of Failure Modes and Effects Analysis (FMEA) are introduced. An application to Cerro do Lobo tailings dam is presented, with the description of the system considered, the functionalities, the potential failure modes of each component, their corresponding root causes and the sequence of effects. Finally, the available measures in place for the detection and control of the sequence of effects are also identified. Although FMEA application in complex dam systems may constitute a time-consuming process, its outcome can be extremely useful as illustrated in this article. It makes it possible to assess and manage the major risks of dams so that mitigation actions, taken at an early stage, can be optimised from an efficiency standpoint.

Keywords: qualitative risk analysis; FMEA; detection measures; control measures; tailings dam

Introduction

Risk-based techniques are becoming an increasingly popular means of dealing with uncertainties in dam safety assessment (Hartford and Baecher 2004, Caldeira 2005). Risk analyses are, in general, developed considering the following phases: system definition, intended objectives and analysis scope; information gathering; definition of the methodology to be adopted; and constitution of a working group of specialists in each area necessary to implement the analysis.

For the *system definition*, a profound knowledge of the following elements is necessary: the objectives of the project (and consequently of the exploration type), the design, the construction and the operation and maintenance policies. In dams, this definition involves the determination, without ambiguities, of the *study limits* for the intended objective and scope and the characterisation of the *system structure*. This characterisation includes the description of the elements of the system, the identification of the functions of the system and of its components (for the characterisation of its possible faults or failures) the establishment of relations and interactions between the various elements including its localisation, and the definition of the operating conditions of the system.

The *information gathering* comprises the description of the environmental conditions (due to the fact that these can constitute the cause of the system failure and, simultaneously, be affected in the case of an accident), the identification of the internal hazards and the ultimate limit state and serviceability limit state analysis of similar projects.

For the characterisation of the environmental conditions, it is essential to conduct a survey of the population potentially affected (both of the site under study and that living and working in the surrounding area), the installations or the equipment that can originate accidents (dangerous equipment, such as mines, solid waste landfills and contaminant deposits), the necessary equipment to maintain the safety level of the installations (energy lifelines, illumination systems and accessibilities), the properties and structures potentially affected, the natural environment (aquifers, water lines, ground, natural habitats, archaeological patrimony, among others) and the external aggression sources (circulation areas, vandalism, war acts, sabotage, extreme meteorological conditions, slope instability, earthquakes, floods and dangerous substance transportation in nearby transport infrastructures).

The internal menaces include anomalies in operational procedures (equipment mechanical locking and human errors), as well as all the phenomena that contribute to the dam deterioration (e.g. clays expansibility and/or dispersivity or alkali-aggregate reaction prone materials, corrosion and fatigue).

The a priori identification of the relevant serviceability and ultimate limit states and the verification of the most frequent causes may be eased by relevant case histories. This also provides precious data about the performance of certain safety barriers.

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Failure modes and effects analysis (*FMEA*) is a technique that considers the various fault (or failure) modes of a given element and determines their effects on other components and on the global system. It is an iterative, descriptive and qualitative analytical methodology that promotes, based on the available knowledge and information, the systematic and logical reasoning as a means to improve significantly the comprehension of the risk sources and the justification for the decisions regarding the safety of complex systems, namely dams. Without requiring mathematical or statistical frameworks, it intends to assure that any plausible potential failure is considered and studied, in terms of: *what can go wrong? How and to what extent can it go wrong? What can be done to prevent or to mitigate it?*

It is a versatile tool with potential scope for application to dam safety assessment, especially for risk identification and qualitative risk analysis. *FMEA* outputs are useful for mapping out the impacts of all the harmful events that can occur during the construction or operation of a dam and, ultimately, for identifying and prioritising the necessary detection and mitigation actions.

Failure modes and effects analysis is based on the following concepts and definitions.

The *system* is the set of all the components that can affect or be affected by the failure of the structure under study. The system is systematically divided into successive subsystems down to the basic component level, for which an adequate understanding of its functions should be available. A *basic component* is a basic part of a system. The *functions* of a component describe its role in the system.

A *failure or fault* is the cessation of the ability of a component, a subsystem or the system to perform one of the functions for which it has been designed. The *failure or fault mode* is the way by which a failure is observed in a component of the system; generally, it describes the ways in which failures occur.

The *failure or fault cause*(s) is(are) the event(s) leading to the failure or fault modes. The failure causes of the basic components are called *root causes*.

The root causes can result from natural or technological phenomena, physical, chemical or biological processes, design or constructive deficiencies, inappropriate or poor-quality materials, operational failures or even human actions, such as sabotage or war acts.

It is worthwhile noting that the failure causes due to human and software errors should not be forgotten. All the possible causes should, also, be described: the independent and common causes of failure (*CCF*). A *CCF* is defined as a condition or an event that, due to its logical dependences, causes failure states in two or more components simultaneously, the secondary failures induced by the effects of a primary failure being excluded (Hartford and Baecher 2004).

The *failure effect* is the impact of a failure mode in terms of the performance of the system and of its components and consists of a set of outcomes associated with the loss of ability of an element to accomplish a required function.

For each failure mode, the *effects* on the component itself (*direct effects*), on other components or subsystems (*intermediate effects*) and on the whole system (*end effects*) are assessed. Based on the sequence of failure events, *detection*, *control* and *mitigation* measures can be identified and recommended. *Detection measures* are the means or methods by which a failure mode can be discovered under normal operating conditions. *Control measures* involve carrying out remedial work, after the failure mode has been detected, to control the sequence of its effects, by stopping or delaying them. *Mitigation measures* intend to reduce the end effects and their consequences.

Failure modes and effects analysis is an inductive method that allows: (1) the assessment of the effects and of the events sequence induced by each failure mode of the components of a system in relation to its various functions and/or operational, maintenance or environmental requirements; (2) the determination of the relative importance of each failure mode in the normal performance conditions of the system; (3) the evaluation of the impact on the reliability and safety of the system; and (4) the ranking of the studied failure modes according to the straightforwardness associated with their detection and control.

The analysis process is hierarchical and sequential, so failure modes are defined as a function of their level in the system hierarchy. The failure effects of the lower level become the failure modes of the next level, and so forth, until the highest level of the system is attained. These effects can result in one or more failure modes of one or more subsystems or of one or more components.

The value and effectiveness of *FMEA* process depend on the degree of expertise gathered in the process of identifying and analysing the failure modes. The involvement of a multidisciplinary team is, therefore, essential for its application, along with detailed analyses of all the elements related to the design, construction and operation of the system.

Additionally, the interaction between the failure modes of different components must be considered, due to its proved contribution to accidents and incidents and because one component might compensate for the functional failure of another individual component, therefore resulting in no observable system effects (Hartford and Baecher 2004). Both aspects are important in the *FMEA* process in order to avoid neglecting some important failure modes and considering others with an irrelevant risk.

The application of these methods can be helped by worksheets, flowchats, block diagrams, diagrams and sketches to illustrate the failure modes and cause-effects diagrams.

A documental final report shall contain a summary of the analysis, with a synthesis of the most relevant aspects, the most significant results of the analysis, as well as conclusions and consequent recommendations, detailed worksheets of the analysis, used diagrams and sketches and references to consulted drawings and data.

In conclusion, the main drawbacks associated with *FMEA* when applied to complex systems, such as dams, are pointed out in the following: the excessive simplification of the dam system in two states – failure or not failure – makes it difficult to apply to a system in which the components can pass gradually from a functional to a non-functional state; the incapacity to include the time dependence and the depreciation of the component performance; the inaptitude for the analysis of multiple and simultaneous failures; the significant volumes of information to consider and the indispensable time for a complete *FMEA*, as well as the effort in the analysis of less relevant failure modes.

