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USE OF RISK MODELS FOR EVALUATION OF RISK REDUCTION MEASURES FOR DAMS(*)

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1. INTRODUCTION: THE RISK INFORMED APPROACH

Risk analysis is a useful tool for decision making due to its capacity to integrate all information regarding the safety of a dam or any other critical infrastructure.

In order to carry out a risk analysis, a risk model of the dam must be set up including the loads of the system (hydrological, seismic or any other), the system response (failure modes) and the consequences (economic, loss of life or any other). This model incorporates information from many studies which can usually be found in the dam's safety file.

Once the model is set up, it is then possible to evaluate the relative importance of each of the safety aspects which up until then might have been studied in an isolated manner. Also, a global evaluation of the dam's safety can be obtained by comparison against existing tolerability guidelines [1, 2]. With risk models, it is possible to evaluate the impact and efficiency of potential risk reduction measures in a homogeneous way. Finally, systems of dams can be analyzed to find ways of optimizing their joint management.

(*)Emploi des modèles de risque pour l'évaluation de mesures de réduction du risque des barrages

2. SOFTWARE FOR RISK ANALYSIS: iPRESAS

The authors approach to carry out risk calculations has been to develop a generic software program which can fulfill all the demands of a risk analysis. The software name is iPresas [3], and was initially presented in ICOLD's 23rd International Congress [4]. Since then, the software has been used in many applications and has been enhanced in several ways. Next, some of its features are explained. Figure 1 shows the user interface of the software.

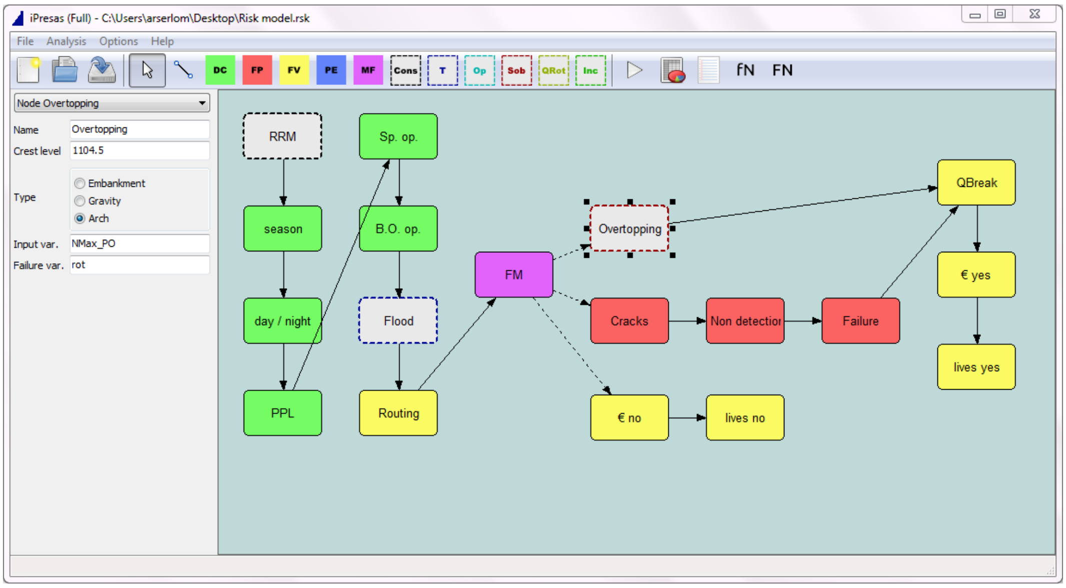

Fig. 1
iPresas software for risk analysis [3]
Logiciel iPresas d'analyse de risque [3]

2.1 Event Trees And Influence Diagrams

Nowadays, the mathematical tool which is usually used for risk analysis modeling is the event tree. An event tree is an exhaustive representation of all the events and possibilities which can lead to a final event. In the case of risk analysis as applied to dam safety, the main event will usually be the failure of the dam. In other fields, other events are modeled, for instance a failure in a nuclear facility [5] or a volcanic eruption [6]. Risk analysis in other critical infrastructures is also similar to dam safety risk analysis in that the failure of the critical infrastructure under study must be captured in the event tree.

In some fields, event trees can sometimes be relatively small, however, a typical event tree in dam safety risk analysis can easily have thousands of branches, especially if the fragility curve approach is used [1, 7]. To manually specify all these individual branches would be impractical, so some type of abstraction must be used.

Some researchers have used cloning and copying techniques to partially define an event tree which can then be expanded into the full event tree [8]. The authors have followed another approach based on the use of influence diagrams, as explained in [4].

