The development of a risk screening indexing tool for prioritizing dam safety remedial works

La mise au point d'un outil d'indexation des risques pour prioriser les travaux de réparation de la sécurité des barrages

Przemyslaw A. Zielinski[1], *Pra`mod* Narayan[2], *C*. *Richard* Donnelly[*3], *Eric* Halpin[4], *Jonathan* Quebbeman[5], *Halla Maher* Qaddumi[6], *Chabungbam Rajagopal* Singh[6], *Satoru* Ueda[6], and *Marcus* Wishart[6]

[1]HYDROSMS Inc., Toronto, Ontario, Canada
[2] Central Water Commission, Ministry of Jal Shakti, Govt. of India, India
[3]Hatch, Niagara Falls, Ontario, Canada
[4]Halpin Consulting, Stafford, VA, USA
[5]RTI International, Fort Collins, CO, USA
[6]The World Bank Group

Abstract. Under India's DRIP program over 5,000 large dams are to be rehabilitated in accordance with modern dam safety standards. In order to prioritize the rehabilitation works for such a large number of dams, India's Central Water Commission, needed a risk screening tool to allow for a portfolio risk screening. The tool was developed by simplifying sound principles of risk analysis followed by a comprehensive validation process. The application of the tool is relatively easy and the process of generating risk index for a single dam may take as little as few hours to 1-2 days, depending on the availability of data and personnel familiar with the dam making the tool ideal for helping to prioritize dam safety remedial projects for India's dam safety program and for other large portfolio's around the world.

Résumé. Dans le cadre du programme DRIP de l'Inde, plus de 5 000 grands barrages doivent être réhabilités conformément aux normes modernes de sécurité des barrages. Afin d'établir un ordre de priorité pour les travaux de réhabilitation d'un si grand nombre de barrages, la Commission centrale de l'eau de l'Inde avait besoin d'un outil d'évaluation des risques pour permettre un contrôle des risques en portefeuille. L'outil a été développé en simplifiant des principes solides de l'analyse des risques

[*] Corresponding author: Richard.donnelly@hatch.com

suivis d'un processus complet d'action valide. L'application de l'outil est relativement facile et le processus de génération d'un indice de risque pour un seul barrage peut prendre de quelques heures à 1 ou 2 jours selon la disponibilité des données et du personnel connaissant bien le barrage rendant l'outil idéal pour aider à prioriser les projets de réparation de la sécurité des barrages pour le programme de sécurité des barrages de l'Inde et pour d'autres grands portefeuilles à travers le monde.

1 Introduction

India ranks third globally with 5,334 large dams in operation and 411 under construction [1] and several thousand smaller dams. In 2012 India, with the assistance of the World Bank, initiated the Dam Rehabilitation and Improvement Project (DRIP) aimed at institutional strengthening of India's dam safety program as well as at improving safety and operational performance of selected dams. The project originally considered the rehabilitation and improvement of 223 large dams in the states of Kerala, Madhya Pradesh, Odisha, and Tamil Nadu but was later joined by Karnataka, Uttarakhand (UJVNL) and Damodar Valley Corporation (DVC) increasing the number of dams to 257.

DRIP is now entering a second phase (DRIP-2) which is to be followed by DRIP-3. The objective of these programs is to address the rehabilitation needs of India's entire portfolio of large dams. The Central Water Commission (CWC) of India guidelines for assessing and prioritizing dam safety risks [2] propose a risk-informed dam safety program aligned with the requirements of India's pending Dam Safety Bill that was approved by India's lower house in 2019. The Bill requires risk assessment studies be carried out for all large dams in India. Given the sheer size of the portfolio in the DRIP-2 and # programs, a need to develop an effective prioritization tool was identified in order to achieve the objective of making risk informed decisions in an effective and timely manner.

This paper outlines a prioritization scheme together with an Excel spreadsheet tool that was developed by the CWC to provide a preliminarily identification of high priority dams that should move into a second tier Dam Safety Risk Assessment. The tool will inform implementation of DRIP-2, with risk estimation allowing for a more transparent and justified decision-making process for potential dam safety investments.

2 Background

The objective of the prioritization scheme was for India's dam safety engineers to conduct an initial risk profile of the entire portfolio of large dams in the country. Considering the size of the portfolio, limited availability of data and the urgency in completing the task within reasonable time limits the decision was to develop a risk indexing scheme allowing to establish a risk-based ranking order of all dams in the portfolio in order to provide necessary and sufficient information for the selection of dams that are the candidates for more detailed risk assessment.

