Protection structures against natural hazards: from failure analysis to effectiveness assessment

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ABSTRACT

Protection structures aim to protect areas exposed to natural hazards. For instance, several clusters of check dams are located in the headwaters of a watershed, each having specific functions. Their structural, functional, and economic effectiveness must be assessed to assist decision makers in deciding on maintenance actions. Nevertheless, expert assessment generally focuses on a single check dam. It is based on the evaluation of several field indicators that are aggregated by experts. This paper aims to show how methods extracted from industry, such as dependability analysis and decision-making approaches, can be used to help formalize expert assessment with expert knowledge taken into account. For this purpose the formal methods are reviewed and their potential application introduced. This paper focuses on the use of indicators and criteria in various objective decision-making tools. For example, it compares the Analytic Hierarchic Process and the ELECTRE TRI methods to assess the functional effectiveness of a cluster of check dams.

KEYWORDS

check dams; effectiveness; functional analysis; Multi-Criteria Decision Methods

INTRODUCTION

In mountainous areas, torrential floods are sudden and destructive. Protection systems have specific functions to protect exposed elements from them. For instance, check dams control material volume and flow through stabilization of bed scouring and banks. More than 21,000 old protection works, including 14,000 check dams, are registered in French public forests (Piton et al. 2015). Assessing their actual effectiveness is a key issue in maintenance decision-making.

The effectiveness of a system may be defined as the level of objective achievement and takes into account three features: structural, functional, and economic. Its assessment is based on its capacity in relation to the objectives that were set. For instance, a check dam structure has to be stable under a debris-flow with a given intensity discharge. Nevertheless, while nominal capacity may be defined through functional and structural design, the real capacity of a structure may be reduced, depending on its condition. When analyzing structural pathology, field practitioners focus on structural and functional features. Degradation criteria that can

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affect structural stability and the functional service of each structure or cluster of structures, are identified and qualitatively assessed. Following this, structural degradation, overall condition and emergency actions required on each structure are established through predefined qualitative classes. Pathology analysis is used by experts to propose adapted actions in order to maintain a structure in good working condition (Suda 2013).
Assessing effectiveness is a multicriteria, multi-feature (structural, functional, and economic) and multiscale (check dam, device, and watershed) analysis. In practice, practitioners qualitatively assess the effectiveness of individual structures; there is no integrative method for this assessment.

Current developments based on decision-aid methods (DAMs) aim to take into account expert knowledge in a formal integrative framework. This paper initially introduces the main principles from functional analysis to multi-criteria decision methods (MCDMs). We then assess the effectiveness of three clusters of check dams, as regards their given objectives and criteria, using two MCDMs. Finally, we review the main steps in assessing the effectiveness of a protection system and discuss remaining gaps.

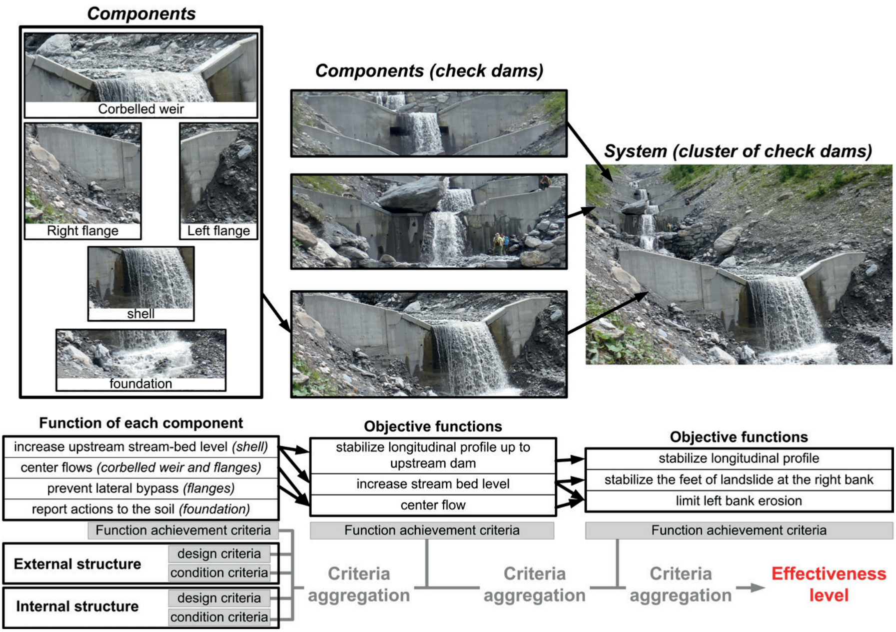

Figure 1: Multiscale and multicriteria aggregation to assess effectiveness of a cluster of check dams.

