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USING PHYSICAL MEASUREMENTS, SENSORY EVALUATIONS AND EXPERT JUDGEMENTS IN A DAM ASSESSMENT SUPPORT SYSTEM

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Abstract: In engineering system control, human beings can play various key roles in particular concerning measurement, global assessment and decision. It is recognised that in such complex systems many involved variables are evaluated with uncertainty. In this paper, we used a possibility theory based approach to formalise all the different uncertain pieces of information. An applicative example concerning the safety assessment of dams is presented.

Keywords: sensory evaluations**,** expert judgements, knowledge uncertainty, possibility theory, dam assessment.

1. INTRODUCTION

The issues of modelling complex phenomena and providing data for their subsequent use are highly prominent and challenging tasks requiring the involvement of interdisciplinary knowledge, in particular expert knowledge [1-2-3-4]. Indeed, numerous examples of system control demonstrate that the models of complex phenomena cannot be fed only with physical measurements. Human evaluated quantities have become an inherent part of system analysis [5-6-7]. In case of decision support systems, human can play various roles (cf. Fig. 1):

- in elementary measurements and sensory evaluations;
- in global judgements of products or processes by aggregation of several evaluations;
- in the decision making, when proposing corrective actions so as to guarantee that the system proceeds correctly.

Therefore, in complex systems, in order to facilitate the information processing, we have to view objective measurements, sensory evaluations and expert judgements on quantities as measurements with a similar representation, in particular concerning associated uncertainty [8-9]. In this paper, we used a possibility theory based approach to formalise all the different uncertain pieces of information [10]. We focus on the two main aspects: sensory evaluations and global judgements. An applicative example concerning the safety assessment of dams is dealt with. The assessment of the dam safety aims at maintaining the infrastructure asset, which is subjected to inevitable ageing, in good and serviceable condition at minimum cost. The objective is to detect and to correct phenomena that can lead to:

- various deteriorations that may result in accelerated ageing, in additional operational and maintenance costs, in significant loss of water in dams;
- failures that can cause dramatic events such as a dam failure.

2. MEN AS MEASUREMENT DEVICES

In many cases, some characteristics or properties of a system are very difficult to quantify by instrumental way due to their cost or to the lack of reliable instrumental sensors. Human evaluation is thus widely accepted as a tool for the evaluation in various domains.

In civil engineering, visual inspection is a key item, for example for the surveillance of dams: cracking, differential movements, seepage, vegetation presence or sinkhole are examples of visual measurements assessed by experts during dam reviews [11-12]. Experts can detect small changes of dam characteristics thanks to their knowledge and experience. These visual measurements are used in addition to instrumental measurements from in situ sensors, data coming from models and, data related to design and construction processes. The whole data are processed by experts and finally combined to assess dam safety (cf. Fig. 2).