Failure modes and effects analyses applied to Cerro do Lobo dam

In this section, *FMEA* is applied to a traditional embankment dam built for the slurry tailing retention – the Cerro do Lobo main dam (Santos 2006).

Brief description of the Cerro do Lobo project

The Cerro do Lobo dam, integrated into the mining complex of the Neves do Corvo Mining Society, located in the Alentejo region, in south-western Portugal, was planned for the sub-aquatic impoundment of tailings resulting from the copper and tin concentration process. Aiming at the minimisation of environmental impacts, the dam was designed adopting a null discharge philosophy (Hidroprojecto 2002). In order to maximise the net storage capacity of the dam, a peripheral drainage system of the reservoir was adopted so as to prevent superficial draining inflow into the impoundment. The drainage system capacity is such so as to make the inflow likelihood insignificant.

Figure 1 shows a satellite image of the Cerro do Lobo complex (*BP*) and Neves-Corvo mine site. The impoundment is limited by the natural ground and four linked zoned embankment dams (Figure 2), constructed by phases, in order to manage the mine production demand, with a total crest length of 3327 m: the main dam (*ME*), two saddle dams at the left bank (*LS1* and *LS2*) and one saddle dam at the right bank (*RS*).

In this application only the main dam is considered. Initially (first phase), a traditional zoned

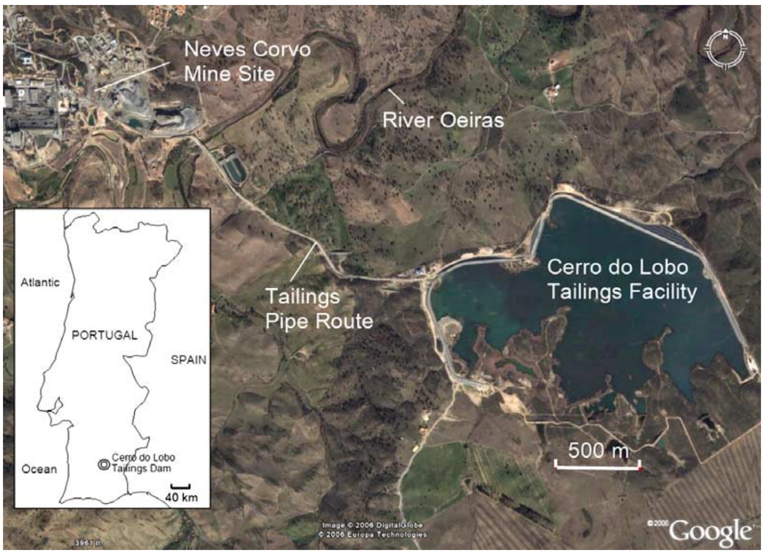

Figure 1. The Cerro do Lobo facility and Neves-Corvo mine site (GoogleTM).

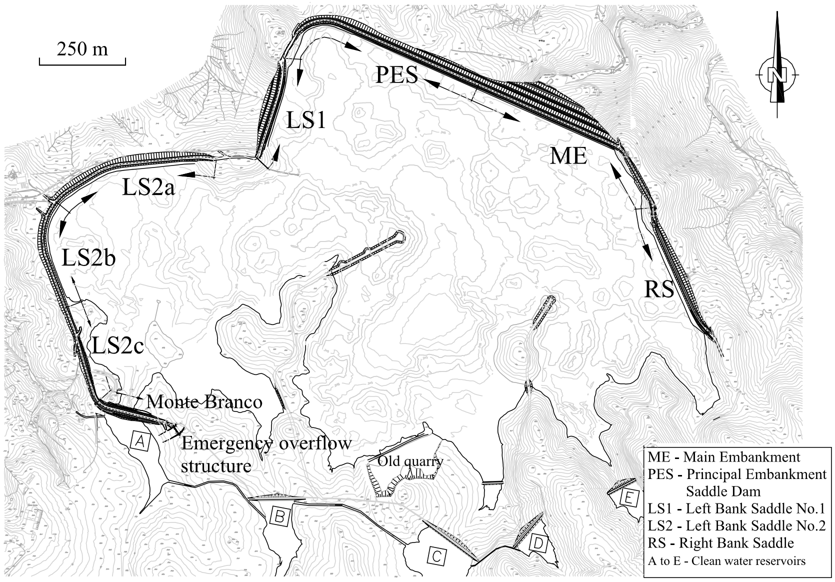

Figure 2. General plan of the Cerro do Lobo complex.

embankment dam was built, with a central core, constituted by clayey soils obtained from weathered schist materials, and upstream and downstream shells, constituted by appropriately processed mine rejected materials and, complementarily, by quarry rockfill materials. In the subsequent phases, the downstream construction method was used for dam heightening, keeping the downstream slope inclination. Table 1 presents the reservoir and embankment's major features for the different construction phases and Figure 3 represents the actual maximum cross section of the dam.

The water proofing of the dam body at elevations higher than 244 m (the core crest elevation) is provided by an inclined geomembrane (2 mm thick, of HDPE), properly sealed, near the downstream edge of the core crest, with a compacted mixture of sand and bentonite and connected to the rock abutments through a reinforced concrete plinth (Cambridge and Maranha das Neves 1991).

For seepage control of the dam body and foundation, an internal drainage system was adopted, composed of a chimney drain, a transversal drainage blanket, located at the valley bottom, and a peripheral downstream toe drain (Figure 4).

The dam foundation and storage basin are constituted by Palaeozoic-metamorphic rock formations, greywacke and shale of the flysch group. Foundation preparation works were limited to slush-grouting of the core trench, with the removal of superficial deposits beneath the shells (Toscano and Cambridge 2006). It was assumed that, in time, the tailings would contribute to rendering the storage basin impervious. Nevertheless, a set of drainage wells for the interception of the sub-superficial groundwater was designed. The collected water is then pumped back into the reservoir.

The embankment crest has reached its maximum height and a closure design is already being developed. A more detailed description of the Cerro do Lobo dam can be found in Toscano and Cambridge (2006).

Analysis scope and reference situation

The present analysis is focused on the reservoir operation period following the last heightening of the dam.

Table 1. Reservoir and embankment major features.

Construction phases	Conclusion year	Storage capacity (10^6 m^3)	Crest elevation	Max. height (m)	NIL[a]
1st	1988	6	244	28	243.0
2nd	1990	11	248	32	246.8
3rd	1993	15.5	252	38	250.5
4th	2005	20	255	42	253.5

[a]NIL = normal impoundment level.

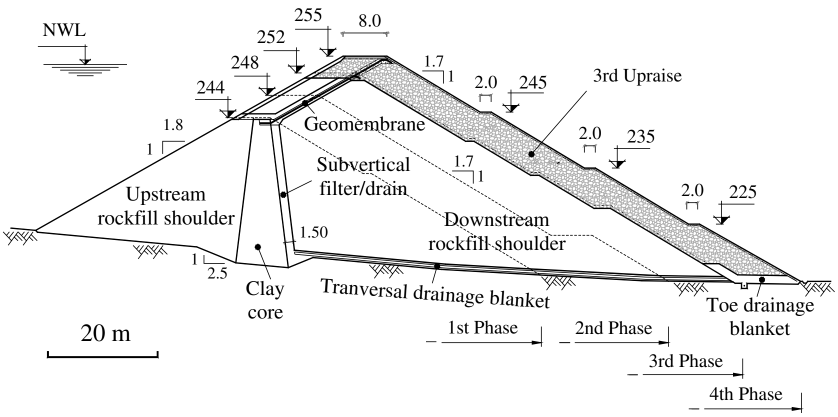

Figure 3. Sequential downstream heightening of the dam (Hidroprojecto 2002).

