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A DAM ASSESSMENT SUPPORT SYSTEM BASED ON PHYSICAL MEASUREMENTS, SENSORY EVALUATIONS AND EXPERT JUDGEMENTS

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Abstract

In engineering system control, human beings can play various key roles, in particular concerning measurement, global assessment and decision. This paper focuses on methods that allow the representation and aggregation of heterogeneous data (sensory evaluations, physical measurements, outputs of mathematical models, etc.) used in a global dam assessment process. It is acknowledged that in such complex systems many of the variables involved are evaluated with uncertainty. We propose a possibility theory-based approach to deal with all the different uncertain pieces of information and propagate them in aggregation models for global dam assessment. Finally, decision-making and communication applications relating to dam safety are presented.

Keywords: sensory evaluation**,** expert assessment, uncertainty, possibility theory, dam safety.

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1. Introduction

Modelling complex phenomena and providing data for their subsequent use in decision-making are crucial and challenging tasks that necessarily involve not only interdisciplinary but also expert knowledge [1-2-3-4]. Human beings can play various roles in such system control procedures (measurement, assessment, decision-making).

In particular, operators in charge of running the system concerned often have to propose corrective actions to guarantee that it runs correctly. For example, in civil engineering, these actions concern major reconstruction, rehabilitation or safety projects, emergency actions and so forth. They aim at preventing accidents and maintaining the infrastructure, subject to unavoidable ageing, in good and serviceable condition at minimum cost. Corrective actions rely on human ability to perform global assessments of processes. Usually, several data aggregation steps are performed due to the large variety and quantity of data available on a system. Indeed, systems are often assessed on the basis of only a few global data that provide a synthetic view of low level system data. In the case of dam safety assessment, it is important to perform a global assessment of dam safety deterioration related to different failure modes along with evaluations of the reliability of different technical functions, such as sealing and drainage [5] that can be viewed as intermediary assessments. The objective is to detect and correct phenomena that, if no action is carried out, can lead to (i) various deteriorations that may result in accelerated ageing, additional operational and maintenance costs, significant loss of water in dams and (ii) failures liable to cause dramatic events such as dam failure. These deteriorations are caused by many more or less interdependent dynamic processes, such as clogging, internal erosion, sliding, having various and often multiple sources [5]. Finally, experts can play an important role in the sensory evaluations involved in global or intermediary assessments. Indeed, numerous examples of system control indicate that models of complex phenomena cannot be supplied only with

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physical measurements, for example in food processing [6-7-8-9] and in civil engineering [10-11-12-13] but also require quantities evaluated by human beings. These have become an inherent part of many complex system analyses [14-15-16-17].

As human knowledge is seldom formalised, it is necessary to develop methods for collecting and modelling the information and knowledge involved in such complex assessments. This paper focuses on methods that allow a coherent representation of the different data (sensory evaluations, physical measurements, outputs of mathematical models, etc.) used in the global dam assessment process (Section 2). These data are heterogeneous in nature: symbolic or numerical, real-time or delayed, absolute values or trends, level of uncertainty different from one variable to another, etc. In order to facilitate information processing, physical measurements, sensory evaluations and expert judgements on quantities must be considered as assessments with similar representations, in particular concerning the associated uncertainties [18-19]. As the latter are often expressed in either a qualitative way, or in the form of partial knowledge of probability, we used a possibility theory based approach to represent all the different uncertain pieces of information [20-21-22-23-24]. Then, local and intermediary assessments have to be aggregated to obtain a global assessment of the complex system considered, i.e. a dam [25] (Section 3). Finally, for decision-making and communication purposes, the global possibility assessment has to be appropriately defuzzified (Section 4).

2. Human beings as assessment devices

2.1. The roles of experts in dam assessment

In many cases, experts can assess system characteristics thanks to their knowledge and experience. For instance, in civil engineering, visual inspection is a key item, for example in the case of dam surveillance, cracking, differential movements, seepage, and the presence of

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vegetation and sinkholes are all examples of visual characteristics assessed by experts during dam reviews [26]. These visual assessments are used in addition to instrumental measurements from in situ sensors (piezometry, crack measurements, leakage, etc.), design and construction data (slopes, top width, permeability, etc.), and outputs of mechanical models (hydraulic gradient, seismic resistance, spillway capacity, etc.) (cf. Figure 1).