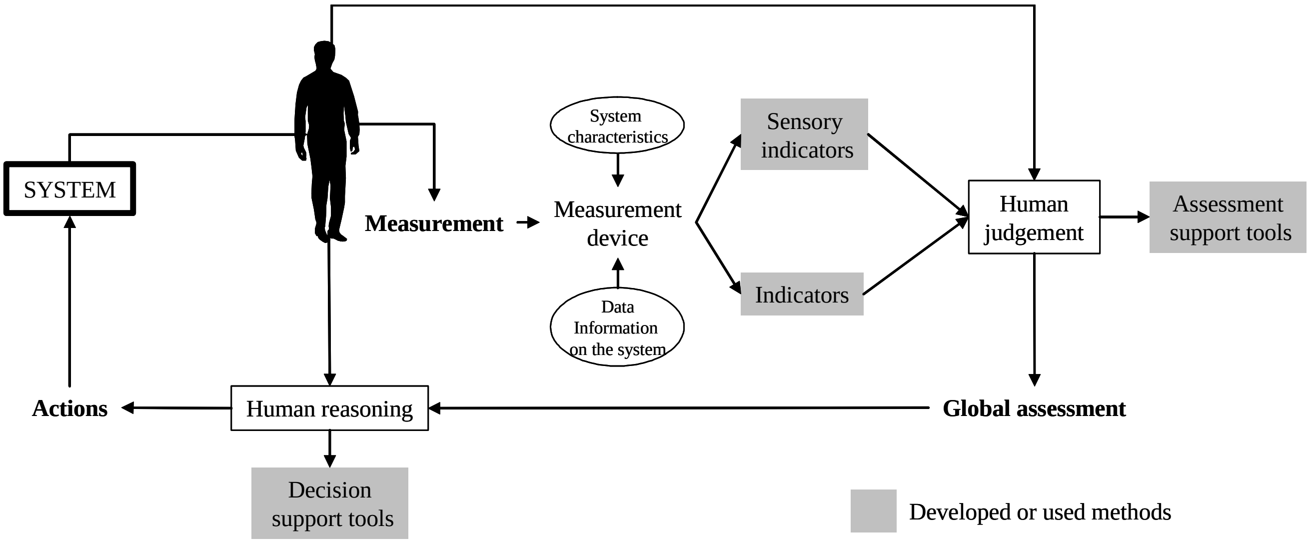

Fig. 1. System Control loop involving human knowledge

We can therefore distinguish two roles concerning the measurement field (cf. Fig. 1): either experts use data which they get directly on the system by sensory evaluation (visual, texture measurement...), or they use data stemming from measuring instruments (piezometer, laboratory device…).

Moreover, at an higher level of decision, they have to interpret these data with respect to their influence on the good functioning of the system or on the subsequent structural or functional deteriorations or failures. Thus, such expert judgements have to be structured in a common representation space, which has led to the concept of indicator [13], in order to benefit from all of these pieces of information in the decision making. Moreover, the indicator representation has to deal with uncertainty inherent to human perception and incomplete knowledge.

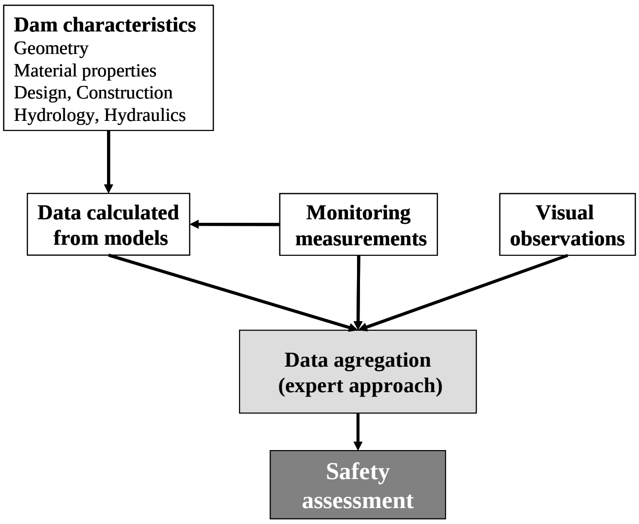

Fig. 2. Data used by experts for the assessment of dam safety

2.1. Direct measurement of system variables

A methodology to capitalize on the skill of the operators or experts in making sensory evaluations has already been proposed [13]. 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 can be based on different senses: vision, touch, smell, taste or audition. In the case of dams, only visual measurements are performed. Table 1 exhibits an example of a formalised visual observation.

Table 1. Description of the visual indicator "Sinkhole – Subsidence cone"

Name	Sinkhole – Subsidence cone
Definition	Local collapse of land surface, usually funnel-shaped, due to spaces and cavern development underground
Scale and references	0: absence of sinkhole or subsidence cone 6: isolated, small (some dm), old (several years) sinkhole OR presumption of sinkhole (presence of subsidence cone) 7 – 9: isolated, small (some dm), new (less than 1 year) sinkhole OR isolated, huge, old (several years) sinkhole 10: huge and new (less than 1 year) sinkhole
Location	Crest or upstream shoulder or downstream shoulder
Time characteristics	Evaluation carried out once a week

In this approach, experts are considered as measurement devices. As measurement devices, their metrological performance should be determined and particularly, repeatability and resolution (discrimination ability). They are defined as [14]:

- the repeatability : « closeness of the agreement between the results of successive measurements of the same quantity carried out under the same conditions of measurement”;
- the resolution: “the smallest difference between indications of a displaying device that can be meaningfully distinguished”. This characteristic is assessed by the discrimination ability of the operators.

