Canadian Consulting Engineering Awards 2015

Dam Safety
RISK SCREENING TOOL

April 23, 2015

CLIENT

Ontario

Ontario Ministry of Natural Resources and Forestry

SUBMITTED BY

HATCH and ONTARIO POWER GENERATION

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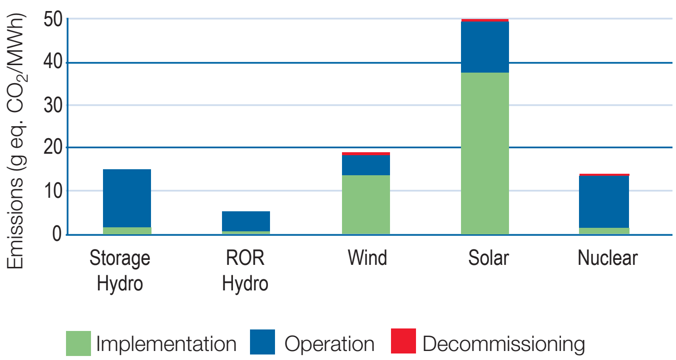
BACKGROUND

The public's perception of dams is complex, ranging from an appreciation of the benefits that arise from their existence (clean electric power from a renewable source, water for domestic and agricultural use, flood control, recreational /tourism, etc.) to an outright belief they should be eliminated because of concerns about green house gas emissions, fish passage and the risks that they present to public safety.

Environmental concerns can, and are, effectively dealt with through the use of fish ladders, and numerous authors have shown that the life cycle emissions associated with waterpower dams are less than what is generated by any other renewable power source. In addition, studies performed in Canada, and elsewhere, have determined that even emissions from large reservoirs decrease over time, reaching zero net emissions after about 50 years [Dones, R., Heck, T., and Hirschberg, S. Greenhouse Gas Emissions from Energy Systems, Comparison and Overview. Encyclopedia of Energy. Vol. 3, 2004]. Therefore, as dams age their benefits with respect to carbon emissions steadily increase.



Comparison of life cycle greenhouse gas emissions from various low emission energy sources

[Donnelly, C. R, A. Carias, M. Morgenroth, M. Ali, A. Bridgeman, and N. Wood. "An Assessment of the Life Cycle Costs and GHG Emissions for Alternative Generation Technologies." Paper presented at the World Energy Congress, Montreal, September 2010)]

Bahman Dam, Iran

Photo Credit /Google

Mizan Dam, Iran

Photo Credit /Google

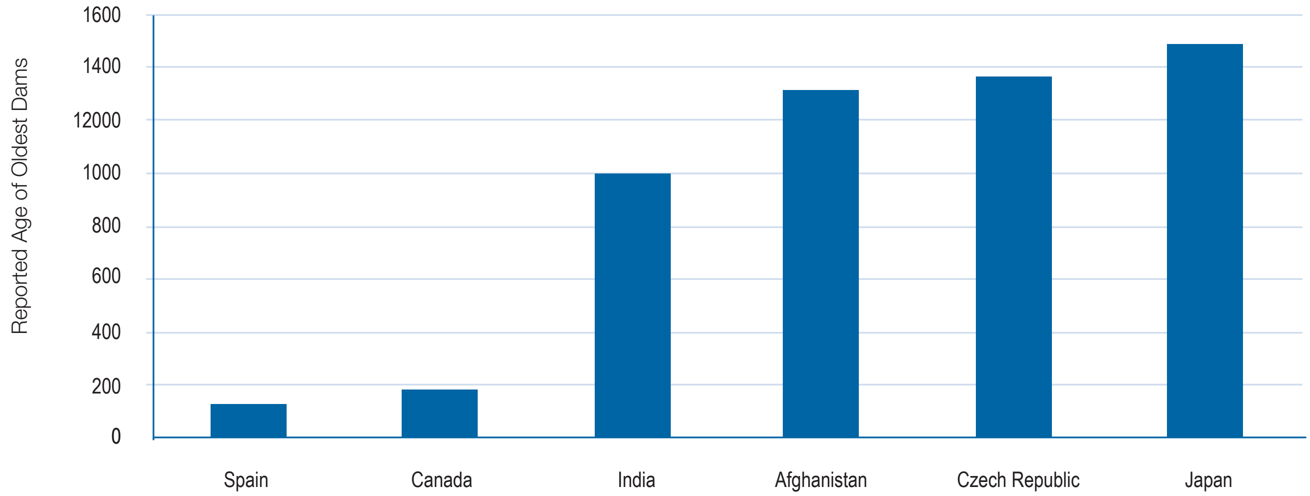
The public's perception of the environmental risks associated with water power dams is perhaps really an issue of public education. On the other hand, concerns with respect to the potential for a dam breach or the risk of mis-operation of a dam are entirely justified. While properly engineered and maintained dams can last 100's or even thousands of years—examples include the Bahman and Mizan dams, built in Iran in the 1st and 4th century A.D. respectively—dams can and do fail.