METHODS

This paper aims to show how DAMs can help to assess the effectiveness of protection systems. Accordingly, we do not go into great detail but provide the main principles.
First, we use the safety and reliability analysis framework (Tacnet et al. 2012). This helps to specify the system components, their objective functions, the failure mechanisms, the criteria gj and the indicators Im that explain them (Fig. 1). Each Im assessment is related to the achievement of a function and is specified through a formal evaluation scale (Curt et al. 2010). A list of Im indicators is an example of the results of a check dam pathology analysis (Suda 2013). In this paper we propose to use examples of these Im to directly show how they can be aggregated.

Whatever the feature and system scale (check dam, a cluster of check dams), assessing the level of effectiveness is a decision-making problem (DMP). From a range of alternatives Ai, it may be necessary to choose the most effective one, sort them into predefined effectiveness classes, or rank them from the most to the least effective (Carladous et al. 2015; Roy 1985). As for any other DMP, the evaluation is based on the aggregation of the evaluations of several gj, assessed through Im (Fig. 1). This process is generally called the "expert judgement" and in our example remains focused on a single check dam as Ai. Nevertheless, several DAMs exist to perform this type of task.

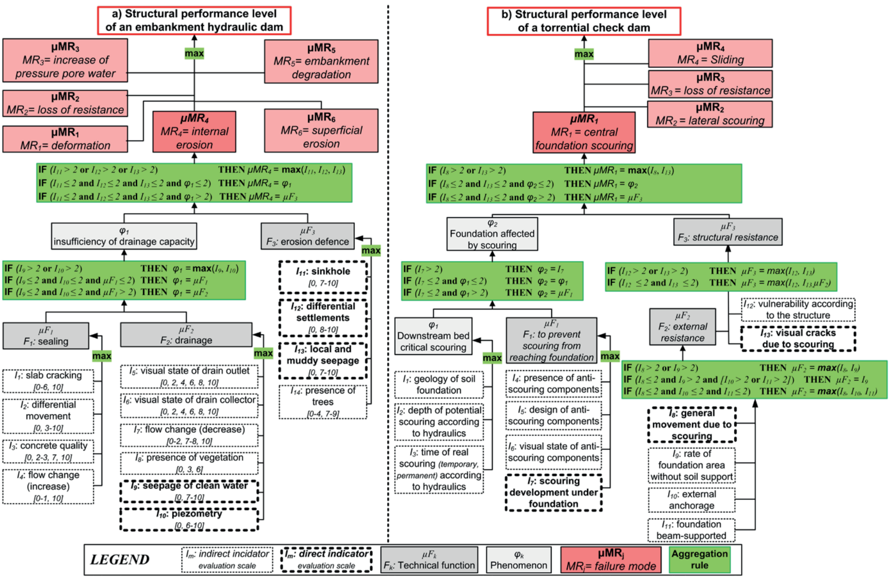

Figure 2: Adaptation of rule-based systems to the assessment of check dam effectiveness. a: An example of the structure of a hierarchical model used to assess the level of structural performance of a hydraulic dam, detailing the internal erosion failure mode (Curt 2010). b: Potential structure of a similar model to assess the level of performance of a torrential check dam.