In case there are more than one expert, reproducibility defined as [14] “the closeness of the agreement between the results of measurements of the same quantity carried out under changed conditions of measurements” can be assessed.

We proposed a methodology to determine these metrological characteristics [15]. This methodology can also be applied to evaluate metrological characteristics of operators through time: repeatability, discrimination ability and reproducibility.

Finally, this method allows a formal description and a transmission of this know-how. We showed that it is possible to train a new operator to carry out the measurement [15].

2.2. Measurement interpretation

Another task devoted to human consists in translating the measurements (issued from a sensor or a human) into judgement values in relation with the global sought information, e.g. safety or performance degradation. Once translated on a same scale, these richer evaluations can be combined to obtain a global assessment of products or processes.

This case is encountered in the domain of civil engineering [11] where measurements used by experts stem from four sources: visual inspection, instrumental measurements (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. Fig. 2).

A formalisation grid was proposed and led to deterioration “indicators”, i.e. measurements which have been referred to suitable values according to their influence on the global safety deterioration judgement. This grid aims at obtaining the information necessary to correctly use the indicators: repeatability and reproducibility must be achieved. All the different types of indicator are described with the same format initially developed for sensory measurement [13] and adapted to other types of data: instrumental measurements, outputs of mechanical models or design and construction data. The same formalisation grid was kept. However, 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, depth crack 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 score and are therefore defined on a 0-10 scale; 0 means no deterioration at all and 10 a high deterioration level.

Table 2 provides an example of a formalised instrumental indicator.

Table 2. Description of the monitoring indicator “Decrease of flow”

Name	Decrease of flow
Definition	Flow measurement allows the quantification of infiltrations controlled by the drainage system
Scale (0-10) and references	0: no decrease observed 1-2: low decrease (<10%/year) 7-8: high and rapid decrease (>50%/year) 10: flow suddenly reaches 0 L/s If the decrease is from 10 to 50 %, no score can be given: the decrease of flow can be due to a drainage collector collapse, a drain clogging as well as a spring drying up
Location	Drain outlet
Time characteristic	Flow measurement is carried out once a week Data processing is carried out once a year

2.3. Integration of imperfections

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 founded a priori on granite”. Therefore it is of main importance to take imperfections into account in the assessment system. This leads to have an assessment of indicators that better represents the perception than a precise numerical assessment. Indeed, to impose the indicators providing precise scores when imperfections exit, can lead the expert to give a very severe score to respect a cautious principle. Consequently, corrective actions are more drastic than they should be.

We propose to represent imperfections using possibility distributions [16-17-18]. Experts express themselves scores of an indicator as a normalised fuzzy subset. The fuzzy membership function is built considering that the core represents the more likely values and the support the possible values. Then a linear interpolation is made. Fig. 3 shows an example of a possibility distribution given by an expert for the indicator “Leakage of clean water through the embankment”.

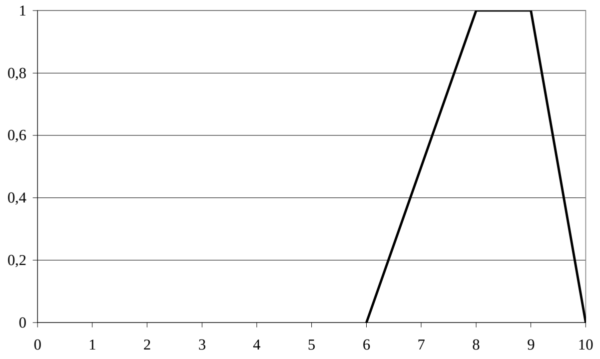

Fig. 3. Possibility distribution of the indicator “Leakage of clean water through the embankment”

3. MEN AND GLOBAL ASSESSMENT

The amount of variables involved in complex system can be very consequent. Managers in charge of their control often try to obtain a more synthetic assessment of the system by aggregation of 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 security projects.