Development of any complete risk measure involves calculating a probability distribution over the range of possible consequences. For large portfolios such task would require extensive effort in terms of time, technical resources and data. Therefore, an alternative in the form of a risk index A was selected instead. A risk index is a simplified characterization of the probability distribution over the range of possible consequences summarizing the actual risk via a real or ordinal number, letter, category or colour. Risk indexing schemes can provide a useful way of characterizing risk at the early stages of a risk assessment and can inform the portfolio owner about how the risk of any dam relates to the risk presented by other dams in the portfolio.

3 The method

Simplification of any methodology begins with the formulation of a complete and full method. The tool methodology was developed following the general risk concept as described in ICOLD [3]. The Bulletin considers the "bow-tie" model (Figure 1) as a powerful tool which combines Fault Tree Analysis and Event Tree Analysis to provide full characterization of risk resulting from dam failure.

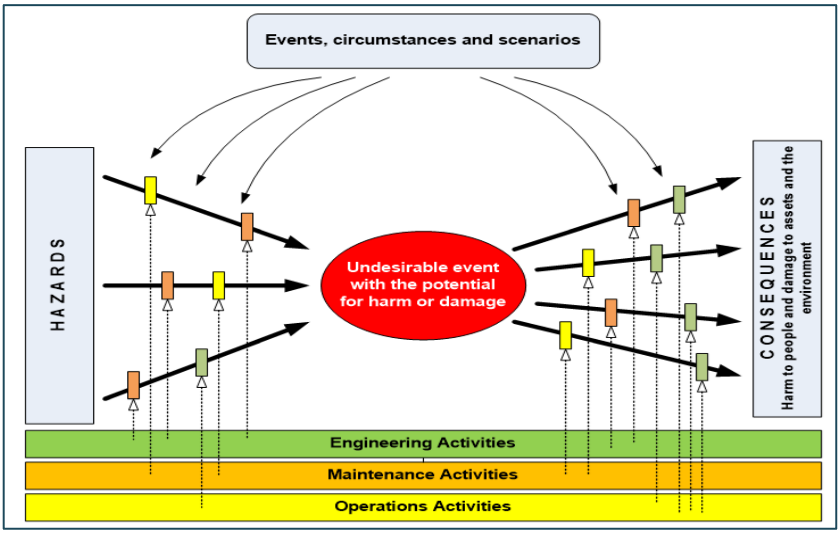

Fig. 1. The Bow-tie model.

The bow-tie model characterizes each failure scenario with the help of a fault tree which comprises the left-hand side of the bow-tie. The right-hand side based on an event tree accounts for adverse consequences caused by the dam failure. Therefore, the bow-tie model provides complete structure for the full characterization of dam failure risk defined and understood as the function of the probability of dam failure (P_F) and the magnitude of adverse consequences (C). In the simplest form this characterization of risk can be expressed as the expected value of risk.

$$R = P_F \times C \tag{1}$$

$$P_F = P(\text{breach due to loss of strength}) + \text{P(breach due to overtopping)} = P_L + P_O$$

$$P_L = P(\text{Loss of stability}) + \text{P(Loss of durability)} + \text{P(Loss of water tightness)} = P_{LS} + P_{LD} + P_{WT}$$

$$P_O = \text{P(Load > design discharge capacity)} + \text{P(Load > Installed discharge capacity)} + \text{P(discharge capacity unavailable)} = P_{DC} + P_{IC} + P_{UC}$$

$$P_{LS} = P_{L,1} + (1 - P_{L,1}) \times P_{L,2} = P_{L,1} + P_{L,2} - \text{and since } P_{L,1} \times P_{L,2} \text{ is much smaller than } P_{L,1} \text{ and } P_{L,2}$$

For risk screening purposes such full development of fault and event tree in the bow-tie model is often not only unnecessary but, in many cases, not feasible due to the time, cost and effort limitations. For the risk screening scheme described in this paper the fault tree technique was developed for only the global and the secondary level failure modes as illustrated by a diagram in Figure 2. The fault tree represents the fragility of the dam (its vulnerability characterized by the likelihood of failure). The diagram can be applied to carry out the calculation of the probability of dam failure (P_F) as illustrated in Figure 3.