The reference situation is defined from the possible values of selected state variables. These variables characterise the aspects that may influence the occurrence of chosen events, their likelihood or the severity of their end effects.

For this demonstrative analysis, the definition of only two state variables – the impoundment (*NWL*) and tailings levels – was considered sufficient.

The *NWL* variation induces the variation of the hydraulic head in the dam body and its foundation. The increase in the *NWL* increases the likelihood of excessive seepage, internal erosion or hydraulic uplift, through the embankment and its foundation. The increase in the tailings deposits, covering the geological discontinuities of the foundation, produces the densification of underlying materials, and due to their high fine content (Figure 5), tends to reduce the seepage velocity and, in this way, to attenuate the problems related to the seepage phenomenon. The tailings segregation is minimised by the deposition technique adopted, i.e. underwater deposition with telescopic tubes, producing slightly stratified profiles that are predominantly homogeneous in horizontal directions. Thus, the worst possible scenario (Figure 6) corresponds to the following state variables: the maximum impoundment water level (*NWL*) and the minimum tailings level, corresponding to the last bathymetric sounding of the reservoir (248 m – May 2005).

Definition of the system

The system shall include all the elements prone to damage due to an incorrect structural, hydraulic or environmental performance of any element associated with the dam. In this way, the influence zone of the dam is included in the system.

This definition comprises two non-dissociable and fundamental tasks of the *FMEA* process: (1) the identification and the organisation of the basic components in a functional and hierarchical structure, forming different subsystems at different levels, until the global system is attained and (2) the definition of the functionalities or the function requirements of each basic component for the normal performance of the system.

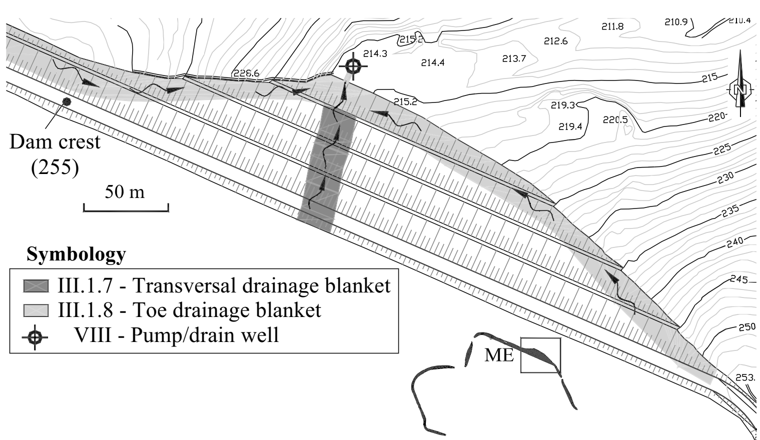

Figure 4. Internal drainage system and pumping well (Hidroprojecto 2002).

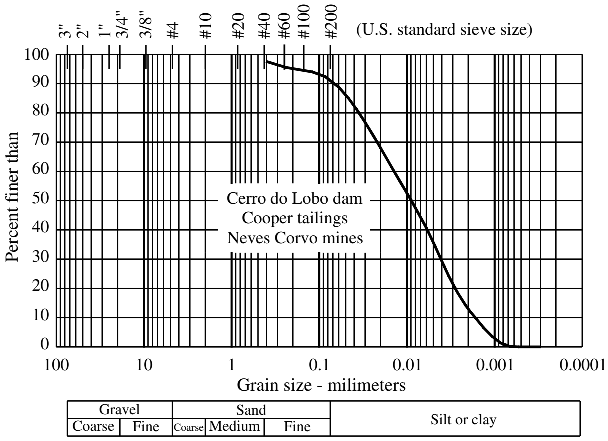

Figure 5. Grain-size distribution of the tailings materials.

Figure 7 partially illustrates the hierarchical structure of the *FMEA* of the Cerro do Lobo complex system, with components and corresponding parent subsystems being introduced. The definition of the system structure began with the identification of the main subsystems, which are the major sets of relevant elements of the system.

In the identification of subsystems and basic components, an alpha-numerical code was used to help localising and differentiating them within the hierarchical structure. According to this scheme, the main subsystems were coded in a sequential order, by roman numerals.

Nine main subsystems were selected: catchment area (*I*); clean water dam (*II*); main dam (*III*); two saddle dams (*LS1* and *LS2*) at the left bank (*IV* and *V*); saddle dam at the right bank (*VI*); spillway (*VII*); pumping wells (*VIII*); and downstream valley (*IX*).

Those were, in turn, divided successively into subsystems of a lower level, until the basic components were reached, e.g. *III.1* subsystem in Figure 7, as detailed below.

In this example, each main subsystem was subdivided into several other subsystems, to a maximum

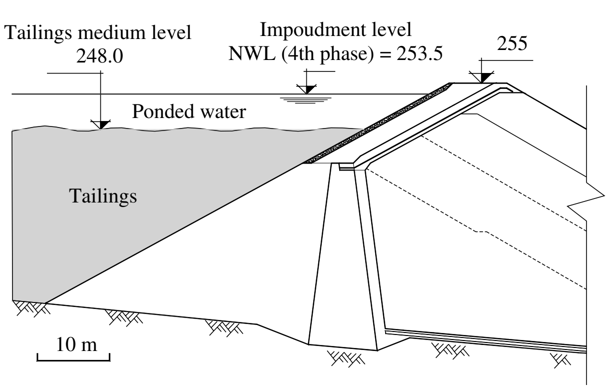

Figure 6. State variables.

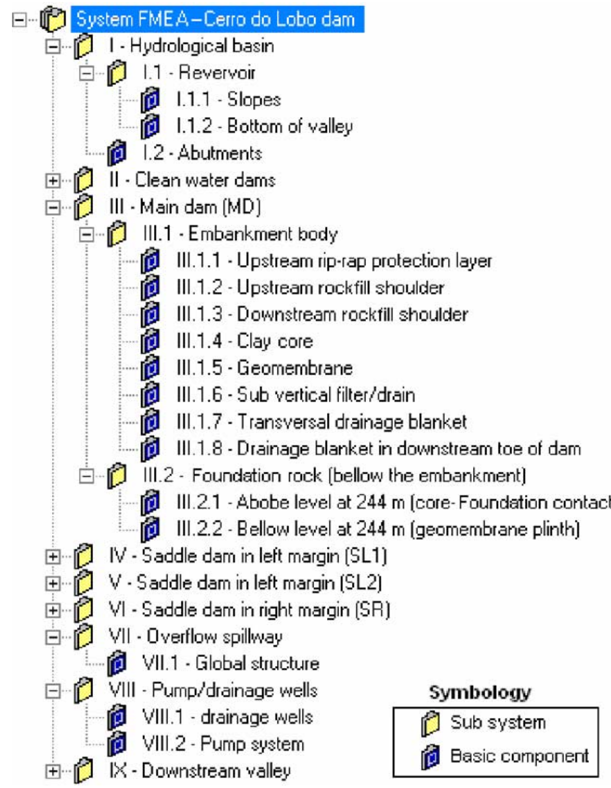

Figure 7. Cerro do Lobo dam system.

of two additional levels, until the basic component level was reached. At this point, a degree of detail was achieved in which it is possible to understand the function(s) of the basic components. A code extension for each successive level of detail of the system was adopted, by the attachment of a sequential number preceded by a dot division.

