EFFICIENCY ASSESSMENT FOR TORRENT PROTECTION WORKS

AN APPROACH BASED ON SAFETY AND RELIABILITY ANALYSIS

Jean-Marc Tacnet[1], Corinne Curt[2], Rey Benjamin[3] and Didier Richard[4]

ABSTRACT

To ensure the prevention and limiting risks, protection works against torrential floods have an essential role to reduce both the causes and effects of phenomena. Decision support tools are needed to analyze the efficiency of these protection works considering both their structural state and functional abilities. In this paper, classic concepts of dependability are discussed to assess the efficiency of protection works against torrential floods. Fuzzy intervals are used to assess the indicators that describe the possible failures and the performance level of disposals. The methodology aims both at eliciting the expert reasoning process and evaluating the danger level of the protection works. The methodology is based on six steps considering both structural and functional types of failure observed.

Keywords: natural hazards, torrent, hydraulics, protection works, civil engineering, decision support, safety and reliability analysis, dependability, expert assessment.

INTRODUCTION

Mountains rivers threaten people and material assets because of the intensity and suddenness of their floods. In this context, measures and emergency evacuation are difficult to envisage.

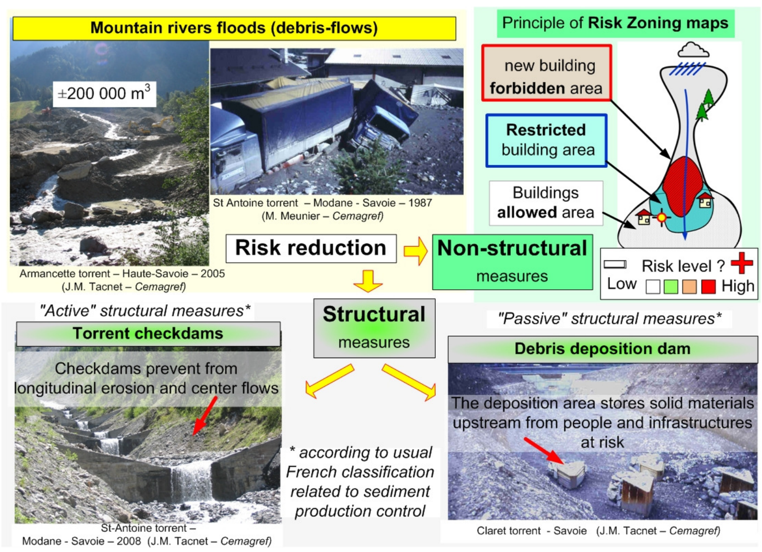

Fig. 1 Structural and non-structural measures are used to reduce risks in torrents and mountain rivers. In France, only structural measures are considered either as passive or active measures.

[1] Jean-Marc Tacnet, PhD., Eng. Sc., IRSTEA, ETGR, Saint-Martin d'Hères, France (email: jean-marc.tacnet@cemagref.fr).
[2] Corinne Curt, PhD., Eng. Sc., IRSTEA (new name of Cemagref) , OHAX, Aix-en-Provence, France
[3] Benjamin Rey, M. Sc. Eng., IRSTEA, ETGR, Saint-Martin d'Hères and EMA Alès, France
[4] Didier Richard, IRSTEA, Head of ETGR, Saint-Martin d'Hères, France.

To ensure the prevention and limiting risks, protection works against flash floods have an essential role to reduce both the causes (“active” structural measures) and effects or consequences (“passive” structural measures) of sediment production (figure 1)[5]. These are often old works whose aging may compromise the sustainability of the overall device. Torrent checkdams (also called "consolidation dams" or “active” structural measures) stabilize profiles along and across streams and limit the intake of materials (figure 2). Lateral erosion generally contributes less than longitudinal erosion in steep channels.

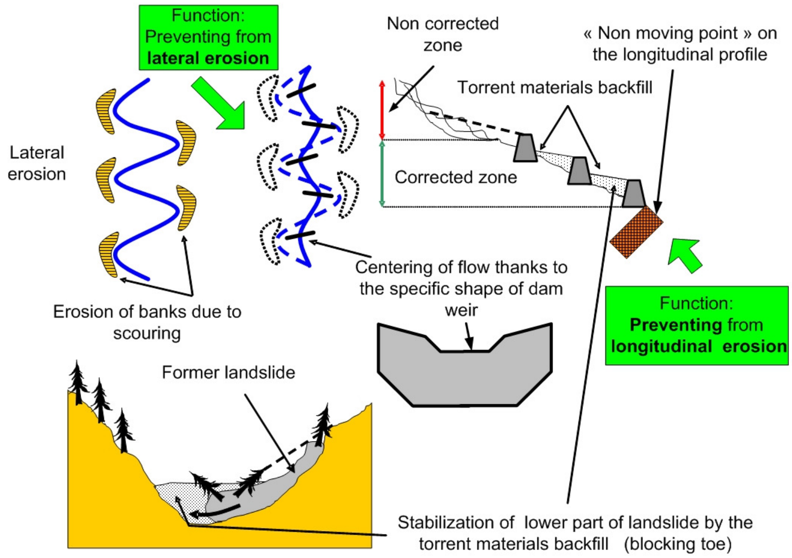

Fig. 2 Preventing from lateral and longitudinal erosion are the two main functions of torrent checkdams (“**active**” **structural** measures)

Sedimentation dams (corresponding to “passive” structural measures) store sediment just upstream and near from the people and assets located on the alluvial fans. Main design issue is to find an optimum between total storage of sediment (with high exploitation costs) and high sediment volume release (with potential increased risk downstream) (figure 3).