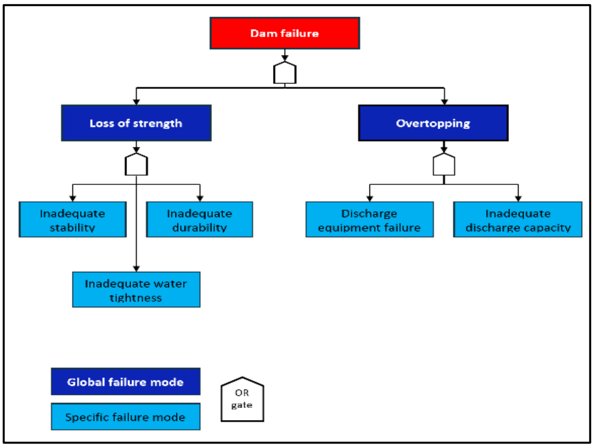

Fig. 2. Fault tree.

The product term can be eliminated and P_{LS} can be approximated as $P_{L,1} + P_{L,2}$. Similar simplifications applied to calculation of probabilities of other failure modes leads to the following formula:

$$P_F = P_{L,1} + P_{L,2} + P_{L,3} + P_{L,4} + P_{L,5} + P_{L,6} + P_{O,1} + P_{O,2} + P_{O,3} \quad (2)$$

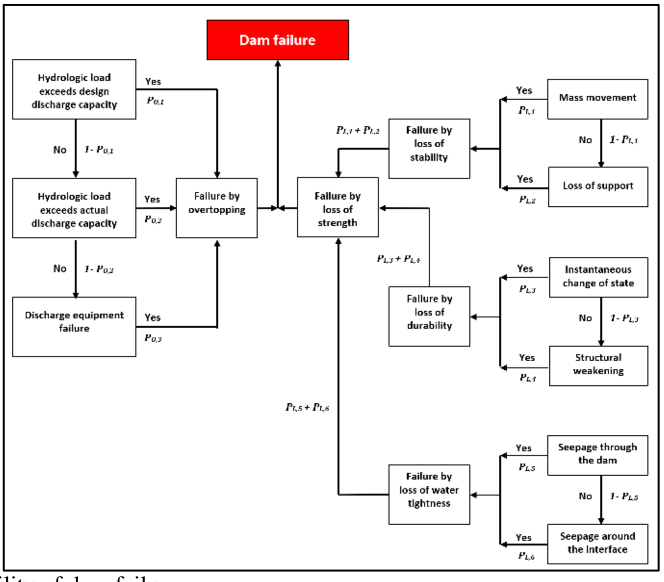

Fig. 3. Probability of dam failure.

Therefore, the simplification process results in approximation of the failure probability by a simple summation of probabilities of all considered failure modes. Estimation of the values of all these probabilities requires in-depth studies involving detailed engineering and probabilistic analyses. Therefore, for screening purposes, a simplification was needed. For the index tool, this involved replacing quantitative estimates of probability by their proxies in the form of scores reflecting relative values of respective probabilities. Development of the event tree on the right-hand side of the bow-tie requires the information about potential consequences of dam failure which typically is not available at the screening-level risk assessment Therefore, for the risk screening purposes, the analysis can be simplified by replacing the event tree analysis with the information about the potential hazard to the downstream area. the hazard potential to downstream using it as a proxy for characterization of consequences.

4 Tool structure

The risk index RI is defined as:

$$RI = FI \times PH \tag{3}$$

Where:

FI - the score for the Fragility Index of the dam,
PH - the score for the Potential Hazards associated with the dam failure.

The Fragility Index is composed of three categories. 1. Technical Characteristics (TC) largely related to the design of the dam, 2. Existing Conditions (EC) relating to the current condition of the dam and 3. Safety Plans (SP) relating to the measures used to maintain the safety of the dam. Each of these three categories contains several fragility factors as shown in Table 1.

$$FI = TC + EC + SP \tag{4}$$

$$TC = \sum_{i=1}^{Ntc} Stc_i \qquad EC = \sum_{i=1}^{Nec} Sec_i \qquad PH = \sum_{i=1}^{Nsp} Ssp_i$$

Stc_i is the score for fragility factor i in the TC category,
Sec_i is the score for fragility factor i in the EC category,
Ssp_i is the score for fragility factor i in the SP category,
Ntc, Nec and Nsp are the numbers of risk factors in categories TC, EC and SP, respectively.