Influence diagrams are a compact conceptual representation of a system's logic. Risk models can be fully specified with influence diagrams. Each node in the influence diagram represents a variable. Nodes are then connected to define the relationships between variables. The developed software reads the influence diagram and expands it into the equivalent event tree, which is finally used for the calculation.

The rules for building an influence diagram and the way in which it can be transformed into an event tree are presented in [4]. The detailed algorithm for making the calculations is explained in [9].

2.2 TYPES OF NODES

iPresas originally had 5 types of nodes. With these 5 types of nodes, the software was able to model any type of event tree. After using the software in several risk analyses, 6 more types of nodes have been added. Since with the 5 original nodes the software was completely general, the purpose of the new nodes is just to make the modeling of common cases more convenient and fast.

Next, the 5 original nodes (which were presented in [4]), as well as the 6 new ones are succinctly presented.

DC nodes are used to specify events where both the outcomes and the probabilities are known quantities which are not function of any other variable. These nodes can be used, for instance, to specify the season of the year when a dam breaks or time of the day (both of them are important variables when calculating consequences).

FP nodes are used for yes/no type events, where the probability of the outcome is a function of previous variables. An example of where this node can be useful is the event where the failure probability is estimated.

FV nodes are used when a variable is a function of another variable, for instance, to calculate life loss as a function of peak discharge.

PE nodes are used for the discretization of continuous variables which are defined in terms of exceedance probability. In dam safety risk analyses floods and earthquakes are usually defined in this way.

MF nodes are a special type of node used to allow for several failure modes to be included in the model and include algorithms for applying mathematical techniques such as common cause adjustments and freezing of variables [10].

Cons nodes are used to introduce constant values in the model. They are useful, for example, to selectively apply or not a risk reduction measure.

T nodes are a simplified form of PE nodes for the introduction of anual exceedance probabilities into the risk model.

Op nodes are specialized nodes to easily include the gate reliability of several spillways and/or outlets and combine them with the aid of the Binomial distribution.

Sob nodes are specialized nodes for the inclusion of an overtopping failure mode in a simplified way. They use different fragility curves for different types of dams which have been defined based on a literature review and the experience of the authors [9, 1, 11].

QRot nodes allow for a simplified estimation of peak discharges in dam breaches as a function of reservoir elevation. At least one flood hydrograph must be calculated and the node then makes extrapolations based on a modified version of Froehlich's equation [12].

Inc nodes allow for a convenient way to calculate incremental consequences.

2.3 CALCULATION MODES

iPresas allows for three calculation modes: direct calculation, direct calculation + postprocessing and incremental mode.

Direct calculation. This calculation mode is useful for calculating total risks. If incremental consequences are included in the model it can also be used to calculate incremental risks.

Direct calculation + postprocessing. Instead of directly including incremental consequences in the model, incremental consequences are automatically calculated by the software after the event tree is developed, by pairing branches of failure and no failure and subtracting the consequences.

Incremental mode. This mode is specifically designed for incremental calculations. Instead of relying on the concept of incremental consequences, incremental risks are directly calculated by comparing a case with 0 probability of failure with the real case. It is mathematically equivalent to the above methods but has some advantages when dealing with systems of several dams. The algorithm was developed by the authors [13].

2.4 OBTAINING RESULTS

Once the model is set up, obtaining results is simple. There are several results that are needed for a risk evaluation: annual probability of failure, economic and social total and incremental risks, F-N curves... All of these can be obtained with iPresas. The results can be explored numerically, plotted in charts or exported to other programs (for example, see figure 2 with an FN chart).