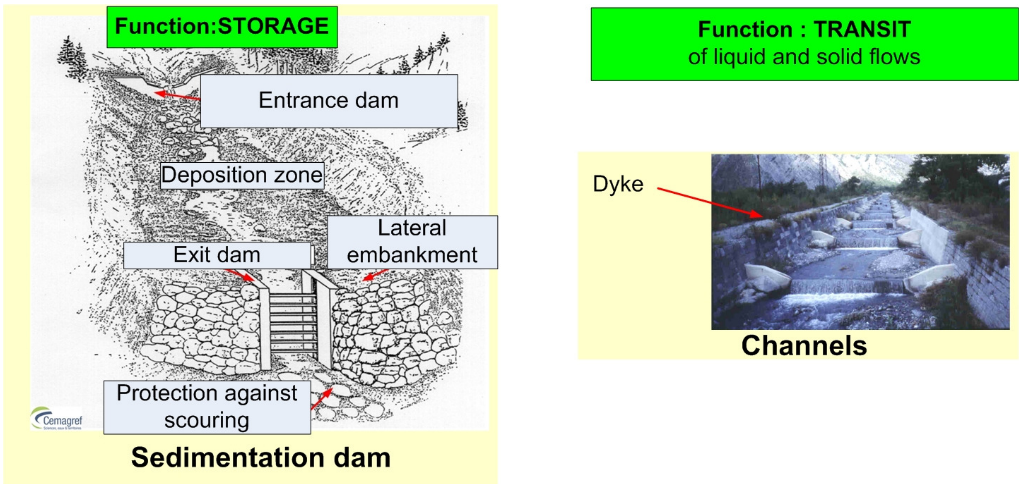

Fig. 3 Storage and transit of liquid flows are the main respective functions of deposition dams and channels (“**passive**” **structural** measures)

---

[5] This corresponds to the usual French classification. In other countries, from one hand passive measures consist in land-use control measures (e.g. risk zoning maps), information and from the other hand any structural measure is an active measure.

The efficiency analysis of those protection works is therefore a very important issue for risk managers especially in the context of danger analysis of dykes and dams (MEEDDAT, 2008). For old protection devices, it is not easy to choose the best strategy for maintenance and to define priorities for selecting the first and more important sites to maintain. It is necessary to characterize the effectiveness of structures and compare their interest and importance in the context of protective devices. Decision support tools are needed to analyze the efficiency of these protection works considering both their structural state and functional abilities. The overflowing, a kind of functional failure of protection works such as dikes, channels or dams of sedimentation, is due both to the strong solid transport and to the liquid fraction (figure 4). This is an essential difference with the more classical context of "clear water" hydraulics.

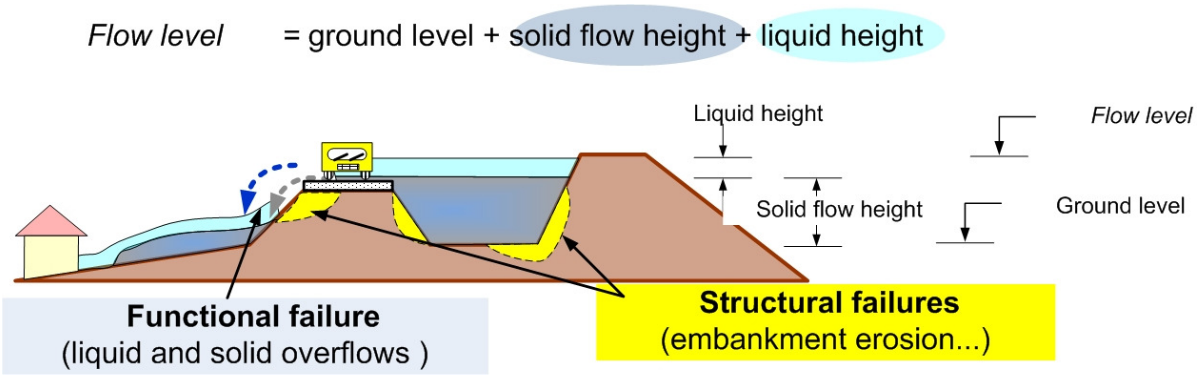

Fig. 4 Functional and structural failures in case of a torrential dyke: erosion can concern inside and outside parts of dykes during the flood (depending on the water level and solid transport rate)

The objective is therefore to characterize and improve the efficiency of these protection works. This concept of efficiency is not clearly defined specially in the context of torrential protection works and requires specific design and building methods and technologies (Tacnet et al., 2010a; Tacnet et Richard, 2010b).
Safety and reliability approaches are currently used to analyse the security of systems mainly in industrial or technological contexts. Despite of their interest to formalize the failure modes of a system, efficiency or performance are not a classical factor considered by those methods. Moreover, the context of natural hazards requires adaptations of the original methodologies. This paper applies a methodology based on dependability analysis including safety and reliability and to the case of torrent control protection works to characterize their efficiency. The first section introduces the topic of efficiency. Section 2 reviews the principles of existing methods of dependability in a context of protection works. Section 3 describes the proposed methodology and discusses the concepts of efficiency and performance: fuzzy indicators are proposed for their estimation. Finally, the discussion and conclusion present the main results and perspectives.