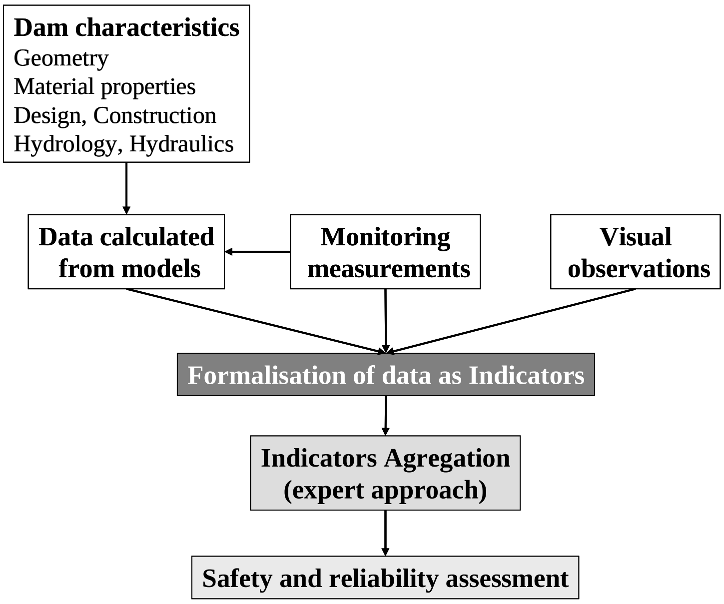

Figure 1: Data used by experts for the assessment of dam safety

All the data are processed by experts, generally in an implicit way. These data indicate degrees of degradation of the system. Degradations can stem from events such as floods and earthquakes or from natural ageing of the structure possibly accelerated by various causes: climatic conditions, poor design or construction conditions, insufficient or inadequate maintenance… These causes involve, during the life of the structure, the occurrence and the development of degradation phenomena, more or less dependent and stemming from miscellaneous and complex sources. Degradation phenomena are detected and assessed by the data used during dam reviews. For instance, the visual observation of a leakage through the

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embankment or the decrease of the drainage flow indicates a degradation of the drainage function. Moreover, at a higher level of decision, these data have to be aggregated and interpreted with respect to their influence on the proper functioning of the system or on subsequent structural or functional deteriorations, or failures. Thus, the different levels of expert assessment have to be structured in a common space of representation, leading to the concept of indicator [27]. The indicator structure is notably defined with a degradation scale allowing the assessment of the system degradation. The scale is here within the range [0, 10]. Moreover, the representation given by this indicator must encompass the uncertainty inherent to human perception and incomplete knowledge.

The notion of degradation scale (identical to a notion of performance scale [28-17]) raises certain philosophical issues in the context of measurement theory [29-30]. Indeed, degradation is not a physical measurement and is subject to subjective assessments. However, as the aim of this paper is to propose operational processing for expert dam assessment, we will not study the concept of degradation “measurability” [31-32], but consider that a small group of experts agrees on a commensurate meaning of dam degradation scores.

Hereafter, we first present the situation where the system variables are directly assessed by the expert, followed by the situation in which the system variables are measured by an instrument and interpreted by experts.

2.2. Direct expert assessment of system variables

Some characteristics or properties of a system are very difficult to quantify with instruments due to their cost or the lack of reliable sensors. Human perception is thus widely accepted as a solution for evaluation in different fields. A methodology aimed at capitalizing the skill of operators or experts in making sensory evaluations has already been proposed and has led to the concept of “sensory indicators” [27]. This methodology is based on a grid composed of seven elements: name, definition, operating conditions, scale, references as scale anchors, spatial characteristics (sampling, measurement location), and time characteristics (measurement frequency, analysis frequency, etc.). The sensory indicators are based on different senses: vision, touch, smell, taste and audition. In the case of dams, only visual assessments are performed. Table 1 provides an example of a formalised visual observation.

For visual sensory indicators implied in dam assessment, operating conditions are usually included in the definition if no specific conditions are necessary. By contrast, they are detailed as specific items if they are important: for instance, crack depth measurements can be performed “at the middle of the length of cracks” or “at the edge of cracks”.

The scores provided by all the indicators are in fact deterioration level scores and are defined on a 0-10 scale. 0 means no deterioration at all while 10 means a high deterioration level. For the purposes of interpretation, the degradation scale is divided into six categories from “excellent” (0 – no deterioration) to “unacceptable” (10– considerable deterioration), ranging through “good” (1-2), “passable” (3-4), “poor” (5-6), and “bad” (7-8-9).

References are key elements for ensuring the meaningfulness of the assessments: they are anchorage points on the scale that facilitate comparison between situations. The aim is to specify the different possible situations so that an assessment performed by several experts, or by the same expert at different times, leads to the same score. They can be photographs, diagrams or textual descriptions. To illustrate this, let us consider the visual indicator “Sinkhole, subsidence cone”: a score of 0 corresponds to an absence of sinkhole or subsidence cone, scores from 7 to 9 to an isolated, small sinkhole (several dm), a new sinkhole (less than 1 year) or an isolated, very large or old (several years) sinkhole. A score of 10 corresponds to a very large, new (less than 1 year) sinkhole.

Spatial characteristics are essential. It is very important to specify where the measurement must be made: crest, foundations, downstream fill, upstream fill and so forth. Indeed, scoring changes as a function of location: the seriousness of a leak depends on the height at which it occurs. Usually, a spatial characteristic is associated with the indicator name: for instance, “leakage on upstream fill”.

Two temporal characteristics can be distinguished:

- the frequency of measurement which varies between the various kinds of measurement: temperature and rainfall are collected daily, piezometry and flow are collected weekly, extensometer measurements are carried out monthly; displacement measurements yearly, etc.;
- the time interval for data processing: monitoring data are processed once a year and trends are analysed by considering a period of several years;

For the complete dam assessment, 60 different visual variables were identified and formalised as sensory indicators. They concern the different components of the dam that can be assessed visually: upstream and downstream shoulders, foundations, drains, external sealing structures (facing), crest, spillway and downstream toe. The sensory indicators were collected and formalized during elicitation sessions that involved five experts, i.e. people involved for at least ten years in dam reviews or analysis.

2.3. Indirect expert assessment of system variables

Experts also have to convert physical measurements (stemming from sensors or models) into assessments in relation with the global information sought, e.g. safety or reliability deterioration. The scale for the monitoring and computed indicators is the same as that used for the sensory indicators: a 0-10 scale with 0 means no deterioration at all while a score of 10

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means a high deterioration level. It should be noted that four categories (instead of six) are considered for the interpretation of such design and construction indicators: "low deviation" (0,1,2), "medium deviation" (4,5,6), "high deviation" (7,8,9) and "non-conformity" (10). Table 2 describes the instrumental monitoring piezometry indicator.