As an example (e.g. Table 2), for the main dam (*III*), two sub-systems of the next level were considered: the dam body (*III.1*) and the rock foundation (*III.2*). These subsystems were then divided into basic components. For the dam body, the following basic components were used: the upstream protection layer (*III.1.1*), the upstream and downstream shells (*III.1.2* and *III.1.3*), the clayey core (*III.1.4*), the geomembrane (*III.1.5*), the chimney filter (*III.1.6*), the transversal drainage blanket (*III.1.7*) and the peripheral downstream toe drain (*III.1.8*).

Functions of the basic components

After defining the system, the functions of each basic component and its relationships with the other components and subsystems must be completely identified. For a better understanding of the interrelationships of component functionalities in a given subsystem, it is useful to construct *functional block diagrams* (*FBD*). An *FBD* provides an useful way of

Table 2. Functions of the basic components.

Comp. ID	Description	Functions and operability requirements
I.1.1	Reservoir slopes	Retention of pounded water and tailings
I.1.2	Reservoir bottom valley	Water-tightness at the reservoir basin
I.2	Remaining catchment basin	Catchment of the rainfall water
III.1.1	Upstream protection layer	Protection of the upstream shell from the waves' action
III.1.2	Upstream shell	To guarantee the mechanical stability of the dam
III.1.3	Downstream shell	To guarantee the mechanical stability of the dam
III.1.4	Clayey core	Positive control of the phreatic surface and seepage flow
III.1.5	Geomembrane	Watertightness of the zones above the core
III.1.6	Chimney drain	To prevent core internal erosion and drain seeping water
III.1.7	Drainage blanket	To drain and filter the water from the chimney drain and from the foundation
III.1.8	Downstream toe drain	To drain and filter the water from the drainage blanket
III.2.1	Rock foundation (below 244 m elevation)	To support the capacity of the embankment and provide some water-tightness at the core base
III.2.2	Rock foundation (above 244 m elevation)	To support capacity of the embankment and provide some water-tightness at the plinth base
VII.1	Spillway structure	To ensure a controlled discharge under exceptional inflow conditions
VIII.1	Drainage wells	To collect all the seepage water (through the embankment and foundation)
VIII.2	Pumping system	To pump the water collected in the wells back into the reservoir

framing the sequential functionality of a particular subsystem. Figure 8 shows an *FBD* related to the *III.1 – dam body* subsystem. Each block represents a component function, whereas the links between blocks are represented by direct paths, in which the orientation indicates the normal functional sequence of the subsystem.

The beginning of a functional flow, in a particular block, depends on the functionalities of the components pertaining either to the subsystem under analysis, or to an external subsystem. The adequate functionality of a block can also be a requirement for the functionalities of other components, even in external subsystems.

Figure 8 illustrates the functionalities associated with the dam body subsystem, namely the mechanical stability and the seepage control. The global stability (sliding) is provided by the upstream and downstream shells and by the dam foundation (external subsystem). The functionality of the upstream shell, on the other hand, depends on the proper performance of the upstream protection layer. The seepage control is essentially guaranteed by the clay core, the geomembrane and the dam foundation (watertightness), and by the drainage system, constituted by the chimney filter and drain, the drainage blanket and the downstream toe drain. The null discharge philosophy, in turn, requires the seepage water to be collected by the drainage well and pumped back into the reservoir (external subsystems).

Table 2 presents the functions and operationality requirements of all the components shown in Figure 7.

Failure modes and their corresponding root causes

*ICOLD (*2001*)* has identified the most common reasons for defective behaviour in tailings dams: (1) lack of water balance control, (2) lack of construction control and (3) lack of understanding of the features that control safety operations. This information is useful for incorporation into the analysis. Still, each

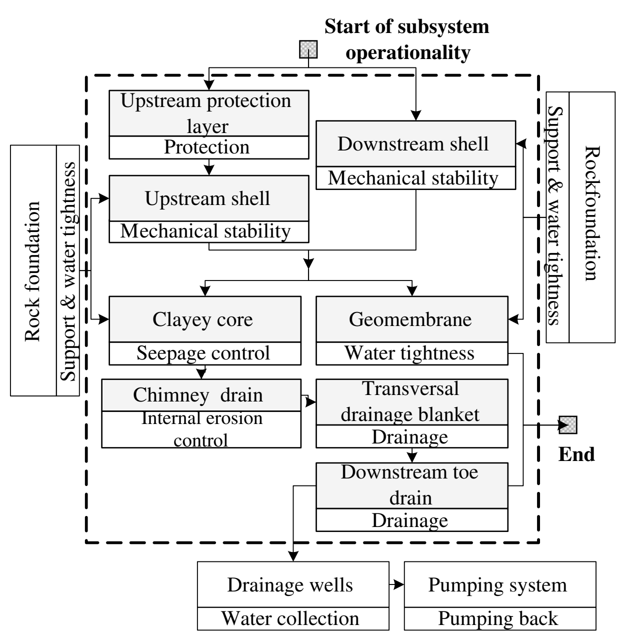

Figure 8. *FBD* for the dam body subsystem.*

dam system has its particular aspects that must be identified and addressed in the analysis.

In the Cerro do Lobo dam, the first cause is not relevant due to the presence of the peripheral drainage system, which prevents the access of the superficial water of the surrounding areas to the reservoir. Due to the implemented construction control methods used in each phase of the dam (initial and heightening phases) the significance of the second cause is similar to the one associated with traditional, well-constructed, earth dams. The failure modes were defined taking into account all the possible lacks of functionality of each basic component, assuming simultaneously that the remaining components keep their functionalities intact (i.e. a caeteris paribus situation). Complementarily, the initialising causes (root causes – not associated with the failure modes of other subsystems or components) of each failure mode were identified. The ranking of the component failure modes is not a simple process and it always has an important subjective character. In this presentation, the following two criteria were adopted: the consideration of failure modes conceivable for the present phase of the Cerro do Lobo dam (fourth phase) that can produce relevant impacts on the system. In this way, failure modes with very low likelihood of occurrence were neglected, unless they are able to lead to catastrophic effects on the system (i.e. the associated risk might be critical).

It has not been practicable to include the analysis of all the identified components of Cerro do Lobo dam system. Thus, only the *FMEA* results for the components of the main embankment (*ME*) subsystem are shown. Table 3 presents the identified failure modes and their corresponding root causes for the components pertaining to the subsystem analysed. In this table, each failure mode is identified by attaching to the basic component code a sequential number

Table 3. Failure modes and root causes.