DEPENDABILITY AND PERFORMANCE

Stemmed from industrial domain, dependability presented as the "science of failures and breakdowns" (Mortureux, 2001) aims at assessing and justifying a confidence level concerning the service performed by a system (Magne et al., 2006). It aims at reducing the number of potential failures of the system and controlling the consequences of the residual failures. Consequently it contributes to optimize the technical and economical performances of the system. Dependability is assessed through four attributes. Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. Maintainability is the ease with which a system can be maintained and refers in particular to the capacity to isolate defects or their cause, to correct defects and to bring the system into service. Availability is the total time the system is capable of being used and insures its tasks. Safety is defined by the absence of catastrophic consequences on the user(s) and the environment.

The first step mainly relies on a functional analysis defined by (AFNOR, 1992) as a demarche that consists in listing, ordering, characterizing, putting in hierarchy and/or valorizing the system functions. This system structuring is followed by a FMEA (Failure Mode and Effects Analysis) and a FMECA (Failure Mode, Effects and Criticality Analysis) for each function fulfilled by the system components (figure 5). The criticality analysis combines the gravity, the frequency and the ability to detect the failure (Mortureux, 2001). The issues in the case of protection works against flash floods concern the identification of the structural and functional failures and the assessment of their criticality related to the main functions the works must comply (centering torrential flows, stabilize longitudinal and lateral profiles….) (figure 2).

Component discharge section				
Function	**Failure mode**	**Possible causes of failure**	**Possible effects of failure**	**Symptoms** (measurable with indicators)
Centering of torrential flow	Inadequate orientation of the flow (not centered flow)	-establishment error (bad location) - insufficient hydraulic section - Section obturation by woods debris or excessive torrent material	- Flow deviation - Downstream bank erosion - Wings (lateral part of dam) foundations scouring - Lateral by-pass - Impact of the upper part of weir	- flow deviation angle (°) - Eroded bank volume (m^3) - Section obturation percentage (%) - Length of flooded wing (m) - Width of erosion at the end of the wing (m)

Fig. 5 Example of FMEA analysis of function “Centering the flow” of component “weir” of a system “Torrent checkdam”

The dependability attributes need the definition of a "reference objective" or "nominal mission" that these attributes should comply with during a given period of time. In first approach, explicit references are lacking in the context of natural hazards. For instance, the design objectives of the consolidation dams are usually limited to the definition of loads related to the structure resistance. Functionally speaking, the design objectives are lacking. The bank volumes to stabilize, the lengths of hillslopes toe to be protected, the functioning modes in case of clear water, hyperconcentrated bedload transport flows or debris-flows, are seldom described. Other technological bottlenecks come from the effective difference between the notions of performance and efficiency and the definition of the studied systems (Tacnet *et al.*, 2010b): does the external environment belong to the system concerned by the description of a protection work? Elements of methodology are proposed and discussed in the following section.

EFFICIENCY: DEFINITION OF THE CONCEPT AND ESTIMATION METHODOLOGY

Global methodology

Our approach is derived from the indicators and methods of dependability and dedicated to the specificity of protection works against natural hazards focusing on the mountain river torrents. The project uses the principles of systems analysis underlying the methods of dependability as they formalize and trace the reasoning associated with expert analysis of the operation and condition of structures (Tacnet, 2009a).

The methodology is based on six steps (figure 6) considering both structural and functional types of failure observed. Classical indicators denoted as RAMS (reliability, availability, maintainability and safety) are analyzed to assess the overall efficiency of the devices (Rey, 2010).

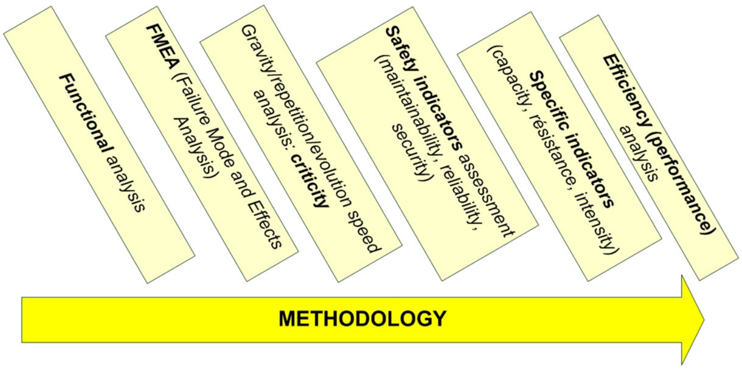

Fig. 6 Functional and structural failure analysis of torrent protection works (examples of dykes)

Functional and structural failures analysis

The concept of failure refers to a predefined, nominal function of a system, identified using functional analysis. Concerning the protection works against flash floods, this type of systemic and exhaustive analysis is lacking contrary to other types of industrial or even hydraulic (dams, dikes) works. It also entails a methodological question because the failure concept concerns not only the anthropogenic components set up to reduce the effects of natural phenomena but also the context of the works implantation (geotechnical, hydro-geological environments…).