For the complete dam assessment, 14 monitoring indicators, 8 computed indicators and 150 design and construction indicators were identified and formalised. Therefore, with the 60 visual indicators, 232 indicators were considered for the assessment of the different types of dam.

2.4. Possibility expression of imperfect assessments

Data handled by experts are frequently "imperfect": they contain uncertainty, imprecision, incompleteness. Examples quoted from dam review reports are: "This stair is quite large and reaches several decimetres" or "Piezometer faulty" or "Dike apparently built on granite". Therefore, it is of great importance to take imperfections into account in the assessment procedure. This leads to an assessment of indicators that represents perception better than a precise numerical value. Indeed, forcing the indicators to provide precise scores in the case of uncertainty can lead the expert to give a very bad score in order to conform to the principle of caution. Consequently, corrective actions are more drastic than they should be.

Generally, the probability theory is used to deal with uncertainty. However, this means that uncertainty pertaining to the parameters representing physical processes can be described by a single probability distribution, but this requires substantial knowledge to determine the probability law associated with each parameter. Moreover, information regarding parameters is often vague, imprecise or incomplete. This lack of knowledge may stem from a partial lack of data, either because collecting this data is too difficult or costly, or because only experts can provide certain items of imprecise information. In this case, the possibility theory provides tools that are better adapted to represent imperfections through the use of possibility distributions [33-

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34-35]. Imperfections were modelled during assessment sessions that gathered a session leader and an expert. These sessions were composed of two phases: a brief presentation was performed by the session leader before the expert began the assessment of the variable considered. The presentation aimed at explaining the objectives of the session, the meanings of possibility distributions ("a distribution of possibility depicts the possibility that a variable takes the value x"), the types of distribution proposed and the expected results of the session. It also allowed the expert to ask questions to clarify possibly obscure points. Next, descriptive worksheets were successively distributed to the experts. The expert had at her/his disposal the description grid for each indicator assessed (i.e. grids such as presented in Table 1 and Table 2). The experts scored an indicator as a distribution of possibility (equivalent to a normalised fuzzy subset) denoted π_I. The core Cor(π_I) and the support Supp(π_I) are defined by:

$$Cor(\pi_I) = \{x \in X \,|\pi_I(x) = 1\} \quad (1)$$

$$Supp(\pi_I) = \{x \in X \,|\pi_I(x) > 0\} \quad (2)$$

The possibility distribution is built considering that the core represents the more likely values while the support represents the possible values. A linear interpolation is then carried out. Types of useful possibility distributions include triangle, trapezoid, interval shapes, etc. To quantify the amount of uncertainty of the possibility distribution, a specificity index *S* defined by the surface under the distribution can be used [21]: $S(\pi) = \int_0^{10} \pi(x)dx$. All the types of sensory, monitored and computed indicators are expressed with this single representation format.

Figure 2 shows an example of a possibility distribution given by an expert for the indicator "Leakage of clean water through the embankment".

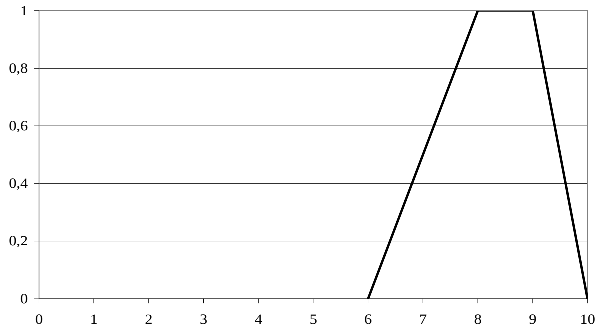

Figure 2: Possibility distribution of the indicator "Leakage of clean water through the embankment"

2.5. Comments on expert assessments carried out

In this subsection we discuss the results obtained during an assessment session in October 2008. Three Cemagref experts assessed fifteen indicators as possibility distributions. Thirteen cases were dedicated to visual sensory indicators while the two others were monitoring indicators. Indicator references were described as typical situations built from completed dam reports written at the end of detailed dam reviews performed by experts. The typical situations are described by a small number of paragraphs (dam description: height, first filling date, reservoir capacity, sealing type, etc.), information from visual inspection or monitoring data and photographs in case of visual indicators. For the assessment, experts used the description grid (cf. Tables 1 and 2 for example) and the references. Various types of possibility distribution were expressed by the experts: trapezoid, triangle-shaped, precise interval and precise score (cf. Table 3). Preference is given to a trapezoidal distribution. It represents slightly over 40% of the cases. The other three types of distribution each represented about 20%. The proposed possibility representation was quickly accepted by the experts and it was seen to be useful for assessing indicators. Moreover, in the first analysis, the experts who performed the exercise found the approach relevant for future application during dam diagnosis and analysis.

Considering the whole set of possibility distributions, the maximal length used to define the support was 5 units (for instance F0 = [2, 3, 4, 5, 6]) while the maximal length to define the core was 2 units (for instance, F1 = [5, 6]) on a scale from 0 to 10.