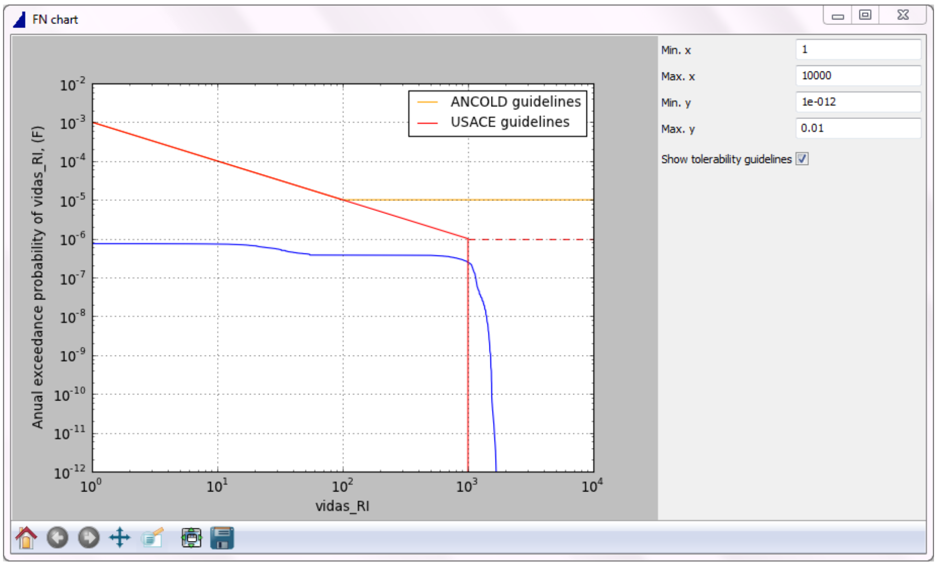

Fig. 2
Example of viewing results with Presas: an F-N chart.
Exemple de visualisation de résultats avec Presas: un graphique F-N

Besides obtaining results for the risk evaluation, the validity of the model should be checked by exploring the results in detail. For instance, branch plots should be explored (Figure 3) and the relationship between input variables and output variables (failure probability, consequences, risk...) should be plotted. iPresas allows for a convenient way of obtaining all these plots and relationships.

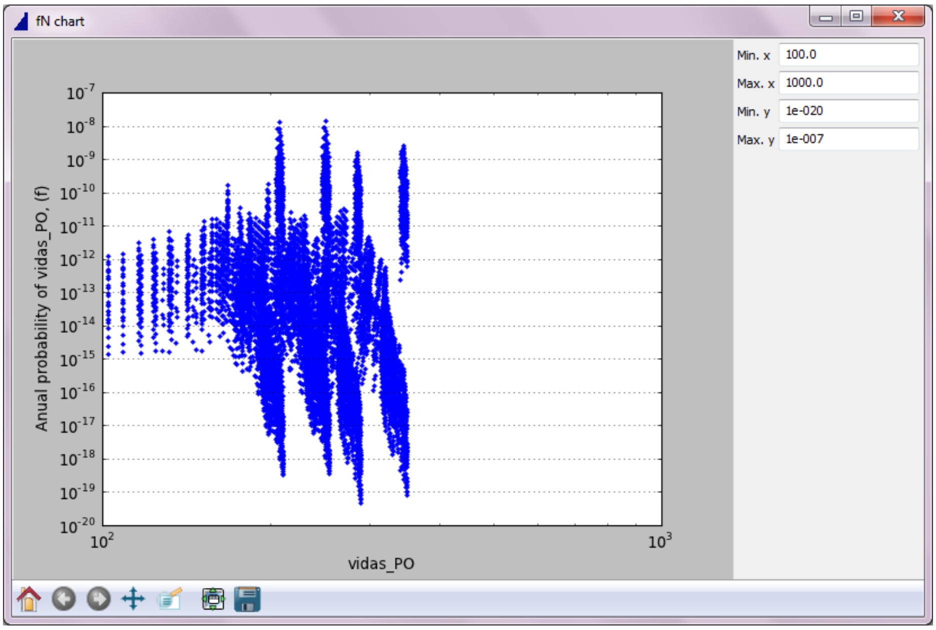

Fig. 3
A branch plot in an fN chart.
Tracé de section dans un graphique fN.

2.5 OTHER FEATURES

The software also has features to allow for the comparison of risk reduction measures, calculation of efficiency ratios, comparisons in portfolios of dams, sensitivity analyses and full uncertainty analyses.

3. APPLICATIONS

Next some applications of risk analysis are briefly commented.

3.1 PORTFOLIO RISK ASSESSMENT

Risk analysis enables us to make meaningful comparisons between the risks of several dams. For this comparison to be fair, consistency in the risk analyses across the entire portfolio must be enforced.

Figure 4 shows a comparison of the risks of 11 dams in a portfolio of dams in a fN chart [2]. The results have been color coded according the level of risk and/or failure probability (red for higher, orange for intermediate and green for lower). With a single chart like this one, dams with high risk are highlighted, showing also whether risks come from high consequences, from high failure probabilities or from both. These charts are very useful for decision makers, who can easily pinpoint which dams deserve a greater attention from a safety point of view.