Rule-based systems are one such DAM. They are used to assess the structural performance level of flood dikes or hydraulic dams. Several failure mechanisms, MRj,, can affect them, e.g. internal erosion. Failure depends on the achievement of technical functions, Fk, such as drainage. The notations µMRj and µFk are the respective performance levels for MRj and Fk (Fig. 2a). Each µFk is assessed through several indirect (e.g. slab cracking) or direct (e.g. clear water leakage) indicators Im.(Fig. 2a). For hydraulic dams, a common discrete scale with a decreasing preference from 0 (excellent) to 10 (unacceptable) has been defined for all values of Im. In order to assess µFk, µMRj and the global performance level, several evaluations are aggregated according to rules such as "MAX" or "IF-ELSE" (Curt et al. 2010). For example, an expert has to assess the structural performance level of two dams, A1 and A2. For A1 he evaluates all values of Im: I2, I3, I5, I6, I8, I12, I13 and I14 = 0; I1 = 5; I7, I9, I10 and I11 = 7; I4 = 10. For A2 he produces another set of evaluations: I1, I4, I5, I8, I11, I12 and I13 = 0; I6, I9 and I10 = 2; I14 = 3; I2 = 5; I3 and I7 = 7. He obtains µMR4(A1) = 7 and µMR4(A2) = 2 (Fig. 2a). The dam A2, which is in good condition, is more structurally sound regarding internal erosion than dam A1, which is in bad condition. Even if rule-based systems are easily understood by practitioners, establishing such a system needs expert elicitation and validation, which can be very time consuming.

MCDMs can also help aggregate several gj criteria. Total aggregating methods are single synthesizing criterion approaches, based on the principle of preference transitivity. Outranking methods do not aim to give a single synthetizing criterion to help in decision making (Schärlig 1985).

The Analytical Hierarchic Process (AHP) is an aggregation-based method (Saaty 1980; Tacnet 2009). It consists of evaluating possible Ai according to preferences (represented by weights ωj) expressed by the decision makers (DMs) on the different gj. The preference . The problem is first broken down from an overall goal to criteria and sub-criteria. At the lowest sub-criteria level (e.g. gj), alternatives Ai are compared in pairs providing their . Finally, for each Ai, the synthesizing criterion xi is given by Formula 1.

$$x_i = \sum_j \omega_j . \omega_{ij}$$

Formula 1: Calculation of the synthesizing criterion xi for the AHP method.

ELECTRE TRI is a progression of the outranking ELECTRE methods introduced in the 1960s (Yu 1992). It aims to sort a number of Ai into predefined categories Ch, according to several gj. The lower and upper limits, respectively bh-1 and bh, of each Ch, have to be specified previously by the DMs, through corresponding evaluations for each gj. A fuzzy preference scale is defined through three thresholds: indifference (qj), strict preference (pj) and veto (vj). Following this, the set of evaluations xij is used to define the outranking relation of each Ai with limits bh. It is based initially on the calculation of partial concordance and credibility indices. Global concordance and credibility indices are then derived based on an arbitrary λ-cut strategy (λ in [0,1]). The final binary assignment of each Ai to a given category Ch, is based on an arbitrary selected attitude choice (optimistic or pessimistic).