In fact, the main problem is the decomposition of the global assessment into causal networks involving elementary evaluations and measurements. This stage relies on experts which are able to deliver a diagnosis of the state of dam, identifying the most probable scenario that would give rise to the measurements that signalled the abnormal values.

3.1. Dam hierarchic system model

In our proposed dam model, the global assessment is the safety deterioration of the dam related to different failure modes (μFM), which are depending on different technical functions (Fi), such as sealing, drainage, internal erosion defence, sliding defence, themselves depending on different indicators (Ii). An example of such decomposition is illustrated in Fig. 4. In a reciprocal way, the values given by indicators (Ii) are bottom-up aggregated to give, first, the function performance degradation (μFi) or a combination of them (φi), and then, safety deterioration of dam related to failure mode (μFM). The aggregation operators involved are the maximum and minimum operators, fuzzy rules…

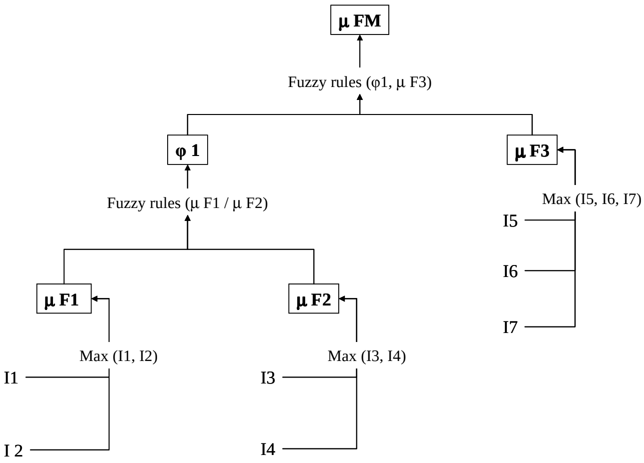

Fig. 4. Example of hierarchic model of a failure mode

For example, function performance (μF_i) is assessed by calculating the maximum of the values of the (n-m+1) indicators ($I_{j,}$) implied in the assessment of the function and appraised by experts:

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

The mathematical justification of this operator used to aggregate indicators that are at the lower level of the hierarchy is linked to the cautious principle that concerns these functions.

Fuzzy rules combining for example $\mu F_{Sealing}$ and $\mu F_{Drainage}$ are:

(R1) IF “Clean water seepage”≤2 AND “Piezometry”≤2 AND $\mu F_{Sealing} \leq 2$ THEN $\varphi_1 = \mu F_{Sealing}$ (2)

(R2) IF “Clean water seepage”≤2 AND “Piezometry”≤2 AND $\mu F_{Sealing} > 2$ THEN $\varphi_1 = \mu F_{Drainage}$ (3)

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

3.2. Propagation of imperfections

Imperfections represented by distributions of possibility have to be propagated into the safety degradation model. The propagation of possibility distributions via an operation *f* obeys Zadeh’s extension principle [19]:

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

(4)

with $s_1,\ldots,s_n$ the deterioration indicator score and s_F the performance deterioration score.

In our context, the function *f* is either directly a mathematical operation (max, mean) or a function stemming from fuzzy rules. A symbolic conjunctive approach for the rule processing (with the product and the bounded sum as combination and projection operators), followed by a defuzzyfication based on the height method, leads to a piece-wise linear expression for the function *f* associated to the set of fuzzy rules [20].

An illustration of propagation of possibility distributions into the global dam assessment is provided in Fig. 5.

