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Dam Risk Analysis Using Bayesian Networks

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Dam risk analysis using bayesian networks

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Abstract

The risks related to existing hydraulic structures have been analyzed using bayesian networks. The proposed multidisciplinary approach allowed the comparison, according to the probability of failure being used as a common denominator, of the geotechnical, hydrological and structural risks. The factors contributing the most to the overall risk have been identified as well as the interventions to be realized in priority. The presented concepts consider dam risk in a more global and holistic way.

1. Introduction

No one can predict risk with certainty because two of its main characteristics are complexity and uncertainty (Denis 1998). Even when a dam is judged to be safe, there still exists a residual risk that is always present if population or property are located in the flood zone. Dam failures are not common but they always have important human, material and environmental consequences. The establishment of risk-reduction measures is therefore an important part of the responsibilities of a dam owner.

A safety assessment of the civil structures of an irrigation and flood control project located in Asia showed that the embankment dam and the spillway present multiple technical problems that could endanger their short-term safety. Risk-reduction measures need to be implemented. Risk analysis methodologies such as event trees or fault trees present some limitations related to the representation of dam risk in absolute terms and also in taking into account the complexity and the uncertainties related to the potential failure mechanisms. The use of bayesian networks is proposed to overcome some weaknesses of the existing tools and to capitalize on their merits.

This paper discusses how bayesian networks were used for the analysis of the geotechnical and hydrological risks related to the embankment dam and the risk related to the reliability of the electrical/mechanical components of the spillway. This assessment considered the interrelations between the potential failure mechanisms as well as the uncertainties and expert judgements always present in risk analyses.

2. Problem description

The analyzed project is comprised of a dam and a spillway. The dam is a 25 m high and 860 m long clay embankment without internal drainage and founded on untreated soil foundation. The fill placement was realized without the use of heavy machinery and quality control procedures. The spillway, located near the left abutment of the dam, is equipped with three gates lifted manually using a winch installed on a mobile gantry crane. A electrical motor is available to facilitate gate lifting.

A dam safety assessment showed that the internal erosion process has initiated and is still progressing due to the absence of filters in the dam and its foundation. This process is somewhat controlled by reservoir level restrictions. An insufficient spillway capacity and a lack of adequate freeboard represent a significant overtopping risk for the dam during typhoons due to the heavy precipitations and waves caused by strong winds. Moreover, the mechanical/electrical components of the spillway are unreliable. Also, during periods of strong winds, the gantry crane becomes unstable and cannot be operated. The risk of overtopping is significant even during less severe flooding events.

Rehabilitation works are needed to increase the safety of the civil works and to reduce the risks imposed to the population living downstream. These measures will also restore irrigation and flood control capabilities. Four options are considered:

1. Rehabilitation of the existing gates and lifting mechanism.
2. Addition of a fourth gate to increase spilling capacity.
3. Construction of a filtering berm to control the ongoing internal erosion.
4. Construction of a parapet wall on the dam crest to increase storage volume and flood routing capabilities.

Considering the importance of this rehabilitation project for the local economy and the numerous interrelations between the failure mechanisms, an assessment of the overall risk is required to select the option offering the maximum risk-reduction potential for a minimal cost.

3. Interrelations between failure mechanisms

The selection of the rehabilitation option to be realized in priority is not evident since the overtopping and internal erosion failure mechanisms are interrelated. When the reservoir level is higher, the risk of overtopping increases as well as the risk of internal erosion since the hydraulic gradient across the dam becomes higher. Also, the reservoir level depends on the precipitations and the reliability of the spillway. The presence of waves and strong winds also affect the overtopping risk and spillway operability. Moreover, the available data and knowledge regarding the hydrological and geotechnical aspects of the project are uncertain.

The problems related to the safety of a dam are unique from one structure to another and do not always fall neatly into the loading categories customarily considered in risk analyzes. The interactive influences between the failure mechanisms can be easy to overlook (Vick 2000). The cause and effect relationships defining these mechanisms are strongly interrelated and cannot be fully represented by conventional event trees or fault trees which consider each mechanism independently. It is necessary to study the details of each failure mechanism and also to consider their interrelations. The complexity of a system is not only due to the number of its components but also to the multiplicity of their cause and effect relationships.

Bayesian networks are used to analyze globally the technical problems related to the probability of failure of the dam by describing the interrelations between the failure mechanisms and taking into account the uncertainties. This analysis provides answers to the following questions:

1. What are the most significant factors contributing to the overall risk?
2. What are the rehabilitation works to be realized in priority?