We first review the concepts used in the civil engineering domain: functional analysis and FMEA aim to describe the system and its components (figure 7) and analyze its failure modes (figure 8). New indicators of dependability are proposed to define the efficiency of analyzed systems. The system analysis first addresses the case of individual protection works and is afterwards extended to a whole set of dams. Structural failures analysis result from a civil engineering based approach (Tacnet et al., 2010b).

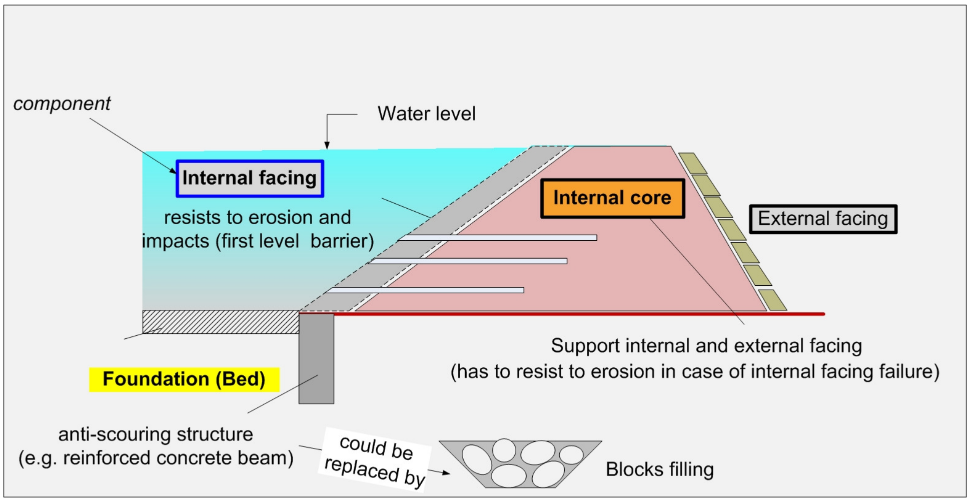

Fig. 7 Functional and structural failure analysis of torrent protection works (examples of dykes)

Failure scenarios (figure 8) are described and are then reused in the FMEA analysis.

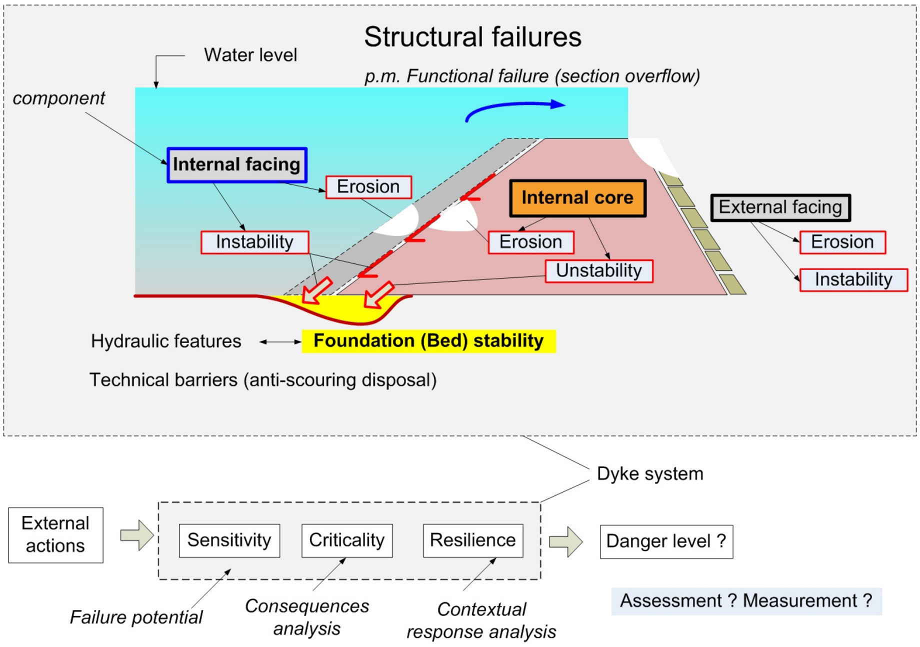

Fig. 8 Example of structural failures of a dyke

An originality of the methodology consists in the description of the functional failures of the system which is used afterwards in the efficiency assessment (figure 9).