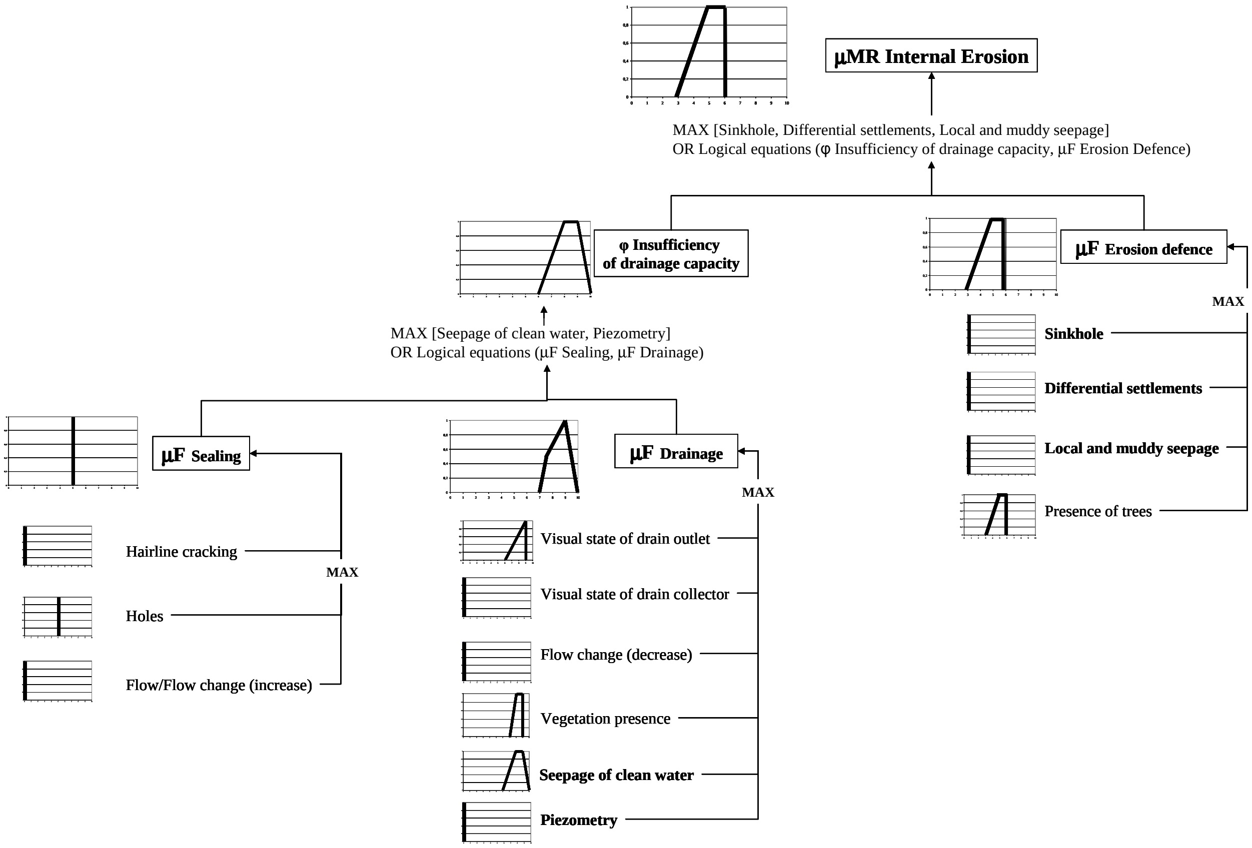

Fig. 5. Example of imperfection propagation in the global dam assessment in relation with a failure mode

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 Defence to obtain μMR Internal Erosion (cf. Fig. 5).

3.3. Defuzzification

Results obtained at the end of the imperfections propagation into the safety assessment model are fuzzy subsets. These information can be used directly by the experts to take decisions or can be the inputs of a decision support system.

However, a defuzzification step is relevant in at least one case: experts have to communicate results concerning the dam safety to other safety actors, for instance, the dam owner or the reservoir operator. To answer this need, our current researches are about the definition of the most pertinent defuzzification method and the required number of defuzzified data. Interval defuzzification processes [21-22] seem relevant and adequate in our case.