The risk tool as described above meets the requirement of (i) positive homogeneity which ensures that n-fold increase in consequences results in n-fold increase of risk index, and (ii) additivity which implies that if two events are combined, the risk of these two events equals the sum of the risks of each event. Multiplication of the fragility index FI by the potential hazard PH ensures that the increase/decrease in risk index is proportional to the increase/decrease of PH as required by the first of the requirements. Aggregation of the fragility index term by adding the scores for individual fragility factors ensures additivity as required by the second property Translation invariance is absent in the risk indexing tool.

However, since the objective of the indexing scheme is to establish relative and not absolute risk ranging of the entire portfolio itis not necessary.

Table 1. Three Fragility categories and associated fragility factors.

	Technical characteristics (TC)		Existing conditions (EC)		Safety plans (SP)
1	Dam age	1	Seismic design	1	Design documentation
2	Inflow Design Flood	2	Installed flow control equipment	2	Operation & Maintenance Manual
3	Seismic zone	3	Flow control equipment condition	3	Emergency Preparedness Plans
4	Landslides, GLOF's, LDOF's and debris flow	4	Presence of backup power	4	Organization, staffing and qualifications
5	Length	5	Access to site	5	Safety inspections, monitoring and reporting
6	Conduits	6	System operation	6	Dam Safety Reports, analysis and interpretation
7	Filters	7	Concrete gravity structure	7	Follow-up actions
8	Foundation and abutments	8	Spillway structure		
		9	Masonry structure		
		10	Embankment, abutments and foundation		

4.1 Fragility Factors

The selected fragility factors are listed in Table 1.

Mapping of relationships between specific failure modes and individual fragility factors (with their corresponding probabilities leading to dam failure) in relation to the hazards and failure modes is displayed in Table 2.

Inspection of Table 2 illustrates how the fragility scores serve as the proxies for the probabilities displayed in Figure 3. Each of the failure modes included in the tool has the corresponding probability of failure in the third row (for example probability PL,1 for mass movement in column 3). √ signs in the cells of column 3 indicate which of the fragility factors can increase the likelihood of mass movement occurring. Increasing the scores for the factors serve as proxies for increasing probabilities of occurrence.

A score is required for each factor, but the magnitude of scores needs to vary based on the relative significance. Determination of weights (scores) within the tool was carried out using an expert elicitation process via pairwise comparisons based on Saaty's Scale of Relative Importance technique [4]. The process included elicitation of technical experts with a wide variety of dam safety backgrounds from the CWC, State Dam Safety Organizations, Dam agencies, as well as the World Bank. Scores were assigned with relative weight based on the level of importance relative to other criteria, but there is disparity between different experts. Figure 3 shows normalized histograms of scores for sub-criteria in the EC category, where the median selected value is labeled.

Table 2. Relationship between fragility factors and failure modes.

		Inadequate stability		**Inadequate durability**		**Inadequate water tightness**		**Overtopping**		
		Mass movement	**Loss of support**	**Instantaneous change of state**	**Structural weakening**	**Seepage through the dam**	**Seepage around the dam**	**Inadequate discharge capacity**		**Discharge capacity**
								design	**installed**	**unavailable**
		$P_{L,1}$	$P_{L,2}$	$P_{L,3}$	$P_{L,4}$	$P_{L,5}$	$P_{L,6}$	$P_{O,1}$	$P_{O,2}$	$P_{O,3}$
1	2	3	4	5	6	7	8	9	10	11
TC-1	Dam age	√	√	√	√	√	√			√
TC-2	Inflow Design Flood							√		
TC-3	Seismic zone	√	√	√	√	√	√	√		√
TC-4	Landslides, GLOF's, LDOF's and debris flow	√	√	√	√			√	√	√
TC-5	Dam length					√	√			
TC-6	Conduits				√	√				
TC-7	Filters	√	√	√	√	√	√			
TC-8	Foundation and abutments	√	√	√	√		√			
EC-1	Seismic design	√	√	√	√	√	√	√		
EC-2	Installed flow control equipment								√	
EC-3	Flow control equipment condition									√
EC-4	Backup power									√
EC-5	Access to site									√
EC-6	System operation								√	
EC-7	Concrete gravity structure		√		√			√		
EC-8	Spillway structure	√	√		√			√	√	√
EC-9	Masonry structure		√		√	√		√		
EC-10	Embankment, abutments and foundation	√	√	√	√	√	√			
SP-1	Documentation	√	√	√	√	√	√	√	√	√
SP-2	Operation & Maintenance Manual	√	√	√	√	√	√			√
SP-3	Emergency Preparedness Plans									
SP-4	Organization, manpower and qualifications	√	√	√	√	√	√	√	√	√
SP-5	Safety inspections, monitoring and reporting	√	√	√	√	√	√			√
SP-6	Dam Safety Reports, analysis and interpretation	√	√	√	√	√	√		√	√
SP-7	Follow-up actions	√	√	√	√	√	√	√	√	√