Comp.	ID	Failure mode	Root causes
Upstream protection layer	III.1.1.(1)	Erosion	Waving under wind action, chemical alterability, wetting – drying cycles and thermal variations (fracture and weathering) of rockfill material
Upstream shell	III.1.2.(1)	Instability	Seismic action, chemical alterability, insufficient interface resistance (soil/geomembrane)
	III.1.2.(2)	Excessive deformability	Chemical alterability, collapse, creep, inadequate compaction
Downstream shell	III.1.3.(1)	Instability	Seismic action, insufficient shear strength in the contact between materials applied in different phases
	III.1.3.(2)	Excessive deformability	Third heightening loading, creep, inadequate compaction of third phase materials
	III.1.3.(3)	External erosion	Overtopping due to exceptional inflow conditions
Clayey core	III.1.4.(1)	Excessive seepage (without cracking)	Chemical alterability, material dissolution, excessive hydraulic head and gradients
	III.1.4.(2)	Excessive seepage (with cracking)	Hydraulic fracturing
Geomembrane	III.1.5.(1)	Cracking	Stress cracking, chemical attack, perforation, incorrect installation (core and foundation connections, overlapping, sunlight exposure and punching)
Chimney drain	III.1.6.(1)	Internal and external instability	Inappropriate materials, incorrect construction, chemical alterability
	III.1.6.(2)	Insufficient drainage	Insufficient thickness
Drainage blanket	III.1.7.(1)	Internal and external instability	Inappropriate materials, incorrect construction, chemical alterability
	III.1.7.(2)	Insufficient drainage	Inappropriate grain-size distribution, insufficient dimensions given the water level increase
Downstream toe drain	III.1.8.(1)	Internal and external instability	Inappropriate materials, incorrect construction, chemical alterability
	III.1.8.(2)	Insufficient drainage	Inappropriate grain-size distribution, insufficient dimensions given the water-level increase, external obstruction
Rock foundation (below 244)	III.2.1.(1)	Excessive seepage	Rock discontinuities, schist chemical alterability, deficient clearing, grubbing and stripping
Rock foundation (above 244)	III.2.2.(1)	Excessive seepage	Rock discontinuities, schist chemical alterability, deficient clearing, grubbing and stripping, deficient connection to the concrete plinth

between round brackets, e.g. mode *III.1.4* (2) *excessive seepage (with cracking)* is the second failure mode considered for the basic component *III.1.4 clay core*.

The identified root causes of a component failure mode correspond to the phenomenological processes initiated in that particular component. The identification and description of the root causes of each failure mode are not absolutely necessary for *FMEA*, if only a qualitative risk analysis is intended. However, if the analysis is to be extended to include some risk prioritisation, it is useful to know the root causes to estimate the probability of the failure mode initiation.

As an example of reasoning, the failure modes and the root causes associated with the drainage blanket are explained as follows. For the first failure mode, *external and internal instability*, the subsequent possible initiating causes were selected: (1) inappropriate selection of materials, violating the filter criteria (Sherard *et al.* 1984, Sherard and Dunningan 1989) in relation to the ground foundation, (2) clogging by adjacent embankment materials; (3) inappropriate construction inducing materials segregation; and (4) chemical alterability of the materials, in view of the local prevailing aggressive conditions. For the second failure mode, *insufficient drainage capacity*, an eventual insufficient section design or an adequate grain-size distribution of the material are considered. It is worth noting that this component will be subjected to increasingly severe conditions, due to the rise in the operation level of the dam and the consequent increase of both the hydraulic head and the saturation surface in the dam body.

Sequence of effects

Having identified the initiating causes of the failure modes and assumed their occurrence, it is necessary to evaluate the effects of the chain of failure modes – contributing modes in the hierarchy of the geotechnical system previously defined.

Due to its hierarchical nature, the analysis must begin at the basic component level. Their failure modes have immediate or direct effects on themselves, which, subsequently, become failure modes of the subsystem of a higher level, either associated or not with other failure modes of other components of that subsystem. These effects can be referred to as parent subsystem failure modes. This principle is applied as a failure sequence progress throughout the successive subsystems until the main subsystems are reached. Thus, the subsequent effects, called intermediate effects, are the outcomes for parent subsystems and the end effects are the outcomes for the whole system.

In synthesis, direct, intermediate and end effects are related to the impacts of a component failure mode, respectively, on the component itself, on the intermediate subsystems, and on the system as a whole. They should not be mistaken for the remote consequences in the downstream valley, such as the loss of lives or economic losses, due, for example, to flood-wave propagation of tailing materials.

The sequence of events between subsystems of different levels is a complex one and, sometimes, difficult to analyse. It is convenient that the method implementation includes a form of representing the sequence of effects of the several failure modes of the basic components in the subsequent subsystems of a higher level.

The items coded with *III.1.(#)* and *III.(#)* are, respectively, direct and intermediate effects of the presented component failure modes, and can also be referred to as failure modes of the *III.1 – dam body* and *III – main dam subsystems*. The items coded with *0.(#)* are the end effects of the presented components failure modes and can also be referred to as system failure modes.

In the development of the failure effects sequence, the *FMEA Item ToolKit Module* (Item Toolkit 2002) was used. This type of software makes it possible to set the failure sequence and to automatically trace it throughout the system hierarchy.

As an example, Figure 9 shows the considered failure modes and their subsequent effects, highlighting the effects induced by geomembrane cracking. The direct effect in this component is the occurrence of the concentrate leakage of water through the geomembrane, possible with a large flow of water downstream, which can cause internal erosion, inducing the clogging of the drainage system (intermediate effect) and, if the wells and the pumping system are not able to return this water into the reservoir, generalised downstream contamination will be produced (end effects), not complying with the null discharge requirement.

Another example is the sequence associated with the internal or external instability of the drainage blanket. The following direct effects can be named: internal erosion, due to the outside entrainment of its particles, and clogging, due to the entrainment of the fine particles from the foundation. These direct effects correspond to the failure modes of the subsystem of the level immediately above (the dam body). The intermediate effect associated with the drainage blanket erosion is the foundation erosion, by loss of the material into the drainage blanket. The blanket drainage clogging prevents progressively the water flow, making the operation of the drainage system impracticable and causing seepage at higher levels in

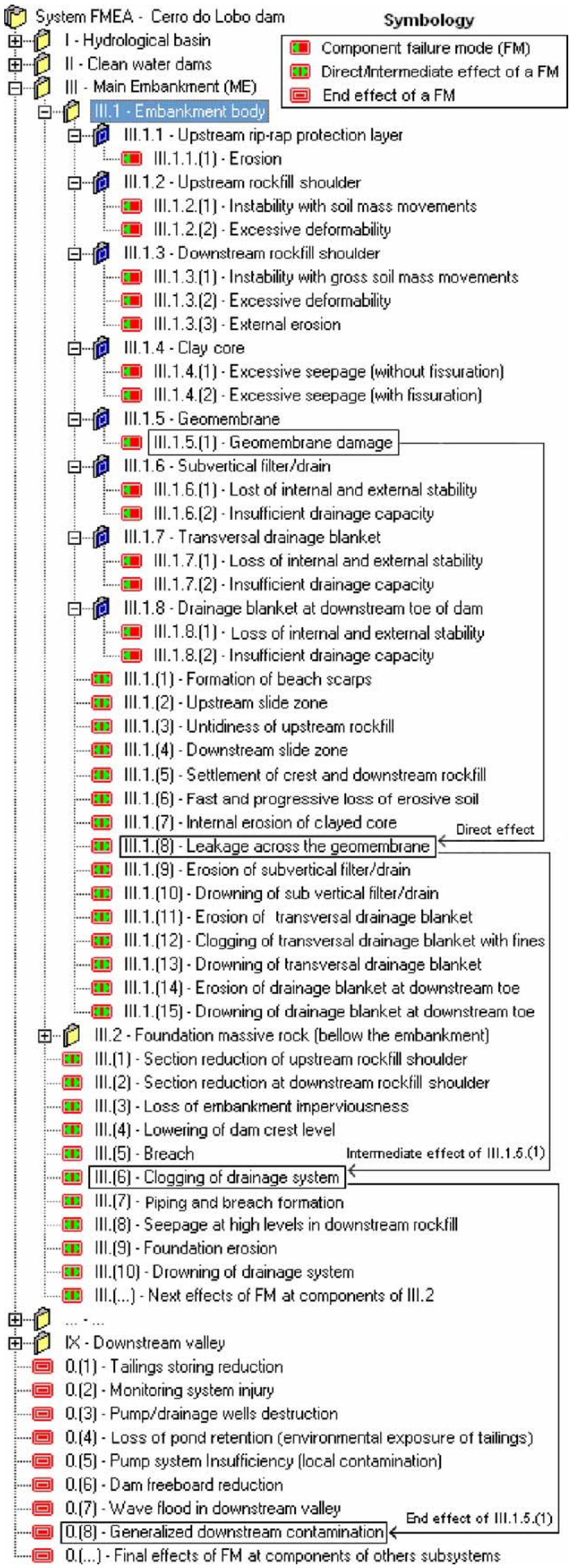

Figure 9. Component failure modes of the dam body and their sequence effects.