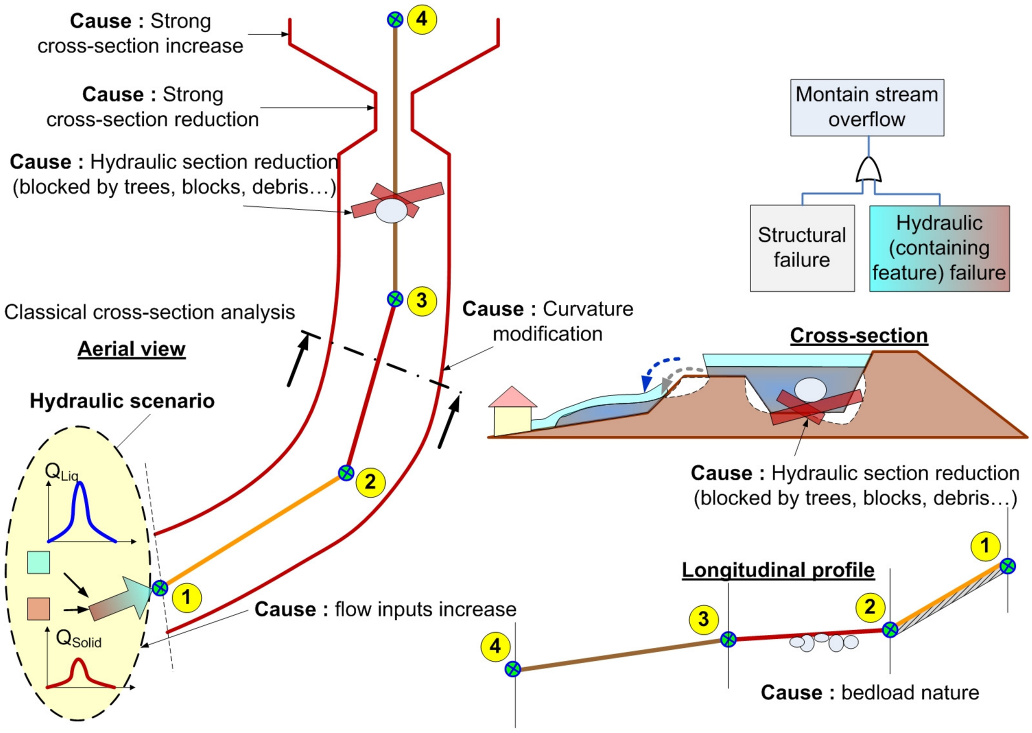

Fig. 9 Qualitative assessment of structural and functional failures of a dyke according to aerial, cross-section and longitudinal profile features (Tacnet et al, 2011)(Irstea-ONF,2011)

Concepts of capacity and efficiency

The loss of performance of hydraulic works, associated to their ageing was analyzed using dependability methods (Peyras, 2003; Peyras et al., 2006; Curt et al., 2010; Breysse et al., 2007). Performance is defined as the capability of an infrastructure to perform the functions for which it was designed. It depends on unitary performances assessed considering the failure of each main function.

The efficiency while being an attribute of main importance for the works managers is not considered as an attribute in dependability approaches. The concepts of capacity, efficiency and performance are linked to the performing of the system functions. The capacity corresponds to the technical characteristics measurable and associated to a function: the torrent materials backfill volume is linked to the function "Stabilize longitudinal profile" (figures 2 and 10).

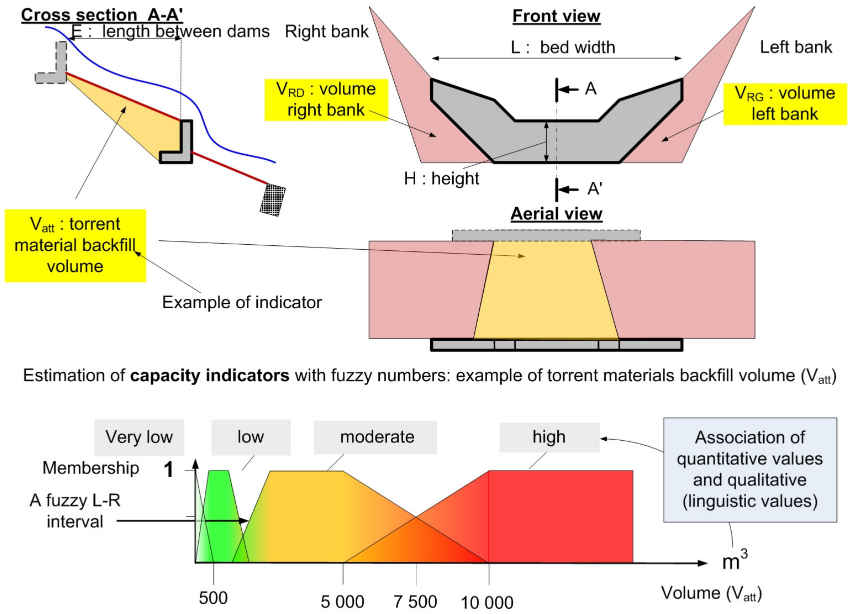

Fig. 10 Example of a capacity indicator of a torrent checkdam based on fuzzy numbers (Tacnet et al., 2011)

The efficiency can be considered as equivalent to the performance concept. It relies on the definition of a nominal objective that links a component, a function and an objective or mission (figure 6). A work is considered efficient if its capacity (or performance level) complies with the design objectives: those two concepts are closely linked (figure 11).