4. APPLICATIONS

Three experts assessed fifteen indicators as possibility distributions. Indicators were described as cases built from completed dam reports written at the end of detailed dam reviews performed by Cemagref experts. The cases are composed of a small number of paragraphs and comprise the following sections: dam description (height, first filling date, reservoir capacity, sealing type, etc.), information from the visual inspection or data for monitoring and, in case of visual indicators, photographs. For the assessment, experts use the description grid (cf. Tables 1 and 2 for example) and the simplified cases.

Various types of distribution were declared by experts: trapezoid, triangle-shaped, precise interval... (cf. Fig. 6). The maximal length used to define the support is 5 intervals (for instance F0 = [2, 3, 4, 5, 6]) and the maximal length to define the core is 2 intervals (for instance, F1 = [5, 6]) on a scale from 0 to 10.

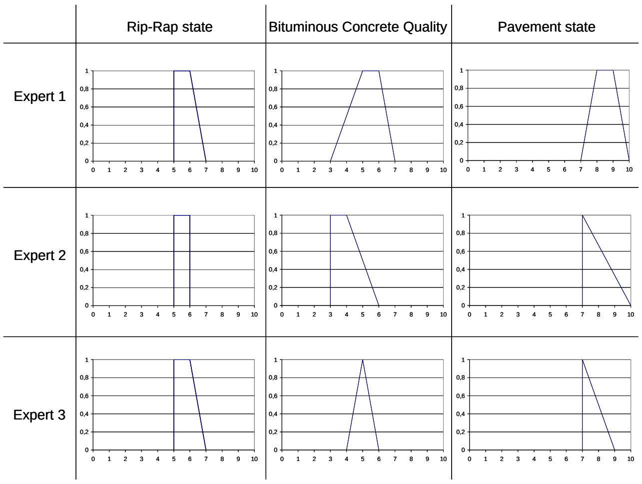

Fig. 6. Examples of possibility distributions declared by three experts for three indicators

Next, these possibility distributions were propagated into the safety assessment model. Fig.5 provides an example of propagation declared by an expert into the model for the global assessment of the dam safety. The fuzzy rules are Equations (1) to (3).

A deterioration of the dam safety concerning a failure mode is necessary due to the deterioration of the whole set of functions implied in this failure mode. For example, the dam safety related to the internal erosion through the embankment comes from the performance of three functions: sealing, drainage and erosion defence. The deterioration of only one or two of these functions does not lead to a deterioration of the dam safety, at the moment of the inspection. Some indicators (seepage of clean water and piezometry) have a direct impact on the assessment of the deterioration of the concerned function. These indicators called “direct indicators” provide information concerning the occurrence of phenomena resulting from the deterioration of two functions. For example, an insufficiency of drainage capacity stemming from an abnormal water incoming into the dam (deterioration of sealing function) and an insufficient drainage of this abnormal amount of water that leads to seepages or an abnormal saturation of the material of the embankment detected by piezometry. The direct indicators are indicated by bold type in Fig. 5.

In addition, in order to identify the main symptoms and evidence related to a deficiency scenario and thus to provide suitable recommendations for solving the problem, the impact of the various indicators on the technical function and on the global dam safety deterioration is under consideration.

In first analysis, the experts that performed the exercise have found the approach relevant for a future application during diagnosis and expertises of dams.

5. CONCLUSION

In this paper, the roles that human can play in complex systems, such as dam safety assessment, have been highlighted, especially concerning the measurement and evaluation of the involved entities.

A common structured representation based on possibility distributions has been proposed to deal with the imperfections of measurements, sensory evaluation and expert judgements, as well as their aggregation along a hierarchic model composed of different simple operations (max, min, average…). The proposed methods have been illustrated on a civil engineering application, *i.e.* dam safety assessment, but they could be applied to other domains where human beings play also an important role in measurement, global assessment or decision. Further developments will concern explanation functionalities in such multi-criteria decision making process involving uncertainty.

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