the downstream shell. To complete the effects sequence, it is necessary to identify the end effects. Those are the pumping system insufficiency (local contamination), caused by its incapability to treat all the downstream flow, and generalised downstream contamination induced by foundation seepage and water exit downstream of the pumping wells.

Other sequences of effects of the failure modes are presented, in a tabular form, in Table 4. It should be noted that some failure modes can show the same effects, for instance *III.1.4(1)* and *III.1.4(2)*, both associated with the clayey core and excessive seepage. Nevertheless, they present distinct likelihood (with mode *III.1.4(1)* having higher likelihood) and severity, so they should be separated if their criticality is to be evaluated.

Failure mode detection and control measures

The available measures for detecting and controlling the failure modes of the components or their effects can be identified. In the previous identification of the sequence effects it was assumed that there was no intervention in the case of detection of some anomalous behaviour of the dam.

These available detecting and controlling measures affect, essentially, the likelihood of occurrence and the severity of the failure modes effects. The efficiency of those measures depends on their capability of fast enough implementation to become effective in the short term.

Detection measures

The detection measure should reveal the occurrence of root causes or of their direct effects in an initial development phase of the failure modes.

In embankment dams, the detection is based, essentially, on routine and specialised visual inspections and reading campaigns of the monitoring system. Visual inspection, performed at regular intervals by trained personnel, will often make it possible to detect abnormal conditions. It may readily identify changed conditions and has the advantage of providing complete coverage, as opposed to instruments, which often only monitor limited areas. It offers an initial impression to evaluate integrity, movements and loads.

However, it allows only the detection of surface anomalies, so it must be complemented by an adequate monitoring scheme.

Some of the aspects to observe during the visual inspection are signs or evidence of the initiation or progression of failure modes, such as displacements, leakages and seepage water turbidity, among others.

Table 4. Effects of the component failure modes of the main dam subsystem in the reservoir operation period.

ID	Failure modes	ID	Direct effects	ID	Intermediate effects	ID	End effects
III.1.1.(1) Upstream protection layer	Erosion	III.1.(1)	Partial destruction (*beaches and scarps*)	III.(1)	Geometry and strength variation of the *upstream shell*	0.(1) 0.(6)	Reduction of the tailing storage Freeboard loss
III.1.2.(1) Upstream shell	Instability	III.1.(2)	Geometry and strength variation (*sliding*)	III.(3) III.(4)	Geomembrane or core damage (*lack of watertightness*) Crest lowering	0.(1) 0.(4) 0.(6)	Reduction of the tailing storage Lack of pond retention (tailings exposure) Freeboard loss
III.1.2.(2) Upstream shell	Excessive deformability	III.1.(2)	Geometry variation	III.(3) III.(4)	Geomembrane damages (*lack of watertightness*) Crest lowering	0.(1) 0.(4) 0.(6)	Reduction of the tailing storage Lack of pond retention (tailings exposure) Freeboard loss
III.1.3.(1) Downstream shell	Instability	III.1.(4)	Geometry and strength variation (*sliding*)	III.(3) III.(4) III.(6)	Geomembrane and core damage (*lack of watertightness*) Crest lowering Malfunction of the drainage system (*toe drain obstruction*)	0.(2) 0.(3) 0.(4) 0.(5) 0.(6)	Monitoring system damage Pump/ drainage well destruction Lack of pond retention (tailings exposure) Pump system insufficiency (local contamination) Freeboard loss
III.1.3.(2) Downstream shell	Excessive deformability	III.1.(5)	Settlements of crest and of downstream rockfill	III.(3) III.(4)	Geomembrane damages (lack of water-tightness) Crest lowering	0.(2) 0.(4) 0.(5) 0.(6)	Monitoring system damage Lack of pond retention (tailings exposure) Pump system insufficiency (local contamination) Freeboard loss
III.1.3.(3) Downstream shell	External erosion	III.1.(6)	Fast and progressive loss of material, geometry variation	III.(3) III.(4) III.(5) III.(6)	Geomembrane and core damage (*lack of water-tightness*) Crest lowering *Breach* formation Malfunction of the drainage system (*toe drain obstruction*)	0.(2) 0.(3) 0.(7) 0.(8)	Monitoring system damage Pump/ drainage well destruction *Flood wave* in the downstream valley Generalised downstream contamination
III.1.4.(1) Clayey core	Excessive seepage (without cracking)	III.1.(7)	Internal erosion	III.(6) III.(7) III.(8)	Clogging of the drainage system Piping and *breach* formation Seepage at high levels in the downstream shell	0.(5) 0.(6) 0.(7) 0.(8)	Pump system insufficiency (*local contamination*) Freeboard loss *Flood wave* in the downstream valley Generalised downstream contamination
III.1.4.(2) Clayey core	Excessive seepage (with cracking)	III.1.(7)	Internal erosion	III.(6) III.(7) III.(8)	Clogging of the drainage system Piping and *breach* formation Seepage at high levels in the downstream shell	0.(5) 0.(6) 0.(7) 0.(8)	Pump system insufficiency (*local contamination*) Freeboard loss *Flood wave* in the downstream valley Generalised downstream contam.

Table 4. (*continued*)

ID	Failure modes	ID	Direct effects	ID	Intermediate effects	ID	End effects
III.1.5.(1)					Geomembrane		Geomemb. damage
III.1.(8)	Leakage	III.(8) III.(10)	Seepage at high levels in the downstream shell Submersion of the drainage system	0.(5) 0.(8)	Pump system insufficiency (*local contamination*) Generalised downstream contamination		
III.1.6.(1) Chimney filter	Internal and external instability	III.1.(9) III.1.(10)	Internal erosion Clogging	III.(7)	Piping and *breach* formation	0.(7)	*Flood wave* in the downstream valley
III.1.7.(1) Drainage blanket	Internal and external instability	III.1.(11) III.1.(12)	Internal erosion Clogging	III.(6) III.(8) III.(9)	Clogging of the drainage system Seepage at high levels in the downstream shell Foundation erosion	0.(5) 0.(8)	Pump system insufficiency (*local contamination*) Generalised downstream contamination
III.1.7.(2) Drainage blanket	Insufficient drainage capacity	III.1.(12)	Submersion	III.(8) III.(10)	Seepage at high levels in the downstream shell Submersion of the drainage system	0.(5)	Pump system insufficiency (*local contamination*)
III.1.8.(1) Downstream toe drain	Internal and external instability	III.1.(13)	Internal erosion	III.(9)	Foundation erosion	0.(5)	Pump system insufficiency (*local contamination*)
III.2.1.(1) and III.2.2.(1) Rock foundation	Excessive seepage	III.2.(1)	Internal erosion	III.(6) III.(8) III.(10)	Clogging of the drainage system Seepage at high levels in the downstream shell Submersion of the drainage system	0.(5) 0.(8)	Pump system insufficiency (*local contamination*) Generalised downstream contamination

While a gross movement of the embankment or foundation would indicate that a very serious condition is occurring or developing, cracking and new areas of leakage through the dam or foundation are more subtle visual clues to possible soil movements.