The three experts did not give exactly the same uncertainty for a given indicator. Table 4 provides the specificity of the possibility distributions (denoted S_{Ei} and corresponding to the surface under the distribution) of each indicator and each expert Ei, considering that a precise score leads to a surface equal to 0. The specificity represents the dispersion of the expert's assessment. On average, E1 gives the smallest margin of uncertainty while E2 gives the largest. Moreover, E1 and E3 give more frequently precise scores (cf. Table 3 and Table 4).

The differences between two possibility distributions can be quantified by the difference of the specificities: three differences were calculated for each indicator, *i.e.* $|S_{E1} - S_{E2}|$, $|S_{E1} - S_{E3}|$ and $|S_{E2} - S_{E3}|$. These differences range from 0 to 3. Over 60% are less than or equal to 1 while over 90 % are less than or equal to 2. The mean values of these differences are about 1. These results indicate good agreement between the experts considering that the support length of the interpretation categories ("excellent" (0), "good" (1-2), "passable" (3-4), "poor" (5-6), "bad" (7-8-9), "unacceptable") is between 1 and 3. The cases for which compatibility is weak or null correspond to weak reference descriptions composed of only a few paragraphs. The references are not precise enough and can lead to interpretations that differ from one expert to another. The second explanation comes from the fact the reference descriptions were made on the basis of completed dam reports written at the end of detailed dam reviews performed by one Cemagref expert. The expert who carried out the review and wrote the completed report obtains more information than the other experts. This can lead to differences in the assessment.

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3. Human beings and global assessment

The amount of variables involved in a complex system can be quite considerable. Managers in charge of dam control often try to obtain a more synthetic assessment of the system by aggregating the available data. This global assessment allows the expert to propose corrective actions if necessary. For example, in civil engineering, these actions concern major reconstruction, rehabilitation or safety projects.

The main problem is to break down the global assessment into causal networks involving elementary measurements and intermediary assessments. This stage relies on expert knowledge capable of providing a diagnosis of the state of the dam and identifying the most probable scenario that would give rise to the measurements indicating abnormal values.

3.1. Hierarchical dam system model

In the dam safety model considered, the global assessment relates to the deterioration of dam safety linked to different failure modes (denoted μFM), that depend on the reliability of different technical functions (denoted Fi), such as sealing, drainage, internal erosion protection and sliding protection, that are themselves assessed by different indicators (denoted Ii). An example of such a breakdown is illustrated in Figure 3.

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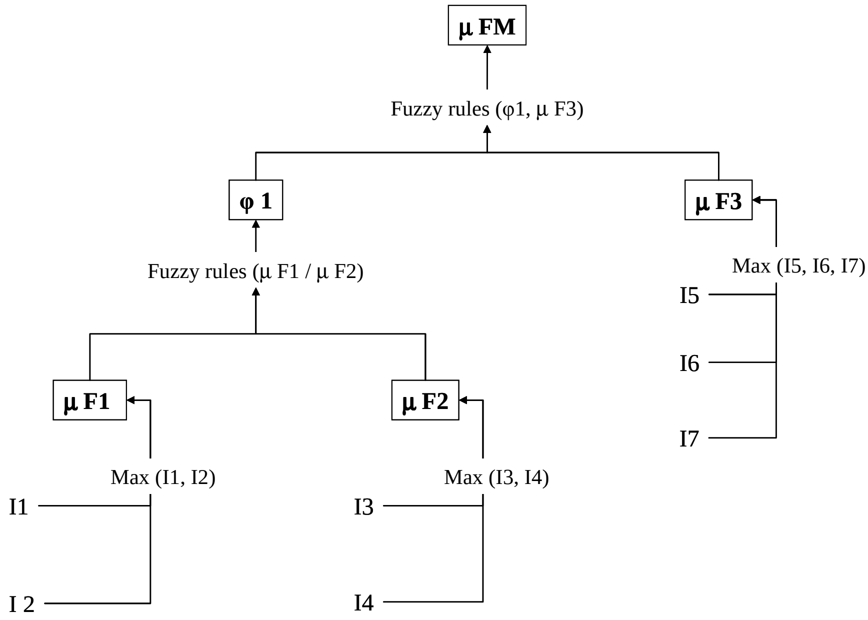

Figure 3: Structure of the hierarchical model of one failure mode

The values given by the indicators (Ii) are bottom-up aggregated to first give the degradation of a technical function (µFi) or a combination of them (denoted φi), followed by deterioration of dam safety related to a failure mode (µFM). The aggregation operators involved are the maximum and minimum operators, fuzzy rules, etc. A deterioration of the dam safety concerning a failure mode is due to the deterioration of the whole set of functions implied in this failure mode. For example, dam safety related to internal erosion through the embankment stems from the reliability of three functions: sealing, drainage and erosion protection.

Certain indicators are qualified as “direct indicators” *i.e.* indicators specific to a phenomenon or a failure mode that assign a direct assessment to it. For example, the phenomenon “insufficiency of drainage capacity” stems from an abnormal water flow into the dam (deterioration of sealing function) and insufficient drainage of this abnormal amount of water (deterioration of drainage function). It leads to seepages or abnormal saturation of the embankment material detected by piezometry. The indicators “Piezometry” and “Seepage of

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clean water" are direct indicators for this phenomenon. This kind of indicator has the particularity of taking only extreme values on the scale *i.e.* 0, 7, 8, 9 or 10: the situation is either totally normal or very serious. The direct indicators are indicated by bold type in Figure 4.

The other indirect indicators correspond to variables whose degradations are related to the global variable through time or can be combined with other variables.