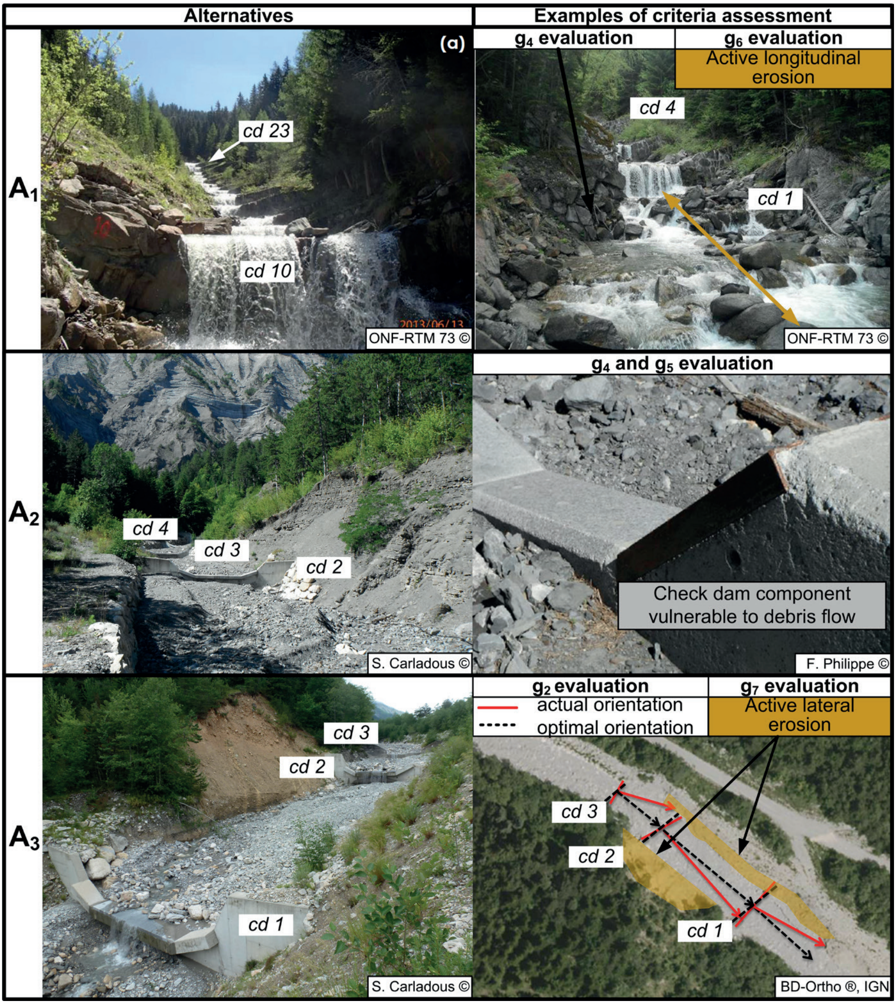

Figure 3: Three clusters of check dams (cd) considered as alternatives and the criteria taken into account to formalize the DMP example.

RESULTS

In this part, we compare the AHP method with the ELECTRE TRI method on the same DMP.

THE ACTUAL DMP

The functional effectiveness of three clusters of check dams is assessed: A1 is a cluster of 28 check dams, A2 contains 25 check dams and A3 contains 3 check dams (Fig. 3). Their purpose is to stabilize the longitudinal profile and limit lateral erosions. Debris flows are considered as the scenario of reference. We propose seven gj (Fig. 3). For each of them, the

DMs have to give the evaluation xij for each Ai in addition to its weight ωj (Table 1).
The preference order of the evaluation scale has to be specified. For example, the structural effectiveness assessment introduced in Fig. 2 is assessed through decreasing preference; indicator evaluation has lower preference while structural evaluation has higher preference.

- g1 (increasing preference): free spillway dimensions, i.e., the rates (0–100%) between the smallest dimensions of all check dam free spillways and the reference scenario discharge.
- g2 (decreasing preference): the orientation of the check dams, i.e., the mean of absolute angle of deviance (0–90 degrees) for all check dams. For each check dam, the angle of deviance is the absolute angle between the actual and the optimal orientations.
- g3 (decreasing preference): the longitudinal implantation of check dams, i.e., the mean difference (in meters) between the optimal and actual implantation of each check dam. The difference can be technically assessed as the height difference between the calculated elevation of the next upstream check dam abscissa and its actual elevation for the lowest compensation slope.
- g4 and g5 (decreasing preference): the mean structural effectiveness of the most significant check dams (g4) and of the others (g5). For each of them, structural effectiveness can be defined as the resistance to stresses due to the reference scenario. We propose an integer rating from 0 (stable) to 10 (unstable). In general, downstream check dams are the most significant.
- g6 (decreasing preference): active longitudinal erosion, i.e., the rate (%) between the length of longitudinal erosion and the objective length of longitudinal stabilization.
- g7 (decreasing preference): active lateral erosion, i.e., the rate (%) between the volume of active lateral erosion and the objective volume of lateral volume stabilization.

Table 1: Data needed to apply the AHP and the ELECTRE TRI to the DMP.

	in general				for AHP			for ELECTRE TRI							
g_j	ω_j	x_{1j}	x_{2j}	x_{3j}	ω_{1j}	ω_{2j}	ω_{3j}	b_0	b_1	b_2	b_3	b_4	q_j	p_j	v_j
g_1	0.1	80	100	100	0.14	0.43	0.43	0	25	50	90	100	10	20	40
g_2	0.2	0	-10	-20	0.54	0.30	0.16	-90	-25	-10	-5	0	5	10	30
g_3	0.1	-1	-0.5	0	0.11	0.26	0.63	-10	-3	-1.5	0	10	0.5	1	2
g_4	0.15	9	1	7	0.08	0.79	0.13	10	8	5	1	0	1	3	5
g_5	0.05	7	3	9	0.17	0.74	0.09	10	8	5	1	0	1	3	5
g_6	0.2	-30	0	0	0.10	0.45	0.45	-100	-80	-50	-10	0	10	20	40
g_7	0.2	-10	-20	-50	0.65	0.29	0.06	-100	-80	-50	-10	0	10	20	40