The appearance of transported material in the seeping water collected in the drainage wells may indicate piping or internal erosion in the clay core. If a rapid increase in the seepage rate is observed, it may be a strong indication of a developing situation and emergency action must be taken. Depressions or sinkholes in the embankment are also strong indicators of piping occurrence (Foster *et al.* 2000a).

The comparison of the monitoring results with the expected tendencies of the evolution of the measured quantities allows, in a safe way, the detection of some failure modes initiation.

The surveillance and monitoring plan developed for the third heightening of the Cerro do Lobo dam established the visual inspection schedule, report forms and communication schemes to apply in the case of detection of anomalous behaviour.

Figure 10 shows the instrumentation system applied to the highest dam cross section. The monitoring of vertical and horizontal superficial displacements is accomplished by precision surveys of superficial marks (*SM*) located on the dam crest and on the downstream berms. Inclinometers (*Ic*) are used to measure horizontal internal displacements of the dam structure. The development of pore pressures and the seepage within and through the dam body

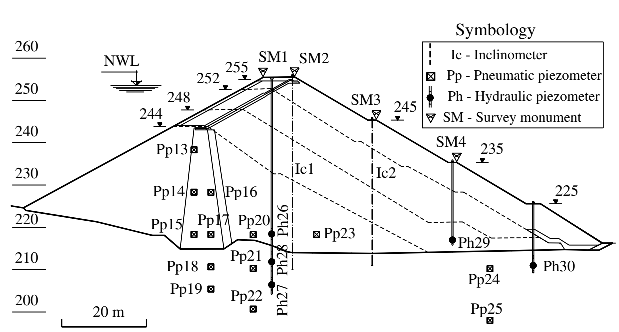

Figure 10. Monitoring equipment of the highest dam cross section.

and foundation is followed with pneumatic or open standpipe piezometers (*Pp* and *Ph*), wells and pumping devices.

Several pneumatic piezometers (*Pp*) have been installed since the first construction phase. To improve the observation system reliability, hydraulic piezometers (*Ph*) were also installed in the last heightening phase.

The volume of tailings stored in the reservoir, the direct rainfall and evaporation balance, as well as the water volume pumped from the wells back to the reservoir are all important variables for detecting malfunctions, as well as the tailings level (by bathymetric sounding), and all are monitored.

Given the type of retained materials in the reservoir, chemical weathering of the dam body and foundation is a possibility, so an environmental monitoring scheme was implemented to reveal material transportation due to internal erosion or dissolution, and groundwater contamination. Evidence of the presence of core or foundation material entrainment requires prompt intervention. Chemical analyses (*pH*, *Ca*, chlorides, sulphates, *As* and *Cu*) of the reservoir water and groundwater collected in wells located in the downstream valley serve to perceive the occurrence of groundwater contamination.

Table 5 presents the available measures identified to detect the component failure modes of the main dam (*ME*).

Control measures

Once abnormal behaviour is detected, the risk management process implies the identification of the associated failure(s) mode(s) and the implementation of the proper available control measures. Usually, that implies taking corrective actions to cease the propagation of sequence failure effects, but only the ones promptly accessible at the dam site should be considered.

These measures may include, given that the materials and equipment are available, for example, the construction of stabilisation structures; the replacement of deteriorated materials; the restoring of the theoretical dam geometry, by placement of additional material; and the improvement of the pump power system to minimise the downstream groundwater contamination due to an increase in the seepage flow rate.

The Cerro do Lobo dam has a siphon type spillway that may slow down the sequence effects of some failures by lowering the impoundment level. This control action has a limited effect and in some cases it is not time-effective, given the fast development of some failure modes. Additionally, it implies environmental impacts due to the direct discharge of contaminated water into downstream valley and tailings exposure to the atmospheric conditions (tailings dispersion in the air due to wind action).

Table 6 presents the existent control measures in the Cerro do Lobo main dam associated with each of the analysed failure modes.

Results and discussion

Given the dated nature of the conclusions of *FMEA* and for transparency and communication purposes its results must be reviewed periodically to take into account the evolution of the dam behaviour. So, it is mandatory to document the *FMEA* process in a worksheet form. All the references available, used and produced by the *FMEA* team, were recorded and key items of data and information, which led to important findings or insights, were appended for easy access.

A large proportion of data used in *FMEA* are descriptive. The preparation of a master phrase table, containing commonly used descriptions of component parts of embankment dams, failure modes, causes, effects and action measures, makes it possible to speed up *FMEA* application. These ‘check-lists’ can be then customised, reviewed and updated to suit particular requirements of other dam systems.

The severity of the end effects of the failure modes was qualitatively evaluated according to their likelihood of impacts on (1) the health and safety of people, (2) the environment, (3) the economy and financial issues, and (4) the public regulatory reputation.

The occurrence of a flood wave in the downstream valley (*0.(7)*), generalised downstream contamination (*0.(8)*) and pumping system insufficiency (*0.(3)*) were found to be the most severe end effects.

The flood wave in the downstream valley (*0.(7)*) has a direct impact on the downstream valley main subsystem. It corresponds to the pouring of several million cubic metres of highly liquefied acid slurry (water and tailings) into the downstream valley. Its occurrence depends on the conditions for breach formation, which can have the following two possible preceding events: fast and progressive erosive loss in the downstream slope or piping. The first one can occur in very exceptional inflow conditions (heavy rainfall), with a high impoundment level and subsequent overtopping.

Functional failures in the clay core (*III.1.4*) or chimney drain *(III.1.6*) components may induce piping.

Piping can begin if leakage exists on the downstream side of the clay core and if backward erosion

Table 5. Detection measures.

Failure modes ID	Visual observation	Instrumentation monitoring
III.1.1.(1) Upstream protection layer erosion	Rockfill deterioration and movement	
III.1.2.(1) Upstream shell Instability	Scarps, crest cracking and curved intersection line with the water plane	Superficial displacements
III.1.2.(2) Upstream shell excessive deformability	Crest cracking, settlements and subsidence and curved intersection line with the water plane	Superficial displacements
III.1.3.(1) Downstream shell instability	Scarps, crest cracking and movement and accumulation of materials at the toe	Superficial displacements, internal displacements, pore pressures in the downstream shell and foundation
III.1.3.(2) Downstream shell excessive deformability	Crest cracking, settlements and subsidence	Superficial displacements and internal displacements
III.1.3.(3) Downstream shell external erosion	Gully erosion and material loss	Impoundment and tailings levels, meteorological data and water pumped volume
III.1.4.(1) and III.1.4.(2) Clayey core excessive seepage	Water turbidity, subsidence and water flow or humidity at the downstream shell	Superficial displacements, impoundment and tailings levels, pore pressures in core and downstream shell and water pumped volume
III.1.5.(1) Geomembrane Damage	Subsidence and water flow or humidity at the downstream shell	Superficial displacements, impoundment and tailing levels, pore pressures in the downstream shell and water pumped volume
III.1.6.(1) Chimney filter internal and external instability	Water turbidity, subsidence and water flow or humidity at the downstream shell	Superficial displacement, impoundment level, pore pressures in the core and downstream shell and water pumped volume
III.1.7.(1) Drainage blanket internal and external instability	Water turbidity, subsidence and water flow or humidity at the downstream shell	Impoundment level, pore pressures in the downstream shell and foundation, water pumped volume and environmental monitoring
III.1.7.(2) Drainage blanket insufficient drainage capacity	Water flow or humidity at the downstream shell	Impoundment level, pore pressures in the downstream shell and foundation, water pumped volume and environmental monitoring
III.1.8.(1) Downstream toe drain internal and external instability	Water turbidity, subsidence and water flow or humidity at the downstream shell	Impoundment level, pore pressures in the downstream shell and foundation, water pumped volume and environmental monitoring
III.2.1.(1) and III.2.2.(1) Rock foundation excessive seepage	Water turbidity and water flow or humidity downstream of the dam	Impoundment and tailings level; pore pressures in the downstream shell and foundation, water pumped volume and environmental monitoring