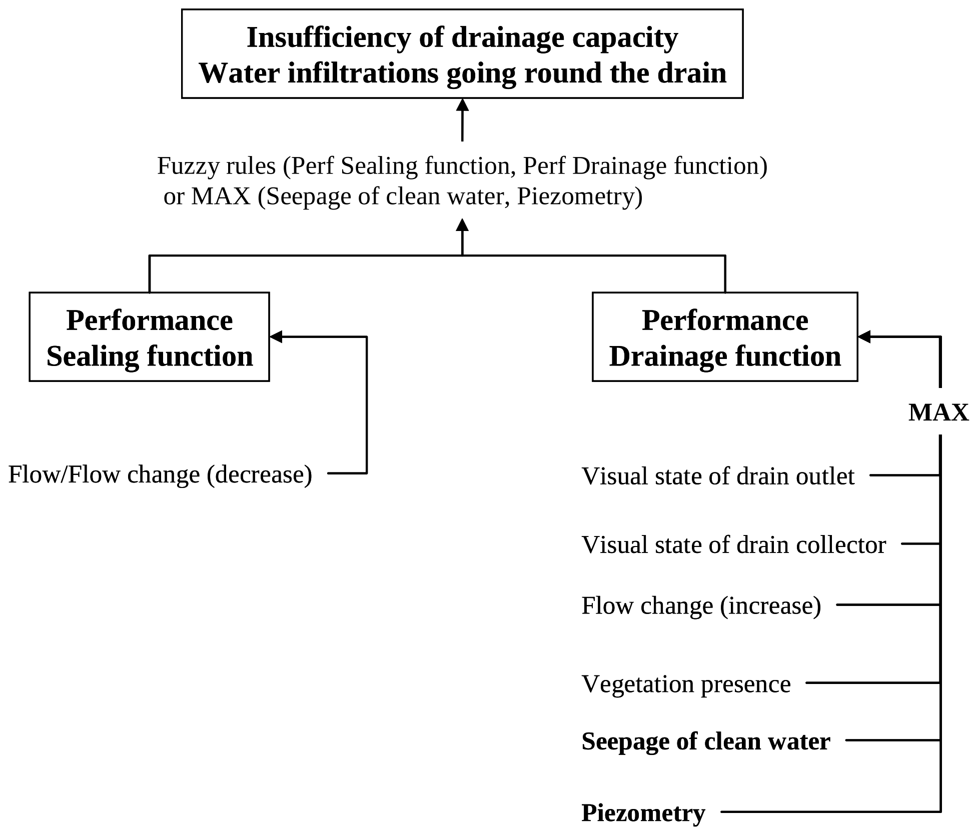

Figure 4: Hierarchical model of one failure mode – Case of homogeneous earth dam

The reliability function (μF_i) is assessed by calculating the maximum of the values of the n indicators (I_j) involved in the assessment of the function and appraised by experts:

$$\mu F_i = \underset{j=1}{\overset{n}{\mathrm{MAX}}} [I_j] \quad (3)$$

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The mathematical justification of this operator used to aggregate indicators at the lower level of the hierarchy is linked to the principle of caution relating to these functions. All the indicators are assessed on the same scale ranging from 0 (“excellent”) to 10 (“unacceptable”). Using the maximum operator, the worst situation is taken into account.

Fuzzy rules for the determination of φ_1 are:

(R1) IF “Clean water seepage” > 2 AND “Piezometry” > 2 THEN φ_1 = MAX (“Clean water seepage”, “Piezometry”) (4)

(R2) IF “Clean water seepage” ≤ 2 AND “Piezometry ” ≤2 AND $\mu F_{Sealing} \leq 2$ THEN $\varphi_1 = \mu F_{Sealing}$ (5)

(R3) IF “Clean water seepage”≤2 AND “Piezometry”≤2 AND $\mu F_{Sealing} > 2$ THEN $\varphi_1 = \mu F_{Drainage}$ (6)

where “Clean water seepage” and “Piezometry” are two direct indicators.

A model using the template presented in Figure 3 was described for each failure or degradation mode: internal erosion through the embankment, sliding of embankment or embankment and foundations, internal erosion initiated around or near a conduit, overtopping, internal erosion through soil foundations, settlement of soil foundations, dissolution of material or leaching of rock foundations. Figure 4 shows part of the model corresponding to the internal erosion.

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3.2. Propagation of imperfections

Imperfections represented by possibility distribution must be propagated in the safety degradation model. The propagation of possibility distributions via an operation *f* obeys Zadeh's extension principle [20]:

$$\pi_F(s_F) = sup_{(s_1,\ldots,s_n)/f(s_1,\ldots,s_n)=s_F}(\min(\pi_{I1}(s_1),\ldots,\pi_{In}(s_n))) \quad (7)$$

with $s_1,\ldots,s_n$ being the degradation indicator score and s_F the technical function degradation score.

In our context, function *f* is either a direct mathematical operation (max, mean) or a function stemming from fuzzy rules. A symbolic conjunctive approach for rule processing (with the product and the bounded sum as combination and projection operators), followed by defuzzification based on the height method, leads to a piece-wise linear expression for function *f* associated with the set of fuzzy rules [9].

An illustration of the propagation of possibility distributions declared by the experts in the global dam assessment is provided in Figure 5. The possibility distribution obtained by the aggregation of μF Sealing and μF Drainage *i.e.* φ Insufficiency of drainage capacity, is then aggregated with μF Erosion Protection to obtain μMR Internal Erosion.