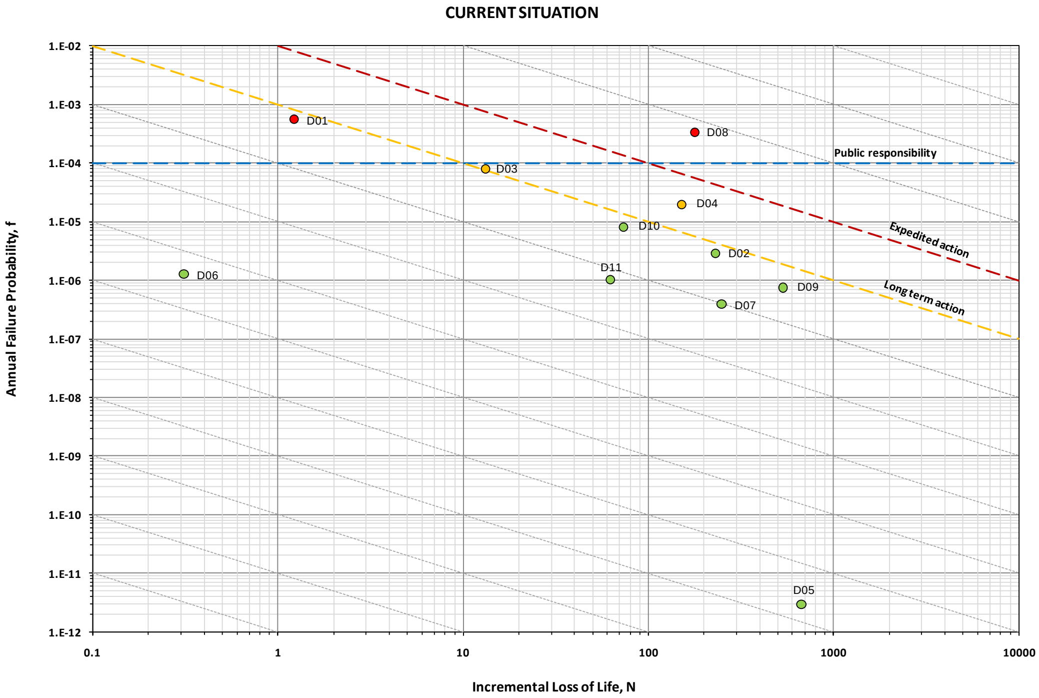

Fig.4

fN chart with tolerability guidelines for the current situation of a portfolio of dams.
Graphique fN avec indicateurs de tolerabilité pour la situation actuelle d'un ensemble de barrages.

3.2 Evaluation Of Risk Reduction Measures

Once the baseline case is characterized, risk reduction measures can be explored, evaluating their effectivity and efficiency. Risk reduction measures associated to human and organisational factors are as easy to evaluate as structural measures and can be compared homogeneously.

For example, figure 5 plots the effect of implementing two types of Emergency Action Plans (EAP) in each of the dams. The shorter arrow indicates the change from the current situation to a scenario where a standard EAP has been implemented. The second arrow indicates the further gain that could be achieved if through means of a Continuous Education Programme (CEP) the awareness of affected population was raised thus improving the effectiveness of the EAP. As can be seen, these RRM don't affect the failure probability, but lower the risk by lowering the consequences. The reduction in consequences was estimated by empirical methods [14].