BACKGROUND

As increasingly larger dams are built closer to populated centers, it becomes even more important to better account for the risks a dam poses to the public and establish mechanisms to minimize these risks to "As Low As Reasonable Practicable".

Returning to the matter of public perception of dam safety risks, management of this perception is complicated by the fact that, in general, a single incident that results in a large number of fatalities is perceived as being much more problematic than cumulative losses arising from a series of smaller incidents, even if the cumulative impact of the smaller events far exceeds the major event. Clearly, any dam failure, whatever the cause, has the potential to be a catastrophic single incident in which many lives are lost.

With this perspective, the ability to assess and reduce dam safety risk is of growing importance worldwide. The development of a method to achieve this aim is something that makes the world a safer place.



Reported ages of oldest dam by country [ICOLD, Question No. 90 Upgrading of Existing Dams, Brazilia, 2009]

Project Outline

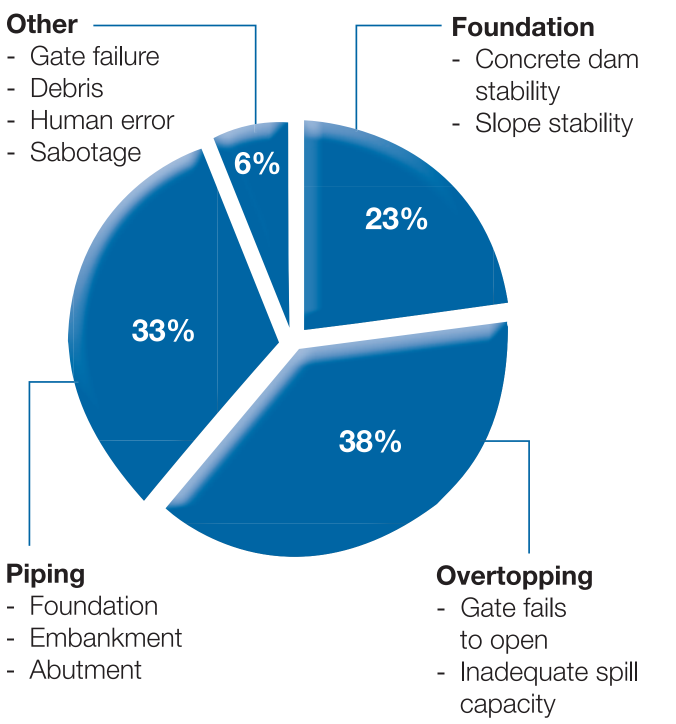
The Ontario Ministry of Natural Resources and Forestry (OMNRF) challenged a team of experts from Hatch and Ontario Power Generation (OPG) to develop a first-of-its-kind Dam Safety Risk Screening Tool capable of quantitatively defining the risks associated with dam failure. The resulting tool has significantly advanced government and private sector understanding of the benefits of risk-informed decision-making. It will reduce the potential for future dam safety incidents and will enhance the protection of Canada's infrastructure, population, and the environment.

Innovation

Traditionally, dam safety management uses a standards based approach. This is a de-facto management of risk achieved by applying a deterministic set of rules for dam design and operation. The drawback is that the assessments are confined to selected hazards that do not include all potential failure modes.

In recognition of this, OMNRF is exploring integrating risk-informed decision making into the province's dam safety program. The Ministry challenged a multidisciplinary team of dam safety experts from Hatch and OPG to develop a new tool capable of quantitatively assessing the probability and potential consequences of dam failure while exploring the individual and societal tolerability of these risks.

The first step involved is identifying the reasons dams fail. Based on research by various organizations, four general causes were identified: foundation, overtopping, piping and other.



General causes of dam failure

Using a variety of peer-reviewed empirical methods and proven mathematical/statistical approaches adapted for the evaluation of dam failure probability, a tool capable of quantitatively determining the probability of failure for all of the key dam failure modes in a transparent and scientific manner was developed.