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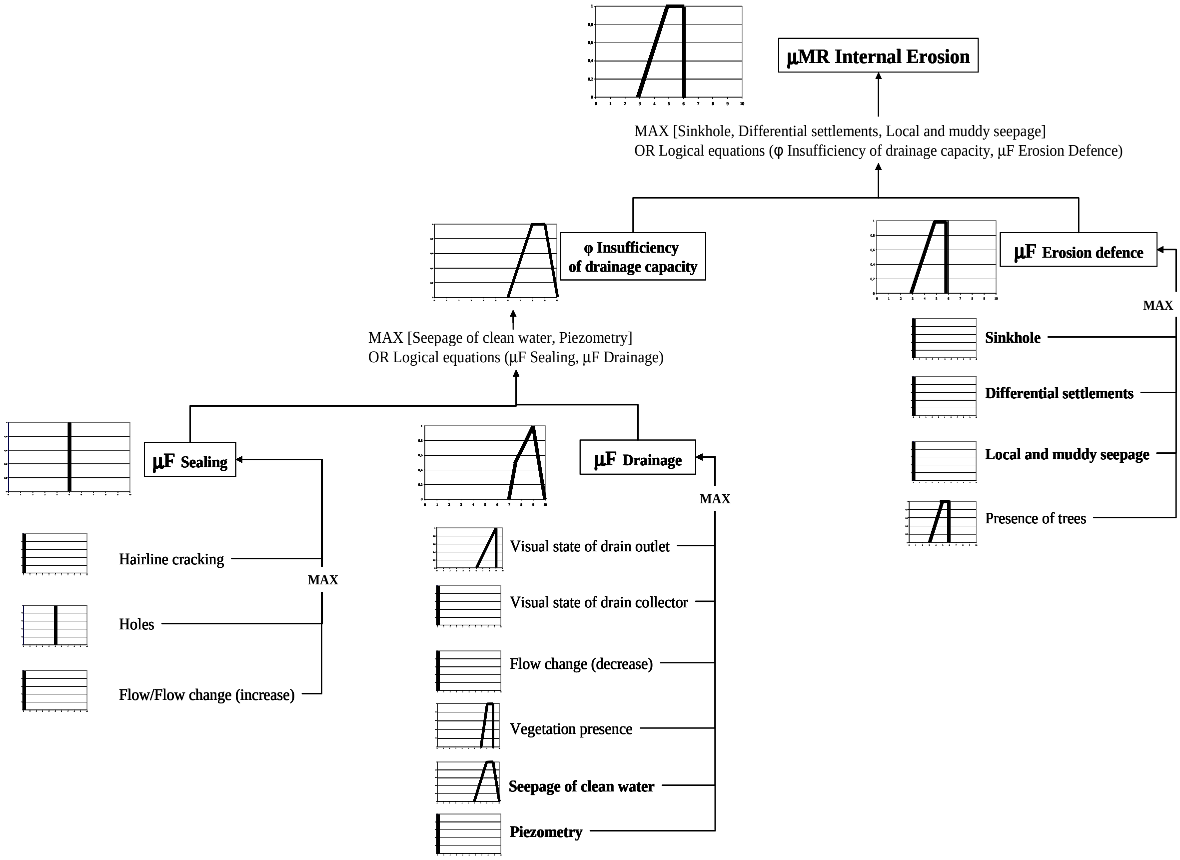

Figure 5: Example of imperfection propagation in the global dam assessment

3.3. Experimental validation of the global assessment

To perform an experimental validation of the global assessment, the precise score given directly by the experts was compared to the result of the propagation of imperfections in the hierarchical model. The assessment was carried out by three experts on the basis of the indicator references presented in § 2.3. The failure mode considered here is internal erosion through the embankment. Three dams were evaluated by the three experts. For eight cases out of nine, the precise score given by the experts intersects with the possibility distribution obtained by the propagation in the hierarchic model. For one case, the precise score given by the expert was equal to 8 and the possibility distribution was calculated as a trapezoidal distribution whose support is [3, 6]. The precise score was out of the possibility distribution support. The expert

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explained the difference between these two assessments by the fact that the information available was not sufficient in the reference descriptions. The need to comply with the need to express the assessment of indicators as precise scores, albeit with imperfections, led the expert to give a very severe score in line with cautious behaviour

4. Communication and decision making on dam safety

The results obtained at the end of the imperfection propagation are useful for communication and decision-making concerning dam safety.

4.1. Communication

Experts have to communicate results concerning dam safety to other safety actors, for instance, the dam owner or reservoir operator. This leads to two kinds of information (qualitative and quantitative descriptions) and two kinds of data (score and dispersion).

The quantitative score is obtained by the assessment of the upper bound of α-cut at 0.8. This α-cut value was chosen by the experts by considering the correspondence between the membership level and the fractile of a probability distribution [36-37] and the analysis of defuzzification methods that provide real values [38]. Indeed, the experts wanted to select the defuzzification value that corresponded to a value between a “mean probable” and “probable”, i.e. between 50 and 90%.

The qualitative description consisted of membership degrees in the six categories of “excellent”, “good”, “passable”, “poor”, “bad” and “unacceptable” defined by intervals, i.e. rectangular fuzzy sets (cf. Figure 6).