4. Bayesian networks

4.1 Concepts

A bayesian network is a causal graph where the variables of the considered system are represented by nodes and their dependencies by directional links. The underlying probabilistic representation allows the quantification of the strength of these dependencies and the realization of inferences to aid decision-making. These calculations are based on Bayes' theorem which can be considered as the mathematical expression of learning from experience.

This form of artificial intelligence allows the global consideration of a problem by putting into perspective all of its components. The representation of knowledge is achieved by establishing the cause and effect relationships between the variables and by determining the conditional probabilities, by calculation or by expert elicitation, associated with these relationships.

These principles are illustrated on Figure 1 in which a causal model (where *A* is the direct cause of *B* and *C*) and the underlying probability tables (including for example the probability of *B* given *A* noted $P(B|A)$) form a bayesian network which synthesizes knowledge related to a given problem (Becker and Nadim 1999). This allows reasoning under uncertainty by means of inferences.

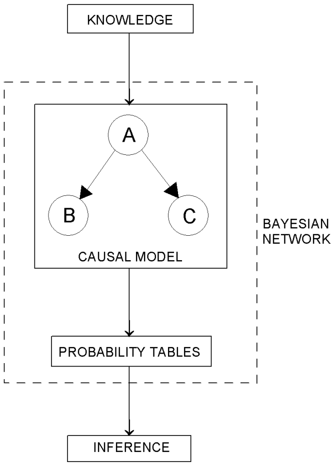

Figure 1. Components of a bayesian network.

Each variable is defined by a series of states which can include numerical values or litteral descriptors. The probabilities underlying the causal model consist in a table for each variable containing a conditional probability for every state of that variable given every combination of states of its causes. The determination of these values has three fundamental components: data analysis, phenomenological models and expert elicitation (Hartford and Baecher 2004).

4.2 Use

One of the main functions of bayesian networks is the realization of inferences where conditional probabilities for some variables are calculated given information (evidence) on other variables. The effects of new evidence is propagated in the network by means of algorithms based on Bayes' theorem which can be expressed in terms of cause and effect:

$$P(cause \mid effect) = \frac{P(cause) * P(effect \mid cause)}{P(effect)} \tag{1}$$

In Eq. 1, prior knowledge contained in the bayesian network, *P(cause)*, is transformed in posterior knowledge, *P(cause|effect)*, considering the likelihood of the new information, *P(effect|cause)/P(effect)*. This approach is used as a vehicle for drawing conclusions from observations. In a dam safety context, these observations can result from changes in the behaviour of a dam or from the implementation of structural or non-structural risk reduction measures. The symmetry of Bayes' theorem allows inferences by diagnosis (*P(cause|effect)*) and prediction (*P(effect|cause)*). The inferences are realized by using a specialized software.

Examples of diagnoses include the determination of the most likely cause of a potential dam failure and the identification of the most significant component of the overall risk. Predictive inferences can help prioritize risk-reduction measures by the comparison of *P(Failure|Risk-reduction measure)* with *P(Failure)*.

5. Bayesian network for the analyzed dam

5.1 Causal model

The failure of the dam (variable *F* on Figure 2) is analyzed by considering internal erosion and overtopping. These failure mechanisms are affected by the reservoir level (*RL*) which depends on the precipitations (*P*) and spillway operation (*SO*). The wind speed (*WS*) influences both the spillway operation and the risk of overtopping.

The spillway is operational if the gates (*G1* to *G3*) and the lifting mechanism (*LM*) are functioning. The latter depend on the gantry crane (*GC*) and the electrical or manual winches (*EW*, *MW*). The three gates are considered separately to model partial opening of the spillway. Overtopping (*O*) depends on the risk of wave runup (*WR*) during strong winds and on the reservoir level. Internal erosion requires carried soil particles (*CSP*) from the dam itself or its foundation which can occur in the presence of an unfiltered seepage exit (*UFE*), erodible soil (*ES*) and a high enough hydraulic gradient (*HG*). The latter depends on the reservoir level and the presence of more permeable zones (*PZ*). These relationships form the causal model of the bayesian network for the analyzed dam (see Figure 2).