The tool was then applied to 12 Ontario dams, six owned by OMNRF and six by OPG, each with different dam safety issues. The results were realistic and repeatable and offered significant value in identifying optimal ways to minimize dam safety risks.

This first-of-its-kind tool positions Ontario's engineering community and the OMNRF as global leaders in the field of dam safety. OPG, and the province's conservation authorities are already making use of the tool and it is expected to have wide-spread practical applications within the global dam safety community.

The components making up a dam and their associated failure mechanisms can be exceptionally complex, requiring the application of state-of-the-art and innovative methods. An overall rational and transparent method to quantitatively determine probability of failure estimates for all of the potential dam failure modes had never before been accomplished.

Module	Description	Basis of Estimate	Remarks
1	Failure of gate to open	Expert judgement	38% of failures
	Potential for overtopping	Standard hydrotechnical statistical analysis	
	PMF analysis	Statistical assessments	
2	Embankment dam piping	Empirical analysis	33% of failures
3	Embankment dam slope stability	Empirical analysis	Part of 23% of failures
4	Concrete dam sliding	Mathematical analysis using the capacity demand methodology	
5	Gate failure	Mathematical analysis using the capacity demand methodology	Part of 6% of all failures
6	Penstock failure		

Basis of the probability estimates

Methodology	Cost	Residual Risk	Description*
Risk assessment	< $1 million	2 x 10-5	Tolerable
Standards based review	> $5 million	4 x 10-4	Additional Risk Reduction Required

Comparison of the effectiveness of the standards based and risk assessment approaches for an example dam in Ontario

** Canadian Dam Association (CDA) Dam Safety Guidelines 2013*

Determining Failure Probability

Determining the Probability of Dam Failure Due to Overtopping

The approach taken to determine the conditional probabilities of overtopping failures needed to include an assessment of the capacity of the system to pass the flood, the probability of various floods occurring, and an understanding of the reliability and availability of one or all gates and one or all stoplog sluices and their state (open or closed). Issues such as the potential for debris blockage and operator error were also included in the assessment.

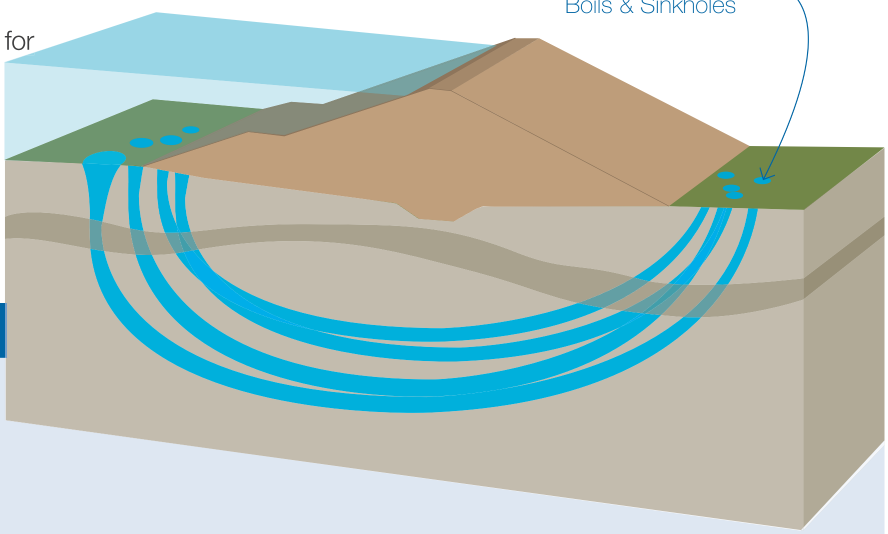
To supplement the statistical assessments the Hatch/OPG team developed a tool for the assessment of spillway (weirs, gates, and stoplogs) reliability, accounting for the ability of each of these components to pass flood events and the hydrological variability.

The aggregate probability due to overtopping for all combinations of season and discharge structure availability is then determined.

Probability of Embankment Dam Failure Due to Piping (Internal Erosion)

The tool makes use of an empirical methodology developed by the University of New South Wales that is based on the analysis of historic failures and accidents in embankment dams. Piping failure modes are assessed within the embankment, within the foundation, and at the boundary.