PROPOSITION OF A RULE-BASED SYSTEM

For the evaluation criteria g4 and g5, the structural effectiveness of each check dam has to be assessed. A rule-based system based on expert knowledge is proposed, in order to allow assessment according to the foundation scouring failure mechanism (Fig. 2b). Foundations may be endangered by a regressive scouring (**φ**2), which depends on the geology (I1) and hydraulic conditions (I2, I3). Check dams with anti-scouring components (I4) are protected, but scouring can occur under foundations (I7) due to design (I5) or condition (I6) problems (μF1). If it occurs, it can affect the external stability of check dams (μF2). Its general movement (I8) is a direct indicator. Even if the unsupported foundation area is significant (I9), check dams with an external anchorage (I10) or with beam-support (I11) are externally stable. Specific visible cracks are a direct indicator of stability failure (I13). If no cracks are visible, structures are more or less vulnerable to scouring, e.g., gravity check dams in dry-stone are more vulnerable than gravity check dams in masonry, which in turn are more vulnerable than self-supporting check dams in concrete (I12).

For the example under consideration, all check dams of A1 are in masonry without any scouring protection. A regressive scouring affects those downstream (Fig. 3). The structural performance level is consequently bad. Evaluation of g4 (for the most important check dams) is worse than for g5 (x14 = 9 and x15 = 7). By making assessments for each Ai, we obtain evaluations for g4 and g5 (Table 1).

RESULTS FOR THE AHP METHOD

Comparing alternatives in pairs provides **ω**ij for each gj, e.g. g4, according to x14, x24,and x34 (Table 1), one prefers A2 to A1 with a level of 9, one prefers A3 to A1 with a level of 5, and one prefers A2 to A3 with a level of 7. It gives **ω**14 = 0.08, **ω**24 = 0.79, and **ω**34 = 0.13 through the preferences matrix. Doing this for each gj, one fills in the Table 1. For each Ai, Formula 1 gives x1 = 0.3035, x2 = 0.4325, and x3 = 0.2640. It is possible to assess the functional effectiveness of each cluster of check dams on a continuous evaluation scale from 0 to 1. Moreover, they can also be compared: A2 is strictly more effective than A1, which is equivalent/more effective than A3.

RESULTS FOR THE ELECTRE TRI METHOD

The DM sorts each Ai into one of the four effectiveness classes: C1 = 'Not effective'; C2 = 'Slightly effective'; C3 = 'Moderately effective'; C4 = 'Highly effective'. For each gj, the DMs must give the lower and upper limits (bh-1 and bh respectively) of each class, and also the thresholds pj, qj, and vj representing the fuzzy preferences on each gj evaluation scale (Table 1). In this example, the same thresholds are considered for each bh limit. Taking into account **λ** = 0.7 and the elements from Table 1, whatever the pessimistic or optimistic attitude of the DM, A1 is in the moderately effective class, whereas A2 is in the highly effective class. The A3 assignment depends on the attitude of the DM: in the pessimistic view it is in the slightly effective class, whereas in the optimistic view it is in the moderately effective class.

CONCLUSIONS

This paper shows how DAMs can help DMs assess the effectiveness of a protection system, such as a cluster of check dams. Several analysis steps are proposed: 1) specification of the DMP, 2) analysis of function, failure mode and pathology in order to extract effectiveness indicators (Suda 2013; Tacnet et al. 2012), 3) specification of the assessment scale and preference order of each indicator and criteria (Curt et al. 2010; Suda 2013), 4) elicitation of aggregation modes (rule-based system, criteria weights) (Curt et al. 2010; Schärlig 1985). This paper integrates results from a hypothetical rule-based system into MCDMs. Two MCDMs are compared demonstrating the data needed (matrices of preferences, thresholds to describe the limitations of classes, λ, etc.) which can actually be difficult to specify.

This paper does not take into account imperfections in the evaluations of each indicator and criterion. Extended decision-support methods have recently been developed to take such features into account (Carladous et al. 2015; Tacnet 2009).
This paper shows how safety and reliability analysis can be complementary to decision-support methods such as MCDMs, allowing expert knowledge to be taken into account in assessments of effectiveness. Actual derivation of expert knowledge for each DMP (systems, scales, effectiveness features), the combination of DAMs, imperfect information, and the validation of results remain challenging.

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