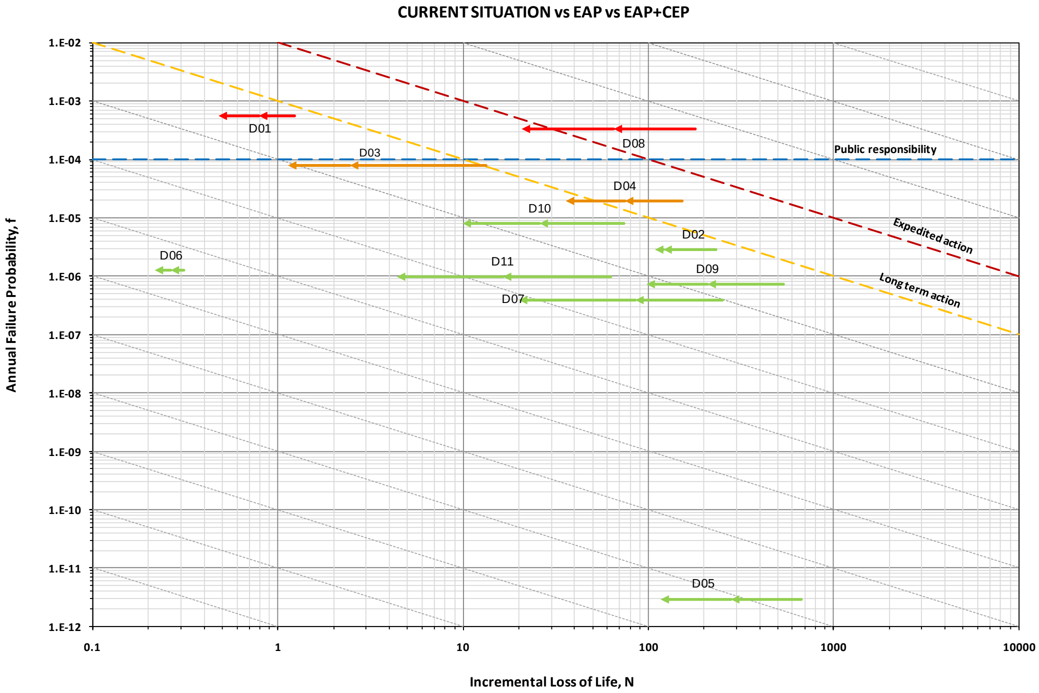

Fig. 5
fN chart with tolerability guidelines for the current situation of a portfolio of dams.
Graphique fN avec indicateurs de tolérabilité pour la situation actuelle d'un ensemble de barrages.

Figures 4 and 5 plot incremental risks, which are useful for evaluating the tolerability of risks, however, total risks should also be examined and the impact of each risk reduction measure should be measured both in terms of total and incremental risks. For example, in some circumstances, an increase of spillway capacity may lower the incremental risk associated to the failure of a dam but increase the total flood risk downstream of the dam. FN charts are also useful to examine the detail of these risk variations.

Following this logic a change in flood routing strategy was proposed for one of the dams in the previous example which managed to lower the total risk by over 10% with a negligible increase in failure probability and incremental risk.

Other risk reduction measures explored for this example include, changes in reservoir exploitation, gate reliability enhancements, better flood management, monitoring, structural measures (including the decommissioning of one dam) and the impact of maintenance.

With a homogeneous way of comparing different risk reduction measures in different dams, several way of prioritizing the implementation of measures can be explored. One way to do this is through the use of efficiency ratios [15, 16].

3.3 FLOOD RISK IN URBAN AREAS

Flood risk in urban areas can have great importance. When studying flood risk in urban areas, all possible risk sources must be analyzed, including those related to dams. A methodology based on the study of total FN curves has been proposed for this purpose [14]. Thank to its flexibility, iPresas has been used to perform these calculations.

3.4 RISK ANALYSIS OF OTHER CRITICAL INFRASTRUCTURES

The growing application of risk analysis, considering natural hazards and manmade threats, has created a paradigm shift that has fostered progress in assessing and managing not only the impacts associated with flooding but also other events and incidents that may affect the public, environment, and economic development. Examples of this paradigm shift are represented through the establishment of European Directive 2007/60/EC on the assessment and management of flood risks, and European Directive 2008/114/EC on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. These directives, and other equivalent international legislation, recognize and explicitly require risk analysis to be utilized as the primary tool for infrastructure management, addressing all aspects of the process to include improving our understanding of natural hazards, implementing more effective operation and maintenance approaches, and developing best practices to minimize impacts to the public and environment [17].

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SUMMARY

Risk analysis is a useful tool for decision making due to its capacity to integrate all information regarding the safety of a dam or any other critical infrastructure. In this paper, a software for risk analysis developed by the authors is reviewed and several applications of the software to evaluate risk reduction measures are presented. Applications include a portfolio risk assessment and evaluation of several risk reduction measures. It is shown how risk reduction measures associated to human and organizational factors are as easy to evaluate as structural measures and can be compared homogeneously. Flood risk in urban areas and risk analysis of other critical infrastructures are discussed.

RÉSUMÉ

L'analyse de risque est un instrument utile dans la prise de décision du fait de sa capacité d'intégrer toute l'information relative à la sécurité d'un barrage ou de tout autre type d'infrastructure critique. Dans cet article, un logiciel d'analyse de risque développé par les auteurs de cet article est analysé et plusieurs applications du logiciel servant á évaluer les mesures de réduction de risque sont présentées. Les applications incluent un portefeuille de contrôle de risque et d'évaluation de diverses mesures de réduction de risque. Cela démontre que les mesures de réduction de risque associées à des facteurs humains et organisationnels sont aussi facilement évaluables que les mesures structurelles et peuvent être comparées de manière homogène. Le risque d'inondation dans les zones urbaines et l'analyse de risque d'autres infrastructures critiques sont également discutés.

DAMS:

Key-words: Dams, risk models, evaluation, risk mitigation.

Mots-clés: Barrages, modèles de risque, l'évaluation de mesures, réduction du risque