As is shown in Figure 4 the elicitation process resulted in generally good agreement between the experts with respect to the relative importance of each of the selected fragility factors.

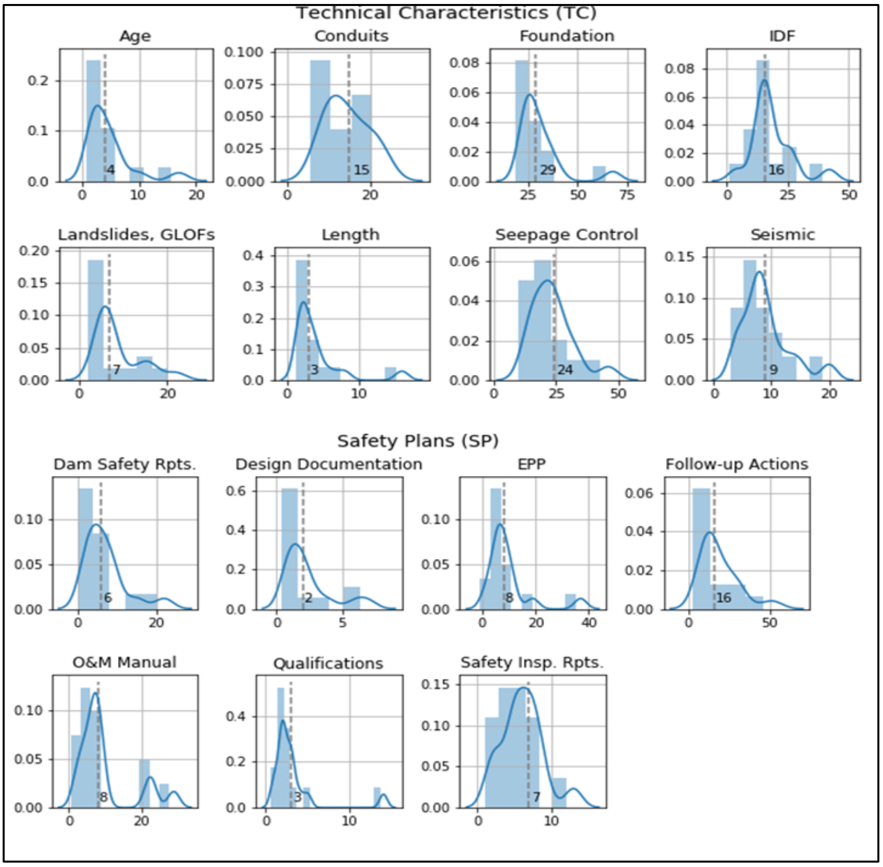

Fig. 4. Elicitation of Relative Importance Between the Fragility Factors in the INDIA Tool.

4.2 Potential Hazard Factors

Table 3. Potential Hazard factors.

1	Loss of life
2	Environmental impact
3	Socio-economic impact

In developing the scores, both components of the Risk Index RI were balanced with the Fragility Index FI and Potential Hazard Index (PH) each having overall maximum scores of 500. The results of the pairwise comparison provided larger weight to the Existing Conditions component of the FI which was allotted a maximum score of 346. In comparison Technical Characteristics component was allotted a maximum score of 104. Safety Plans were determined to be of lessor importance, representing 10% of the maximum Fragility Index with a maximum score of 50.