The method accounts for the average historic frequency of failure embankment dams by mode of failure. These historical averages are then modified based on the known characteristics of the dam under study, including factors such as dam zoning, filters, age of the dam, core soil types, compaction, foundation geology, performance, monitoring, and surveillance.



Failure Due to Piping (Internal Erosion)

The following steps are needed to assess the annual likelihood of failure of an embankment dam based on reference tables:

1. Determine the average failure frequency of the dam type based on its age and type of construction (P_e, P_f & P_{ef}).
2. Calculate embankment weighting factor, W_e, based on the details of the embankment construction.
3. Calculate the risk of foundation failure, W_f, below the embankment based on geotechnical information.
4. Calculate the risk of the embankment failing into the foundation, W_{ef}, based on the details of the embankment construction and the foundation.
5. The annual probability of failure by piping, P_p, is determined by $P_p = (P_e \times W_e) + (P_f \times W_f) + (P_{ef} \times W_{ef})$.

Probability of Dam Embankment Slope Failure

Research in 2008 (T.W. Lambe et al.) provided a method to correlate failure probability to the calculated factor of safety modified by factors that account for the quality of the embankment slope. This quality is based on three main factors:

- The quality of the design, including the investigations, testing, and analysis
- The quality of the construction of the structure
- The level of monitoring performed.

Each factor is assessed on a number of characteristics and assigned a weighting that is used to adjust average failure probabilities for embankment dams in order to estimate a failure probability specific to the structure under evaluation.

Probability of Concrete Gravity Dam Sliding Failure

The calculation of the probability of a sliding failure is calculated using the capacity-demand analysis method in which dam probability of failure is defined as occurring when the resistance (C) is less than the demand (D) using a technique adapted from the metallurgical industry by Hatch 15 years previously (Morgenroth et al., 1998). The principle of calculating the probability of failure for a given component can be expressed as a Warner Diagram.

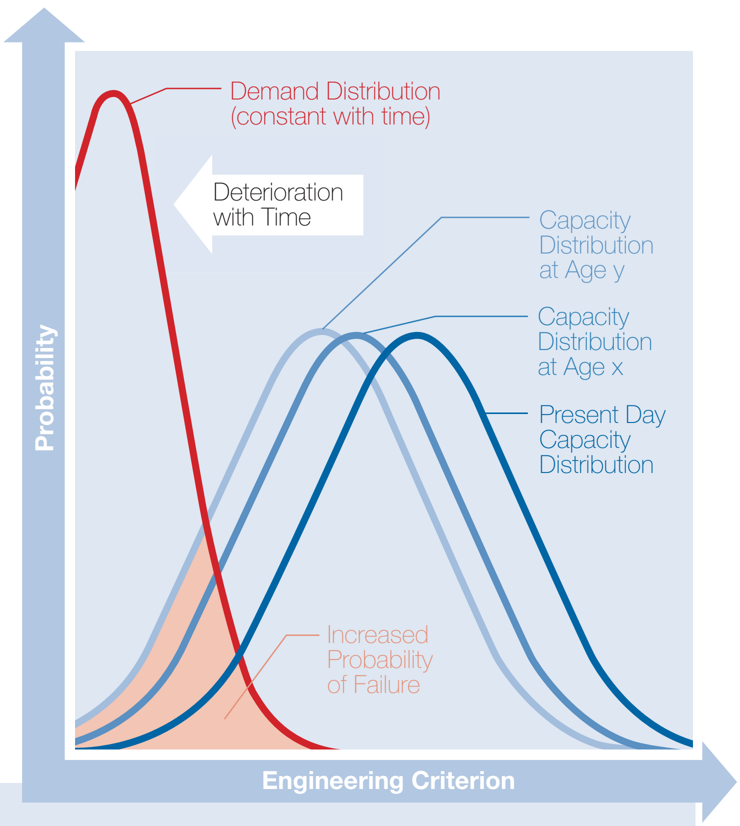
The probability distributions can be established on the basis of a determination of the mean and standard deviation of the random variables which, in the case of a concrete dam sliding instability problem, include the density of the concrete, reservoir and tailwater levels, shear resistance, ice loadings, peak ground acceleration, silt loads, uplift, and the density of the concrete.

Based on the aggregated mean and standard deviation of all of these variables, probability distributions can be determined and the overall probability of failure can be mathematically calculated.

Gate Structural Failure and Penstock (Pipe) Failure

The probability of occurrence of these types of failures is also assessed using the capacity-demand methodology as described previously.