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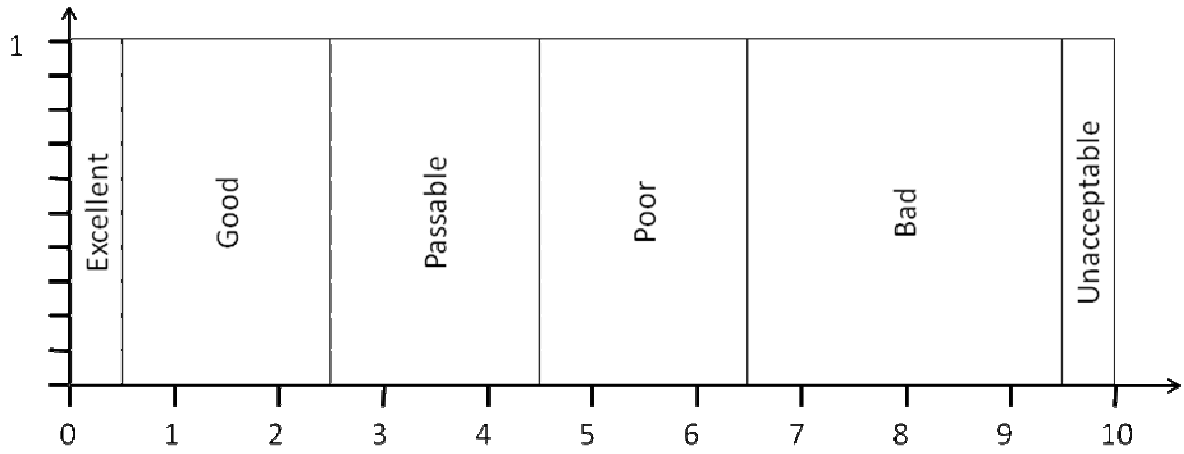

Figure 6: Fuzzy sets for the calculus of membership percentage

The calculus of the membership degree of each category is based on a notion of compatibility between the possibility distribution and the fuzzy set associated with each category. A $DC_{\pi k}^{Ci}$ (degree of compatibility between a possibility distribution πk and category Ci) is computed by Equation 8.

$$DC_{\pi k}^{C_i} = \frac{S_{\tilde{I}}}{S_{Ci} + S_{\pi k} - S_{\tilde{I}}} \times 100 \tag{8}$$

S_{Ci} is the surface associated with the reference fuzzy set i ($i \in [1,6]$), $S_{\pi k}$ is the surface associated with the degradation assessment and $S_{\tilde{I}}$ is the surface of the subset $\tilde{I} = C_i \cap \pi_k$:

$$\mu_{\tilde{I}}(x) = \mu_{Ci \cap \pi k}(x) = \min(\mu_{Ci}, \mu_{\pi k}) \tag{9}$$

For each πk, six compatibility degrees are calculated (one considering each category). An example is given in Table 5.

The qualitative dispersion is based on the interpretation of a quantitative dispersion assessed by using the relative specificity. The relative specificity corresponds to the specificity of the possibility distribution obtained divided by the specificity of the possibility distribution

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corresponding to complete ignorance (i.e. having a membership degree of 1 on the whole scale. 0-10). It is therefore defined by:

$$SpR(\pi) = \frac{\int_0^{10} \pi(x)dx}{10} \quad (10)$$

Four categories of qualitative dispersion were considered: “no dispersion”, “low dispersion”, “high dispersion” and “very high dispersion”. Then, typical fuzzy sets for each category were defined. Typical fuzzy sets associated with qualitative dispersion categories and the corresponding relative specificity are presented in Table 6. Table 5 presents an example of the communicated results for a possibility distribution of safety deterioration obtained by using the hierarchical safety model.

4.2. Decision-making

Decision-making aims at proposing corrective actions to restore the dam to standard operating conditions. The objective is to guarantee that safety and reliability criteria are satisfied. Corrective actions are of various types:

- emergency action: partial or complete emptying of the reservoir;
- major reconstruction, rehabilitation or safety projects;
- maintenance actions such as drain outlet cleaning, scraping of the downstream slope, renewal of monitoring devices, etc.
- upgrading dam safety monitoring: increasing measurement frequency, performing laboratory tests, etc.

As a dam can be affected by several failure modes, a possibility distribution is obtained for each failure mode. A defuzzification method that allows comparing possibility distributions

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with each other [39-40-41-42] was selected with experts in order to rank these possibility distributions. Defuzzification consisted in reducing the possibility distributions into single values. The method considered is based on the mean of the α-cut at 0.8. A correspondence between this score for decision-making and the score for communication (upper bound of the α-cut at 0.8) was chosen by the experts. This choice was carried out in order to obtain the same interpretation of the results from both cases, that is to say higher membership values were preferred, without taking into account the core of the fuzzy set. This defuzzification approach allows ranking the safety related to the various failure modes and thus prioritizing corrective actions.

5. Conclusion

This paper focused on the roles that human beings can play in complex systems, such as dam safety assessment, especially when assessing the entities involved. A unified and structured representation based on a formalisation grid and possibility distributions was proposed to offset the imperfections of measurements and expert assessments, aggregate them in a hierarchical model composed of different simple operations (max, min, average, etc.) and then synthesize them by using defuzzification methods. All the failure modes of embankment dams were dealt with. The method was applied by three experts on simplified cases: the representation scheme was quickly accepted by the experts and showed that it is useful for assessing indicators. The comparison of the results provided by several experts showed that good agreement was obtained between them, apart from a few indicators. The methods proposed were applied to a civil engineering application, *i.e.* dam safety assessment, but they could be applied to other fields in which human beings also play an important role in global measurement, assessment and decision-making.