Both Technical Characteristics and Existing Conditions scoring is dominated by factors which are linked to the most frequently occurring failure modes, namely overtopping, internal erosion and structural issues. The scores for Safety Plans attach the highest importance to the timely implementation of dam safety follow up actions.

The distribution of weights for each individual fragility factor differed depending on the nature of the factor itself, available information and the specific features of dams in India. An example distribution of weights for a concrete gravity dam is displayed in Figure 5. The maximum scores for four categories of dam existing condition (good, adequate, poor and very poor) are respectively 0, 3, 12 and 26). The user selects which requirements or conditions listed in columns 1, 3, 5 and 7 are met and the score is interpolated automatically. In order to preserve engineering judgement and specific knowledge, if some of the conditions or requirements as described in the table do not accurately reflect the actual conditions, the user can make manual adjustments to the final score.

Concrete Gravity Dam (EC-7)							
1	2	3	4	5	6	7	8
GOOD – max score	0	ADEQUATE – max score	3	POOR – max score	12	VERY POOR - max score	26
Requirements to be met				Exisitng conditions			
		Cracking					
Dam is in good overall condition. No signs of distress		1. No major structural cracking		1. Deep cracking		1. Extensive in length and/or width and worsening	
				2.Numerous new shallower cracks		2. Uplift pressures are exceeding design assumptions	
				3. Presence of some structural cracks		3. Multiple structural cracks	
		Foundation drains					
		2. Fully functional and adequate for the designed foundation seepage		4. Operable but not functioning as designed, flows are reduced		4. Inoperable	
		Concrete deterioration					
		3. Normal, age-related deterioration of concrete is in progress, but distress is not considered to adversely impact performance or risks in the next 10 years		5. Rust staining of the concrete indicates the contact of water with embedded reinforcing steel		4. Continuing and increasing deterioration of concrete mass with numerous locations where large portions of reinforcing bars are visible	
		Wet surfaces					
		4. Localized moist or wet surfaces on concrete		6. Numerous moderate moist or wet surfaces on concrete		5. Large number of extensive moist or wet surfaces on concrete	
		Leaching					
		5. Only few signs of leaching		7. Numerous signs of leaching		6. Number of new leaching locations steadily increasing	
		6. No signs of any substantial concentrated leakage through or along concrete monoliths		8. Significant concentrated leaching in previously identified locations		8. Large concentrated leaching in previously identified locations	1
				9. New moderate leaching in new locations		9. New substantial leaching in new locations	
		7. Leakage rates are stable		10. The rates slowly but steadily increasing		10. The rates rapidly increasing	
		Movement/misalignment					
		8. No differential misalignment, or displacement		11. Signs of only some, limited differential movement and/or misalignment		11. Clear and numerous signs of movement within and between monoliths	1
						12. Development of offsets observed in joints and constructed features	
				12. Instrumentation begins to show adverse trends in alignment, uplift pressures, and leakage		13. Instrumentation readings indicate accelerating movement and pressure trends	
		Rock formations					
				13. In the abutment and foundation show some signs of distress including changing leakage patterns, minor movement, and deterioration		14. Numerous indications of weakening rock foundation and abutments that require remedial stabilization	
						15. Erosion and loss of foundation at the toe	
		Anchors					
						16. Some anchors have failed due to deterioration.	
	0	Total	0	Total	0	Total	2

Step 1 - exercising professional judgment

Enter number 1 into cells in columns 2, 4 ,6 and 8 if corresponding requirement is met or the corresponding condition is present.

Step 2 - exercising professional judgment

The suggested score is calculated assuming that the importance of individual requirements and conditions is the same or similar and consequently the interpolations is based on the number of conditions present or requirements met.

If the significance of some of the requirements or conditions is greater than others, the score can be adjusted manually. The reasoning behind the need for manual adjustment must be explained.

Step 3

Enter the adjusted score as the **FINAL SCORE** into red shaded cell

Fig. 5. Guidance on distribution of weights for concrete gravity dam.

5 Tool validation

5.1 Comparison with case studies

The tool was first evaluated by conducting pilot screenings on several case studies. These included examples from North America, South America, the Middle East, and India representing a wide range of dams including dams with a variety of failure modes, dams presenting a range of potential hazards, dams with a variety of types and sizes, dams with a variety of information available. As illustrated in Figure 6, the results of screenings for the pilots made sense and agreed with the current degree of belief in risk associated with these projects that was developed from other methods. That is, projects understood to be high, moderate, and low risks contain risk indexes that are individually and collectively in these same categories. The results also provide reasonable relativeness between dams in the pilot study. The INDIA tool was found to have sufficient integrity to risk prioritization into three broad groups: high priority (red), moderate priority (yellow), and low priority (green)[1] .