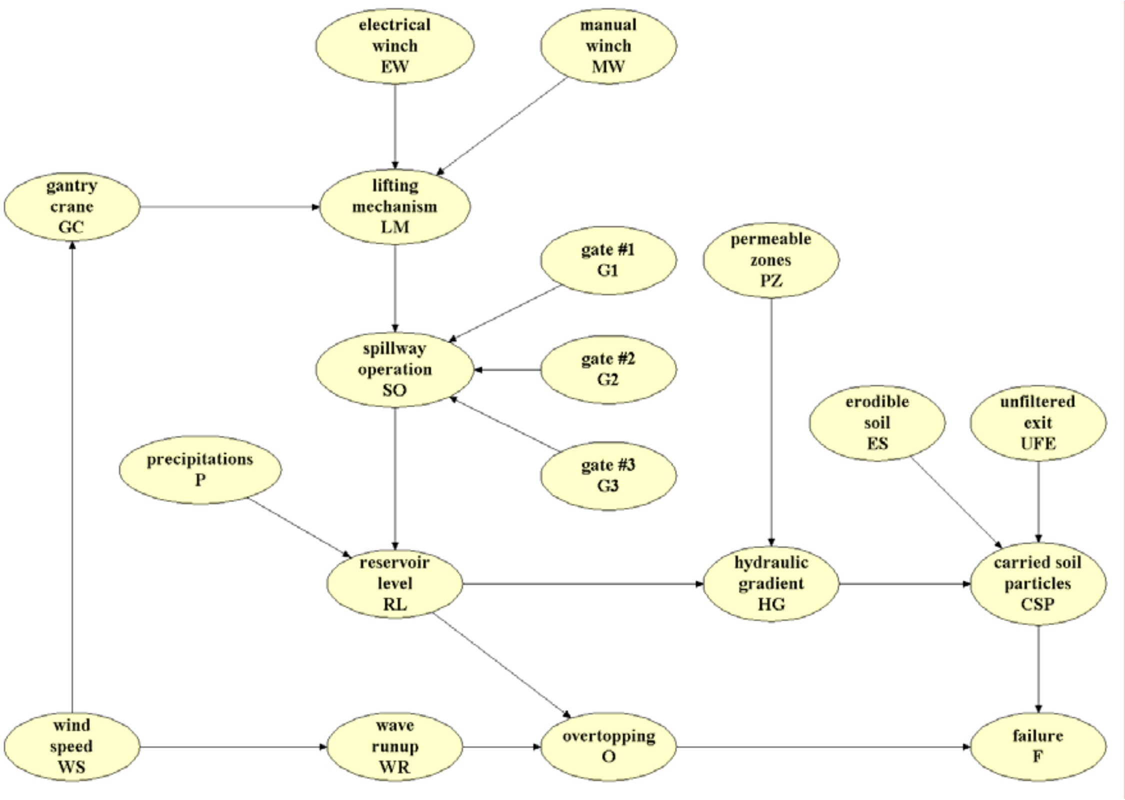

Figure 2. Bayesian network for the analyzed dam.

5.2 Probabilities

Each variable shown on Figure 2 is related to a conditional probability table expressing the strength and degree of uncertainty of its causal dependencies. An example for variable *LM* is shown on Table 1.

Table 1. Probability table for the lifting mechanism (variable *LM*).

GC =	*yes*				*no*			
MW =	*yes*		*no*		*yes*		*no*	
EW =	*yes*	*no*	*yes*	*no*	*yes*	*no*	*yes*	*no*
LM = yes	1	1	1	0	0	0	0	0
LM = no	0	0	0	1	1	1	1	1

The lifting mechanism (*LM*) is always functional, $P(LM = yes) = 1$, if the gantry crane (*GC*) is functional and the electrical winch (*EW*) or the manual winch (*MW*) is also functional. The probability values in Table 1 were determined with the help of a fault tree. The logical relations on that fault tree were transposed in the bayesian network to consider the reliability of the mechanical/electrical components of the spillway in a more global manner which includes also the geotechnical and hydrological risks.

Other approaches can also be used to determine the conditional probability values. When large data sets are available, the probabilities can be computed with the help of statistics. This option is often used for meteorological data. Other evaluations are based on mathematical models such as hydrological and flood routing calculations to determine maximum reservoir levels for different recurrence periods. For this study, these models took into account the precipitations and the number of gates in operation (*0* to *3*). Other probabilities, for example those related to internal erosion, are determined by expert judgement based on geotechnical models and knowledge about the specific characteristics of the dam and its behaviour.

6. Optimal risk-reduction measures

6.1 Contributing variables

Inferences are realized on the bayesian network of Figure 2 to identify the variable contributing the most to the overall risk. The probability of failure of the dam represent here the overall risk and the decision basis for the selection of the optimal risk-reduction measure.