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Figure Captions

Figure 1: Data used by experts for the assessment of dam safety

Figure 2: Possibility distribution of the indicator “Leakage of clean water through the embankment”

Figure 3: Structure of the hierarchical model of one failure mode

Figure 4: Hierarchical model of one failure mode – Case of homogeneous earth dam

Figure 5: Example of imperfection propagation in the global dam assessment

Figure 6: Fuzzy sets for the calculus of membership percentage

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Table 1: Description of the visual sensory indicator "state of drain outlet"

Name	Visual state of drain outlet
Definition	Clogging assessment of drain outlet. Clogging may occur due to deposits and concretions such as ferruginous bacteria, concretions and roots
Scale and references	0: drain outlet free 2: drain outlet partially clogged by deposits (ferruginous bacteria type) 4: drain outlet partially clogged by concretions or roots 6: drain outlet very clogged by deposits 8: drain outlet very clogged by concretions or roots or totally clogged by deposits 10: drain outlet totally clogged by concretions
Location	Drain outlet
Time characteristics	Evaluation carried out once a week

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Table 2: Description of the monitoring indicator "Piezometry"

Name	Piezometry
Definition	Piezometry allows the quantification of water infiltrations not controlled by the drainage system
Scale (0-10) and references	0: Piezometry in the downstream toe of the dam lower than 1 to 2 m relating to the ground surface 1-2*: Piezometry in the downstream toe of the dam lower than 0.5 to 1 m relating to the ground surface 5-6*: Outcropping piezometry in the downstream toe of the dam 7-10*: Artesian piezometry in the downstream toe of the dam *: The assessment must take into account the change in the piezometry.
Location	Downstream toe of the dam
Time characteristic	Piezometry is assessed once a week Data processing is carried out once a year

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Table 3: Number and types of possibility distributions used by the experts

Experts	Precise score	Precise interval	Trapezoidal distribution	Triangle distribution	Total
E1	3	5	2	5	15
E2	1	1	12	1	15
E3	4	4	5	2	15
Total	8	10	19	8	45

Table 4: Specificities of the possibility distributions declared by experts

	S_{E1}	S_{E2}	S_{E3}	$\lvert S_{E1}-S_{E2}\rvert$	$\lvert S_{E1}-S_{E3}\rvert$	$\lvert S_{E2}-S_{E3}\rvert$
I1	1.5	1.5	1	0	0.5	0.5
I2	0	1	2	1	2	1
I3	0	2.5	3	2.5	3	0.5
I4	1	1.5	0	0.5	1	1.5
I5	2.5	2	0	0.5	2.5	2
I6	0	2	0	2	0	2
I7	1	2.5	2	1.5	1	0.5
I8	1.5	3.5	3.5	2	2	0
I9	1	0	2	1	1	2
I10	2	2	2.5	0	0.5	0.5
I11	1	2	0	1	1	2
I12	0 5	2	2	1.5	1.5	0
I13	0.5	2.5	2.5	2	2	0
I14	1	2	1.5	1	0.5	0.5
I15	1	2	1	1	0	1
Mean	0.97	1.93	1.53	1.17	1.23	0.93

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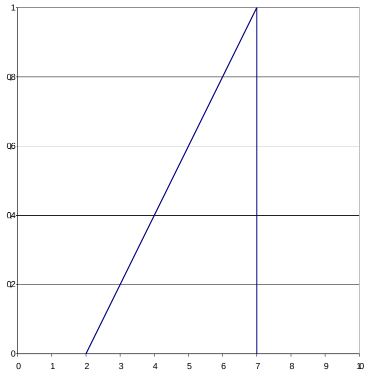
Table 5: Example of communicated results obtained by the hierarchical safety model for a considered possibility distribution

Considered possibility distribution



Defuzzified value	Qualitative description	Qualitative dispersion
7	12% Passable 72% Poor 16% Bad	Very high dispersion

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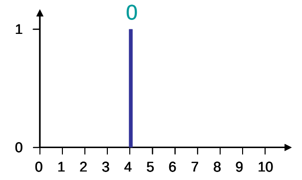
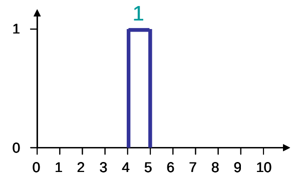
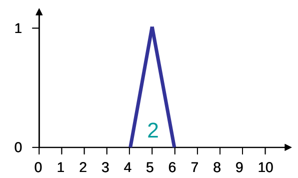
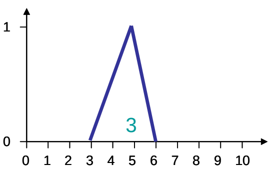
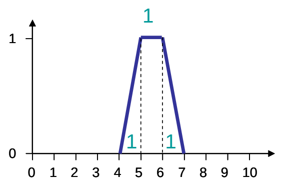
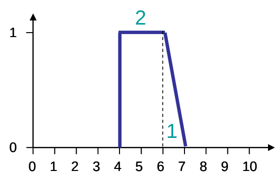
Table 6: Typical fuzzy set for relative specificity categorization

Qualitative dispersion Category	Typical possibility distribution and their specificities		
No dispersion	 SpR = 0		
Low dispersion	 SpR = 0.1	 SpR = 0.1	
Important dispersion	 SpR = 0.15	 SpR = 0.2	 SpR = 0.25
Very important dispersion	Beyond 0.25		