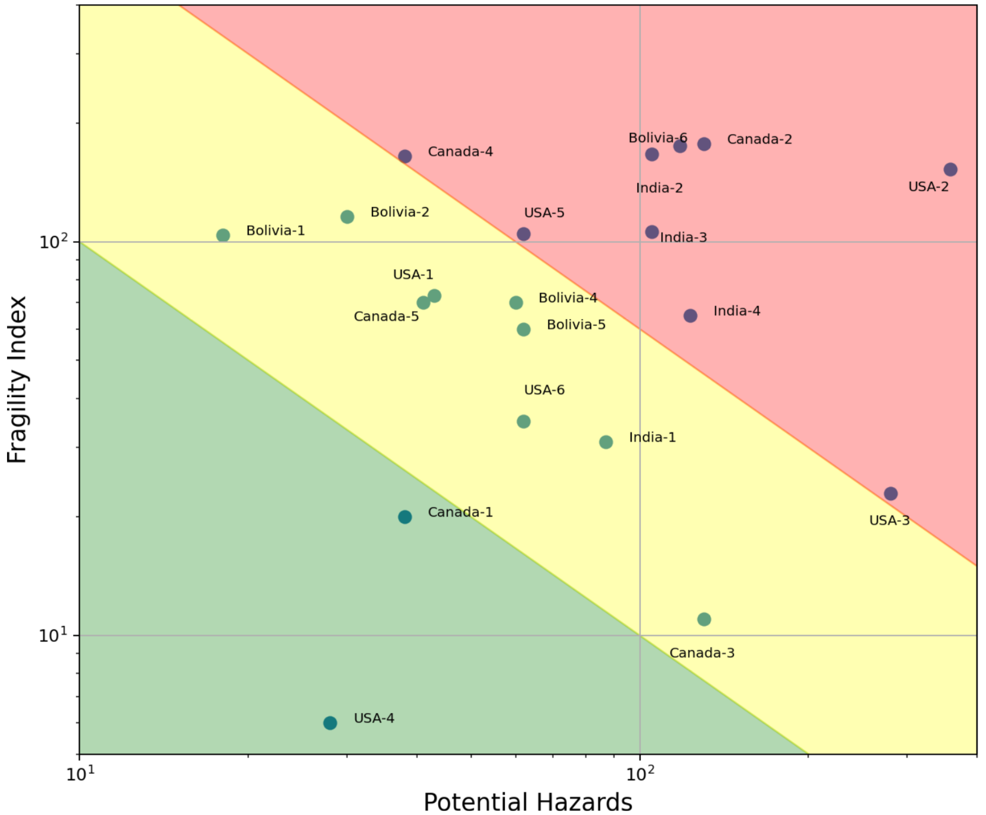

Fig. 6. Results of Screening of Case Example Dams.

[1] The prioritization zones depicted in Figure 4 are still under development and can be expected to change as the tool continues to be used.

5.2 Calibration to World Average Failure Modes

Many authors have studied incidents of dam failure. While the actual reasons a dam fails are often a function of many complex factors that may act individually or in combination the key failure mechanisms are generally attributed to one or a combination of the key failure modes illustrated in Figure 7.

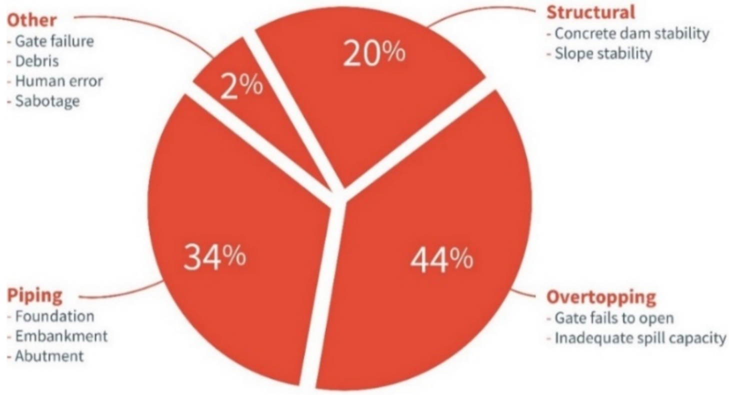

Fig. 7. Key Dam Failure Modes (ICOLD, update of Bulletin 99, in press) [5].