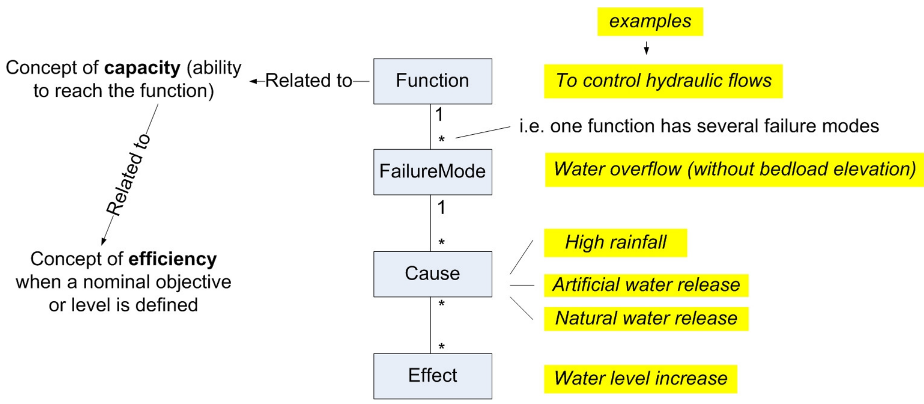

Fig. 11 Relations between failures mode analysis, capacity and efficiency concepts

This definition leads to a difficulty for its application to the context of the natural hazards because the nominal objectives (e.g. stabilisation) of the protection works are seldom explicit, particularly in the case of consolidation dams. Moreover, as the protection works aim at limiting the risk level, their efficiency which depends on the observed failures, is also indirectly linked to the risk level downstream or near the works. The global efficiency depends on the structural and functional aspects. The structural efficiency is a necessary but not sufficient condition to insure the work global efficiency. The efficiency results from the association of the capacity (feature, technical ability) and a predefined objective (figure 12) that has to described.

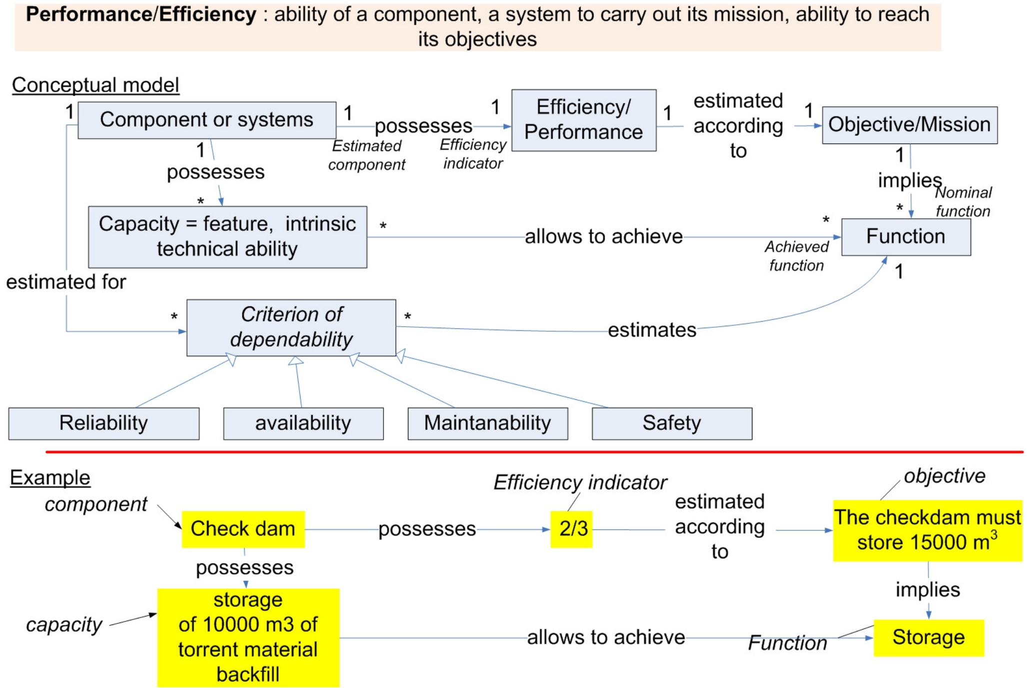

Fig. 12 Definition of the concepts of efficiency and capacity (Tacnet et al., 2011)

Indicators for efficiency estimation

Concepts of reliability, maintainability, safety and availability can be used in the context of torrent floods on the condition of setting temporal references and functional objectives. These concepts are measured by specific indicators. Reliability corresponds to the achievement of system requirements and functions during the initially chosen period corresponding to the device lifetime (e.g. one failure per year during ten years). The maintainability of the system is linked to maintenance conditions and strategy chosen by the protection device managers. The safety corresponds to the analysis of the incoming threats resulting from the environment or the external systems that may induce a critical situation.

Measurable indicators are required to estimate the criteria of dependability and the efficiency of the studied system (i.e. the torrent protection system gathering several dams, dykes...). Indeed, tables of failures analysis resulting (FMECA) are not sufficient to estimate directly the efficiency of any protection work. Specific indicators are necessary (Curt et al., 2010). We propose here indicators that associate the capacities and functions of protection works. Fuzzy sets (Zadeh, 1965) and possibility (Dubois et al., 1988) theories are used to represent and combine imprecise and uncertain knowledge resulting from expert judgements (Curt et al., 2011).

The approach consists in basing the performance (or efficiency) estimation on the use of fuzzy numbers (and/or intervals) (Zadeh, 1965). Thus, quantitative values such as possible volumes, torrent materials backfill volumes, scouring depths...are linked to qualitative classes (linguistic values) on which experts can more easily reason and express their opinion. The scouring depth is an example of a numerical value associated to qualitative linguistic classes (low, moderate...) using fuzzy intervals (figure 13). The identification of these fuzzy numbers allows at the end to the comparative estimation of protection works and torrent sections even when knowledge is incomplete. In that way, this simple method is a way to formalize and capitalize the know-how and the thematic knowledge of experts in torrential hydraulics.