The methodology accounts for uncertainty in such factors as the thickness of the steel skinplate, the spacing of stiffeners, and headwater levels to establish a probability-density function. Similar to what was described for sliding failure of a concrete gravity dam, this probability density function is integrated with the cumulative probability function of capacity to yield the likelihood of failure.



Warner Diagram

The capacity-demand methodology is not concerned with the chance of failure at a specific, given value of loading; instead it looks for an overall evaluation of the total chance of failure. This is done by integrating the function over all values of the selected engineering criterion to produce a single, quantifiable value for the total mean probability of failure.

Social and Economic Benefits

As dams age, owners face increasingly difficult decisions about the ways in which finite financial and human resources should be allocated to ensure their continued safe operation. Without such investments, dam failure is not only a possibility but can be an expected consequence.

The goal of a properly managed dam safety program is to reduce the risks to the public, property, and the environment that are associated with a dam failure.

However, decisions on the extent and timing of the often significant expenditures required to maintain, rehabilitate, or, in some cases, decommission a dam are seldom clear-cut because a dam failure usually occurs as a result of an uncertain chain of events, with the chance of any individual event happening along the chain conditional on all of the other events preceding it occurring first.

A quantitative risk assessment allows the failure modes that constitute the highest dam safety risks to be defined and provides a means to evaluate the optimal measures to reduce these risks to tolerable risk thresholds in a transparent and structured manner. As a result, the application of this risk-based methodology and tool addresses economic goals, in combination with social safety objectives. This avoids expenditures on perceived dam safety deficiencies that, in fact, present little risk to the public. Indeed, during the validation of the tool it was shown that traditional methods of assessing dam safety would have resulted in expenditures of many millions of dollars without any appreciable risk reduction due to the fact that the most significant risk at this example dam could not have been identified using standard methods.

Application of this new tool will benefit Canada's already enviable safety record, reducing the potential for future dam safety incidents, such as that which occurred in 1996 as a result of the Saguenay flood, thereby enhancing the protection of Ontario's infrastructure, population, and the environment by helping to identify and prioritize appropriate risk reduction measures. In the years to come it is anticipated that this important new tool will be embraced globally, with the inherent benefits that will arise from safer dams worldwide.

Environmental Benefits

In the spring of 1889, the largest dam failure incident in North American history took place. Following a period of heavy rains, the 22-metre-high South Fork dam, located just upstream of Johnstown, Pennsylvania, broke, releasing over 20 million cubic yards of water and debris into a narrow valley, killing more than 2,200 people. Over a century later, also following a period of unprecedented rainfall, Canada's most significant dam safety event took place during the devastating Saguenay floods of 1996. In this case, eight dams were overtopped, significant and long term environmental losses occurred and, tragically, seven lives were lost. In addition, thousands were displaced making this event one of the largest natural disasters in Canadian history. This event, and others like it, highlights the uncertainties associated with dam safety and the consequences of "getting it wrong".

Photo Credit / LE GRAND MAGAZINE

Saguenay Flood, July 21, 1996

As the use of the Dam Safety Risk Screening Tool becomes common practice within the dam safety industry, risk-informed decision-making will provide another means to further reduce the potential for a reoccurrence of major dam safety incidents and the consequences that these incidents have on the environment and society as a whole.

Meeting Client's Needs

OMNRF challenged Hatch/OPG to accomplish something that had never been done before:

1. Establish a risk-based methodology to quantify the probability of failure of key dam failure mechanisms and the aggregate risk these failure modes present to the individual and society.

2. Define guidelines and criteria for evaluating the tolerability of the aggregate risk to individuals and society.

3. Devise a methodology to evaluate potential remedial measures to reduce the risk of dam failure is tolerable levels in a manner such that the costs of risk reduction are not disproportional to the risk reduction they provide, and the result is acceptable to the public.

4. Develop a computer-based set of applications that enable expert analysts to apply the above-stated methodologies.

5. Apply the tool to six OMNRF dams and six OPG dams in Ontario to prove the concept and illustrate the application of the methodology.

The Hatch/OPG team met and exceeded each of these mandates by developing a tool that can quantitatively determine the probability of failure of all of key dam failure modes.

In a parting message to the OMNRF Dam Owners' Advisory Committee on its many accomplishments, committee chair Jennifer Keyes specifically identified the Dam Safety Risk Screening Tool, as well as the training program developed by the Hatch/OPG team on its use, as one of the accomplishments the committee was most proud of.

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