In the INDIA tool, the maximum scores that were developed for each of these fragility factors can be roughly mapped to one of the key dam failure modes that have been identified for the world's dams as is illustrated in Table 4[2].

Table 4. Mapping of key fragility Factors from the INDIA tool to key failure modes.

Fragility Factor	Failure Mode		
	piping	overtopping	stability
TC			
Age			X
IDF		X	
Seismic Zone			X
GLOFs		X	
length			X
Conduits	X		
Filters	X		
Foundation	X		
EC			
Seismic Design			X
Capacity		X	
Condition		X	
Backup Power		X	
Access		X	
Concrete Dam			X
Spillway			X
Masonry			X
Embankment	X		
System operation		X	

[2] It is recognized that dam failure is usually the result of several complicated and interlinked processes. However, for the purposes of validation of the tool, the fragility factor that was the most common cause of a particular failure mode was selected for validation purposes.

In calibrating the INDIA tool, the selected maximum scores for each of the fragility factors were calibrated against world averages for failure to help ensure that tool correctly assigned appropriate total weight to key failure modes that govern the overall risk an individual dam may present. The results as illustrated in Figure 8 show that good agreement was reached between the weighting factors assigned to each of the individual risk factors and world averages for failure mode frequency.

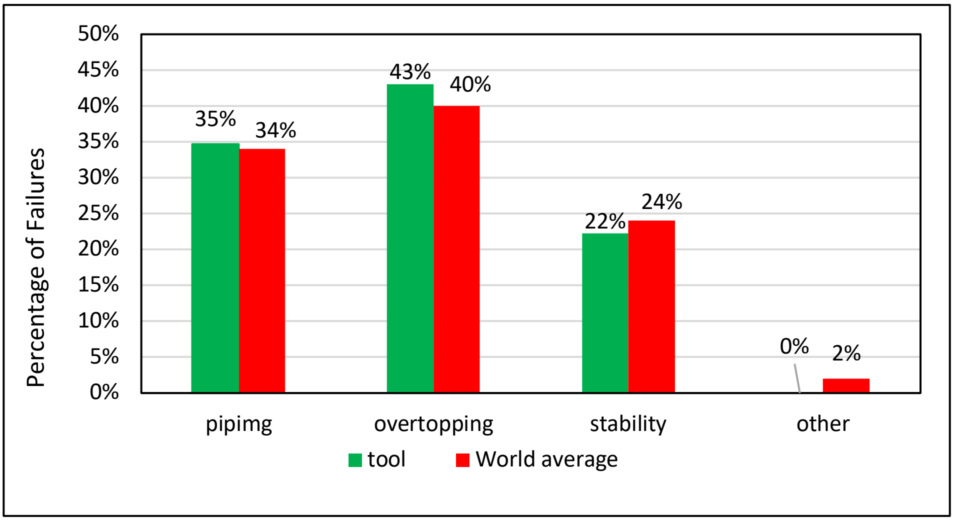

Fig. 8. Comparison of mapped failure modes in the tool with world averages.

6 Conclusions

Risk-informed decision making in dam safety does not have a long history of applications around the world but the demand for the analytic methods and tools supporting various kinds of dam safety risk assessments is constantly growing. While there is a consistent progress in improving existing analytic techniques and developing new methods the area of risk screening has not received the same attention as semi-quantitative and full-scale quantitative risk assessment. While the development of a risk screening method may seem to be a relatively simple task, developing a tool that provides consistent and reliable results requires considerable thought. What typically users need is a method or a tool meeting the time and efforts constraints in applications without loosing the credibility and with providing high level of confidence in application outcomes.

The tool presented in this paper meets both criteria. It was developed by simplifying sound principles of risk analysis and then thoroughly validated and verified. The application of the tool is relatively easy and the process of generating risk index for a single dam may take as little as few hours to 1-2 days, depending on the availability of data and personnel familiar with the dam making the tool ideal for helping to prioritize dam safety remedial projects for India's dam safety program and for other large portfolio's around the world.

Acknowledgments

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