The probability of failure serves as a common denominator with which the negative impact of the observation or non observation of one or more variables *Va* is calculated using Eq. 2.

$$impact = \frac{P(F) - P(F \mid Va)}{P(F)} \tag{2}$$

The variables contributing the most to the overall risk have a greater negative impact as well as a greater probability of occurrence. These parameters define the criticality of a variable which is calculated using Eq. 3.

$$criticality = \left| impact * P(Va) \right| \tag{3}$$

Inferences and calculations using a bayesian network software and Eq. 2 and 3 indicate that overtopping is the most probable failure mechanism. Specifically, the most critical variable is the gantry crane which is affected by the low reliability of its components and also the frequent strong winds. A functional failure of the gantry crane is a cause of an non operational spillway which increases greatly the overtopping risk. Therefore, a rehabilitation of the gantry crane would be the most efficient specific risk-reduction measure.

The carrying of soil particles (*CSP*) is related to the internal erosion failure mechanism and is also one of the most critical component of the overall risk. The construction of a filtering berm at the downstream toe of the dam would provide filtered seepage exits (*UFE = no*) which will normally stop particle erosion (*P(CSP|UFE = no) = 0*) therefore reducing the internal erosion risk.

6.2 Priority rehabilitation work

The main objective of structural rehabilitation works is to reduce risk by decreasing the probability of failure. The most efficient options are directed to the most critical variables where the potential positive impact (see Eq. 2) would be maximum. However, rehabilitation measures always carry a cost. In most circumstances, a dam owner tries to optimize its investments by realizing in priority the measures offering the greater risk-reduction potential for the minimal cost. The priority index is defined by the potential positive impact of the rehabilitation option and its projected cost (see Eq. 4).

$$priority\_index = \frac{impact}{\cos t} \tag{4}$$

The rehabilitation of the gates and lifting mechanism will greatly increase the spillway operability (*SO = 3 gates*). It should include all the mechanical/electrical components of the spillway and not only the gantry crane since, in this case, all the equipment is in such a bad shape. As a first approximation, the effect of this intervention is translated as *P(F|SO = 3 gates)*. The increase of the spillway capacity will include the addition of a fourth gate and also the rehabilitation of the existing spillway. The effect of this option is translated as *P(F|O = no)*. The construction of a filtering berm on the downstream toe of the dam will provide filtration to every seepage exit. The effect on risk is calculated using *P(F|UFE = no)*. The construction of a parapet wall will reduce the risk of overtopping (*O*) but increase the maximum reservoir level (*RL*) thus affecting negatively the internal erosion risk. The evaluation of the net effect on overall risk is taken into account by creating a new variable (parapet wall *PW*) linked to *O* and *RL* and considering *P(increased RL|PW)* and *P(O|PW)* in the impact and priority index calculations.

The analysis has shown that the optimal risk-reduction measure is the construction of a filtering berm (option 3) followed by the rehabilitation of the existing spillway (option 1). The failure mechanism contributing the most to the overall risk is overtopping. This mechanism is mainly controlled by the spillway operation and more specifically by the gantry crane. However, the construction of a filtering berm is the optimal risk-reduction measure in technical and monetary terms and is to be realized in priority.

This analysis should be considered as an aid to decision covering the technical aspects of the problem which has also social, environmental and legal aspects. Also, rehabilitation measures can sometimes have negative net outcomes. For example, an increased spilling capacity would provide more safety for the structures but could endanger the population living downstream during the eventual spillway operation. This problem could be analyzed in an even more global way by adding consequence variables (which can include *population at risk*, *potential inundated area* and *available warning time*) to the bayesian network of Figure 2.

7. Conclusions

The presented concepts allowed the determination of the overall dam risk by taking into account the numerous interrelations between the failure mechanisms as well as the uncertainties and the expert judgements that are always present in the analyses. Risk was characterized without reference to an absolute interpretation of the probability of failure of the dam which can cause problems related to its interpretation and use. The probability of failure was rather considered as a comparison basis, or a common denominator, used for the determination of the relative importance of each uncertain element that could cause failure and to judge the potential effectiveness of structural or non structural risk-reduction measures.

The use of bayesian networks has contributed to solve an actual risk analysis problem for a project involving irrigation and flood protection works. It was possible to compare, according to the probability of failure being used as a common denominator, the geotechnical and hydrological risks related to the embankment dam as well as the risk related to the reliability of the electrical/mechanical components of the spillway. The analysis has allowed the identification of the factors contributing the most to the overall risk and the interventions to be realized in priority. The proposed multidisciplinary approach has contributed to the integrated analysis of essential infrastructures by concepts which consider risk in a more global and holistic way.

8. References

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