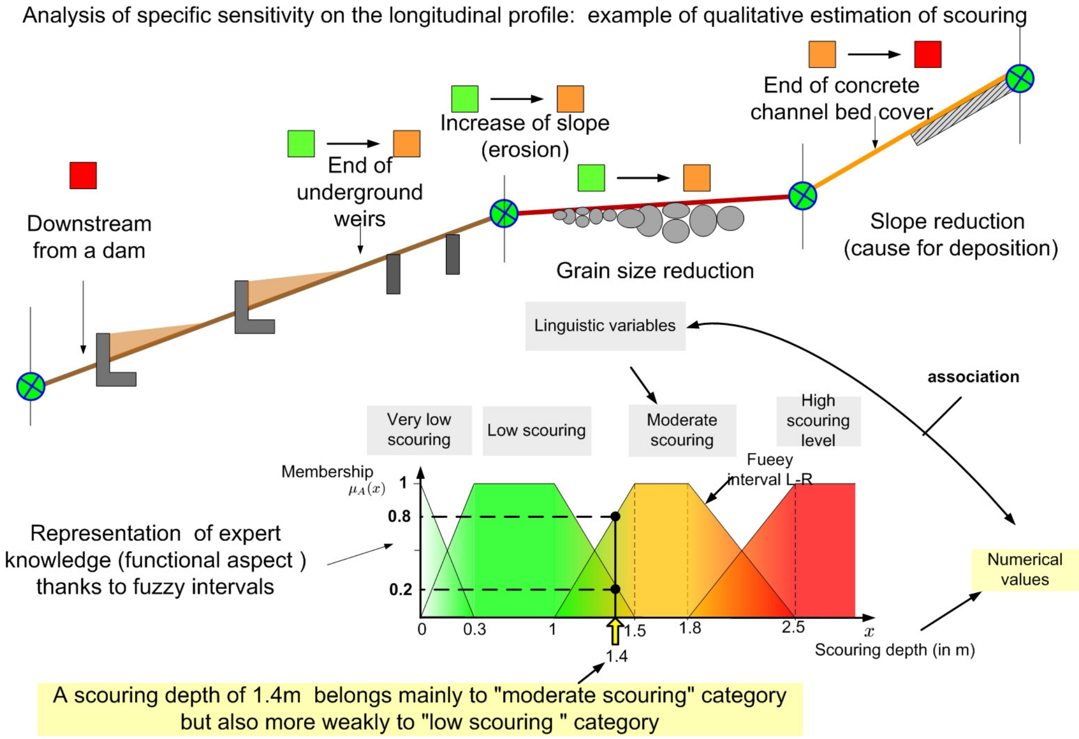

Fig. 13 Qualitative assessment of scouring sensitivity of the different zones of the longitudinal profile (Tacnet et al., 2011)

The implementation consists first in defining explicitly the capacities of protection works (in relation with their technical features) which are the basic criteria to describe the system. Secondly, the efficiency of the components is estimated as soon as the reference objectives of the system have been identified.

Each feature of protection works are analyzed in relation with the failure modes previously identified. This is an essential step, done in collaboration with experts, for a further operational use and application of the methodology (figure 14).

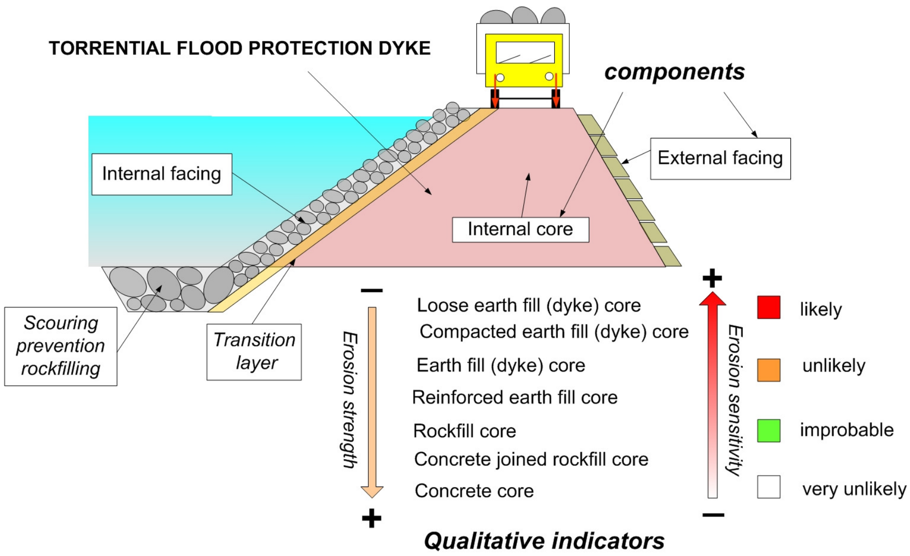

Fig. 14 Building qualitative indicators for structural features of a dyke

CONCLUSION

The concepts of dependability analysis (functional analysis and FMEA) used in the civil engineering domain to describe the system and analyze its failure modes are valuable but quite new tools to analyze the efficiency of protection works. A first methodological framework is proposed to adapt them to the context of natural hazards. The definition of indicators of dependability as fuzzy numbers is a practical way to assess the capacity and efficiency levels. They are also used to analyze the danger level related to the protection works.