to the reservoir is initiated. It can take place (failure mode *III.1.4.(1)*) due to chemical weathering and alterability of clay minerals, material dissolution, high gradients associated with a reduced clay core thickness or improper functioning of the chimney drain, or due to cracking (failure mode *III.1.4.(2)*) caused by hydraulic fracturing.

For the chimney drain (*III.1.6*), the violation of retention, permeability, filter uniformity, self-stability and granular criteria can lead to the internal erosion development (failure mode *III.1.6.(1)* – internal and external instability). The initiation of this failure mode can result from either hydraulic, grain-size or chemical unsuitability of the materials used in the drain and from their incorrect field placement.

Soil-rockfill dams have less likelihood of failure due to piping through their body (Foster *et al.* 2000b). Nevertheless, given the progressive increase in the water level, these failures were herein considered due to their catastrophic severity and because some uncertainties related to both the geometry and the materials of the filter used in the previous construction phases, and also to its future performance can be present.

The generalised downstream contamination (*0.(8)*) corresponds to the likely environmental pollution, especially of the groundwater in the downstream valley main subsystem. This can occur if physical clogging of the drainage system takes place. In this case, the groundwater in the more superficial zone of the foundation is not collected by the pumping wells.

The clogging of the internal drainage system can be preceded by internal erosion of the clay core or by water leakage across the geomembrane.

Table 6. Control measures.

Failure modes ID	Control measures
III.1.1.(1) Upstream protection layer erosion	Placement of additional rockfill
III.1.2.(1) Upstream shell Instability	Upstream stabilising berm construction
III.1.2.(2) Upstream shell excessive deformability	Dam geometry restoration
III.1.3.(1) Downstream shell instability	Downstream stabilising berm construction
III.1.3.(2) Downstream shell excessive deformability	Dam geometry restoration
III.1.3.(3) Downstream shell external erosion	Dam geometry restoration
III.1.4.(1) and III.1.4.(2) Clayey core excessive seepage	Increase of the pumping system capacity and impoundment level lowering
III.1.5.(1) Geomembrane damages	Increase of the pumping system capacity and impoundment level lowering
III.1.6.(1) Chimney filter internal and external instability	Increase of the pumping system capacity and impoundment level lowering
III.1.7.(1) Drainage blanket internal and external instability	Increase of the pumping system capacity and superficial-impoundment level lowering
III.1.7.(2) Drainage blanket insufficient drainage capacity	Increase of the pumping system capacity
III.1.8.(1) Downstream toe drain internal and external instability	Increase of the pumping system capacity and impoundment level lowering
III.2.1.(1) and III.2.2.(1) Rock foundation excessive seepage	Increase of the pumping system capacity, execution of additional wells and impoundment level lowering

The phenomenological processes that can lead to geomembrane leakage are: stress cracking, punching, chemical or *UV* attack. Additionally, incorrect installation, namely deficient connections to the core crest or abutments, or insufficient overlapping and welding of layer sheets, could also originate leakage. These construction anomalies can only be detected when particular water levels are reached.

The most vulnerable component of the drainage system should be the drainage blanket, given its reduced section, when compared with the other components. Both the chimney filter and the downstream toe drain are implanted along the entire extent of the dam. Additionally, the last heightening has been mainly executed with rockfill materials (see Figure 3), providing extra drainage for possible blocking of the drainage system in this area.

The initiating causes of the loss of internal and external stability of the drainage blanket by clogging are the unsuitability of materials, their incorrect placement or the chemical alterability of granular materials.

The root causes of the failure modes of the foundation are its fracturing and weathering conditions, chemical attack of schist and greywacke formations, defective clearing, grubbing and stripping or the malfunction of the concrete plinth.

The insufficiency in the pumping system represents the incapacity to pump back to the reservoir all the water collected in the wells. As a result, an overflow of the wells takes place and the polluted water contaminates the foundation in the well surroundings. If the available control measures are activated in advance, this end effect becomes circumscribed to this zone. Otherwise, the contamination spreads out and causes the pollution of downstream groundwater. This end effect can occur if one of the following failure modes is initiated: instability (*III.1.3.(1)*) or excessive deformability (*III.1.3.(2)*) of the downstream shell, loss of internal and external stability of the drainage blanket (*III.1.7.(1)*) or of the downstream toe drain (*III.1.8.(1)*), insufficient drainage capacity of the drainage blanket (*III.1.7.(2)*) and excessive seepage through the foundation (*III.2.1.(1)* and *III.1.2.(1)*).

The instability of the downstream shell has, as direct and intermediate effects, the possible movement of the crest, the downstream shell and the subsequent loss of the watertight capacity of the dam body if the clay core or the geomembrane becomes damaged and possible obstruction of the drainage system.

The root causes of downstream shell instability can be the occurrence of a severe earthquake or insufficient shear strength of the materials or the contact between materials applied in different construction phases. The excessive deformability of the downstream shell can result from the additional load caused by the last dam heightening, material creep or inadequate compaction.

Some of the described failure modes have no available actions for controlling their effect sequence. One example is the occurrence of hydraulic fracturing at the core (*III.4.1.(2)*) and subsequent erosion. The lowering of the water level with the siphon spillway is a procedure that can be considered ineffective given the development speed of the related phenomenon.

Concluding remarks

The *FMEA* methodology presented can be considered as a preliminary approach to performing quantitative risk analyses of large embankment dams.

Failure Modes and Effects Analysis is conceptually simple and its application to dam safety appears to be straightforward. However, with the increase in the number of components and their interaction, its use becomes more complex.

It allows to identify the most relevant hazards and vulnerabilities of the dam system analysed, by isolating each component and describing the effects of the individual component failure modes on the global system.

FMEA uses the concept that the majority of the components failure modes can be broken down into several stages of development. Typically, these stages comprise initiation, functionality breakdown and progression, respectively related to the root causes, the sequence of effects and the system failure modes.

FMEA outcomes can be useful in future developments through more complex approaches, such as event tree analysis (*ETA*) or fault tree analysis (*FTA*), for the most critical failure modes.

The case study of the Cerro do Lobo tailings dam shows the potential of this method to identify the conceivable failure modes of all the components of the dam system. It also demonstrates that the *FMEA* procedure may provide the basis for a comprehensive dam surveillance and warning system. It allows the identification of the potential failure modes and their warning signs. It includes considerations of how failures can occur and how potential problems can be detected and controlled fairly prior to their development into incident or accident stages.

The final product of *FMEA* is a worksheet form, which provides a structured, repeatable and documented process, facilitating the communication between technical and front-line staff.

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