This approach has another interest and objective for works whose function is to limit risks: the estimation of performance (or efficiency) indicators is directly linked to a danger level downstream from them. A very efficient (or performing) work will play its protection role completely. A low performing dam does not satisfy its functional objectives and can therefore induce an additional danger downstream from itself in case of failure. These indicators allow identifying differences between the more or less exposed areas to structural and functional failures. They have an interest in the framework of risk prevention but also in the context of danger analysis which focus on additional dangers due to protection works collapse (Irstea-onf, 2011).

Developments of the methodology are still under progress. Combination with other techniques such as multicriteria decision analysis methods, information fusion (Tacnet, 2009; Tacnet, 2009b) is a perspective of this work.

ACKNOWLEDGEMENTS

This research has been partially funded by the the PARAmount Project (www.paramount-project.eu) of the European InterReg Alpine Space program and the ANR Program.

REFERENCES

Breysse D., Vasconcelos E., Schoefs F. (2007). Management Strategies and Improvement of Performance of Sewer Networks. Computer-aided Civil and Infrastructure Engineering, 22, 462-477

Curt C., Peyras L., Boissier D. (2010). A knowledge formalisation and aggregation-based method for the assessment of dam performance. Computer-aided Civil and Infrastructure Engineering, 25, 171-183.

Curt C., Talon A., Mauris G. (2011). A dam assessment support system based on physical measurements, sensory evaluations and expert judgements, Measurement, 44, 2011, p. 192-201.

Deymier, C., Tacnet, J.M., Mathys, N., 1995, Conception et calcul de barrages de correction torrentielle, Cemagref Éditions, Antony, 287 p.

Dubois D., Prade H. (1988). Possibility Theory: an approach to Computerized Processing of Uncertainty, Plenum Press, New York, USA.

Irstea, O.N.F (2011). Etude de dangers des digues du torrent de La Salle. Rapport technique réalisé pour le compte du MEDDTL, à paraître.

Magne L., Vasseur D. (2006). Risques industriels. Complexité, incertitude et décision : une approche interdisciplinaire, Lavoisier, Paris.

MEEDDAT (2008). Arrêté du 12 juin 2008 définissant le plan de l'étude de dangers des barrages et des digues et en précisant le contenu (J.O. du 19 juin 2008), Journal Officiel de la République Française.

Mortureux Y. (2001). La sûreté de fonctionnement : méthodes pour maîtriser les risques in Traité « L'entreprise industrielle » - « Sécurité et gestion des risques », Techniques de l'Ingénieur, - Ref. AG 4 670.

Peyras L. (2003). Diagnostic et analyse de risques liés au vieillissement des barrages-Développement de méthodes d'aide à l'expertise - Thèse de doctorat (PhD thesis), Université Blaise Pascal - Clermont 2, France.

Peyras L., Royet P., Boissier D. (2006). Dam ageing diagnosis and risk analysis: Development of methods to support expert judgement, Canadian Geotechnical Journal, **43**, 169-186.

Rey B. (2010). Analyse de l'efficacité des dispositifs et stratégies de protection contre les crues torrentielles, Rapport de stage de fin d'études d'ingénieur, Ecole des Mines d'Alès, Alès, Cemagref (Grenoble), France.

Serre D. (2005). Evaluation de la performance des digues de protection contre les inondations : modélisation des critères de décision dans un système d'information géographique. Thèse de doctorat en sciences de l'information géographique, Université de Marne-La-Vallée, Marne-La-Vallée, France.

Suda, J., Strauss, A., Rudolf-Miklau, F., and Hübl, J. (2009). Safety assessment of barrier structures. Structure and Infrastructure Engineering, 5(4):311--324.

Tacnet J.-M. (2009a). "Considering uncertainty in the natural risks expertise process using multicriteria decision analysis and information fusion". PhD Thesis in Environmental Sciences Engineering (in French), Ecole Nationale Supérieure des Mines de Saint-Etienne, France.

Tacnet J.-M., Batton-Hubert M., Dezert J. (2009b). Information fusion for natural hazards in mountains in Advances and applications of DSmT for Information Fusion - Collected works - Volume 3 - http://fs.gallup.unm.edu//DSmT.htm, American Research Press, Rehoboth, USA, p.565-659.

Tacnet J.-M., Richard D., Dezert J., Batton-Hubert M. (2010a). Decision support and information fusion for expert assessment of natural risks : analysis of the efficiency of civil engineering protection works (in French), 6 èmes journées de la fiabilité des matériaux et des structures, JFMS'10, Toulouse, France, 24-26 mars 2010.

Tacnet J.-M., Richard D. (2010b). From design to safety analysis of torrent control checkdams, Revue SET (Sciences, Eaux, Territoires), vol. 2, p. 164-175, 2010a.

URL : http://www.set-revue.fr/de-la-conception-la-surete-des-barrages-de-correction-torrentielle

Tacnet J.-M., Curt C., Richard D., Rey B. (2011). « Efficacité des ouvrages de correction torrentielle : indicateurs basés sur la sûreté de fonctionnement », Annales du bâtiment et des travaux publics,n °4-5, 78-86.

Zadeh L. (1965). Fuzzy sets, Information and Control, vol. 8, p. 338-353, 1965.