BC Hydro’s Dam Safety Program and Risk Management Processes

Stephen Rigbey  Director, Dam Safety, BC Hydro
BC Hydro Overview

COMPLEX INFRASTRUCTURE

- 80 dams at 41 sites
- 31 hydroelectric facilities
  - ~ 9500MW installed currently
  - 1100 MW started construction
- 3 thermal generating plants
- Off-grid diesel stations
- 18,500 kilometers of transmission lines

Provincial ownership, but international implications
Concrete Gravity Dam

BC Hydro has 19 Major Concrete Gravity Dams:
Aberfeldie
Buntzen, Clayton Falls
Clowhom
Comox
Eko
Elliott
Falls River
Ladore
Peace Canyon
Puntledge Diversion
Quinsam Diversion
Quinsam Storage
Ruskin
Seton
Seven Mile
Spillimacheen
Stave Falls
& Whatshan
Large Embankment Dams

WAC Bennett
183 m high; 2 km crest length
Volume = 44 million m$^3$

Large by height; volume
Mica
243 m high
Consequences – Extreme category

Columbia River: breach at Mica Dam
- flood reaches US border in 22 hrs
- peaks at 48m above river bank the next day
  Flooding all the way to Portland
  >>> 10,000 people
  US Nuclear Plant

Fraser River: breach at La Joie, Terzhagi
still about 10,000 people at risk

All BC rail and road transportation routes
All Power interconnects
Issues Database and Vulnerability Index

Deficiencies

  Actual – known to exist, measureable

  Potential – require further investigation

Normal Conditions

Unusual Conditions
  flood
  seismic
Vulnerability Index -

Risk = Probability of Failure x Consequence

\[ \text{Vulnerability Index} \ (AD) = 10 \times \sqrt[3]{(\text{Magnitude of "Concern"})} \times (1 - (0.1 \times \ln(1/AEF))) \]
Vulnerability does not equal Risk

Developed simply as a way to track and prioritize issues
Does not justify need/urgency

NOT a robust method to track risk

Different consequences in many cases
Different levels of residual risk not quantified
Quantifying the issues we’re dealing with...

Combination of increasing knowledge (positive) and deteriorating conditions (negative)

Known deficiencies
Potential Deficiencies

Coursier decommissioning
New Coquitlam Dam
Seven Mile upgrades
Elsie rebuild
Quarterly Reporting Metrics

Vulnerability Index

For comparison against investigations and capital plans
Quarterly Reporting Metrics

F11 Q1 Risk Overall

Very Low
Low Consequence
High Consequence
Very High Consequence
Extreme

Vulnerability Index

0  5  10  15  20

Spillway Gates  AN  AU  PU & PN  Reduction

* Active risk reduction project
Prioritization of Projects

Vulnerability Index – only the starting point

Vulnerabilities relative to Consequence (LOL, PAR, Economic)
  ▪ Compile, sort and compare parallel lists

Management practicality
  ▪ Time to effect repairs
  ▪ Sequencing with other planned work
  ▪ Resource availability

Enabling projects

Corporate considerations
BC Hydro’s 10-yr Capital Plan ~$20B
Corporate Risk Matrices - prioritization

RISK = Probability \times \text{Consequence}

Additive if both are logarithmic

Decreasing Frequency or Probability

Increasing Consequence
### BC Hydro Generation Risk Matrix

<table>
<thead>
<tr>
<th>Frequency (Yearly)</th>
<th>Frequency of Consequence</th>
<th>L8</th>
<th>L7</th>
<th>L6</th>
<th>L5</th>
<th>L4</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10 \leq f &lt; 100)</td>
<td>At least 10 times every year</td>
<td>10.5</td>
<td>11.0</td>
<td>13.5</td>
<td>14.0</td>
<td>14.5</td>
<td>15.0</td>
</tr>
<tr>
<td>(1 \leq f &lt; 10)</td>
<td>At least once every year</td>
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<td>10.5</td>
<td>13.0</td>
<td>13.5</td>
<td>14.0</td>
<td>14.5</td>
</tr>
<tr>
<td>(1/10 \leq f &lt; 1)</td>
<td>At least once every 10 years</td>
<td>9.0</td>
<td>9.5</td>
<td>11.0</td>
<td>11.5</td>
<td>12.0</td>
<td>12.5</td>
</tr>
<tr>
<td>(1/100 \leq f &lt; 1/10)</td>
<td>At least once every 100 years</td>
<td>7.5</td>
<td>8.0</td>
<td>9.5</td>
<td>10.0</td>
<td>10.5</td>
<td>11.0</td>
</tr>
<tr>
<td>(1/1,000 \leq f &lt; 1/100)</td>
<td>At least once every 10,000 years</td>
<td>6.5</td>
<td>7.0</td>
<td>7.5</td>
<td>8.0</td>
<td>8.5</td>
<td>9.0</td>
</tr>
<tr>
<td>(1/10K \leq f &lt; 1/1000)</td>
<td>At least once every 10,000 years</td>
<td>6.0</td>
<td>6.5</td>
<td>7.0</td>
<td>7.5</td>
<td>8.0</td>
<td>8.5</td>
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</table>

### Consequence Type

<table>
<thead>
<tr>
<th>Consequence Type</th>
<th>S2</th>
<th>S2.5</th>
<th>S3</th>
<th>S3.5</th>
<th>S4</th>
<th>S4.5</th>
<th>S5</th>
<th>S5.5</th>
<th>S6</th>
<th>S6.5</th>
<th>S7</th>
<th>S7.5</th>
<th>S8</th>
<th>S8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety</td>
<td>Worker</td>
<td>Treatment by Medical Professional</td>
<td>Temporary Disability</td>
<td>Permanent Disability</td>
<td>Fatality</td>
<td>Multiple Fatalities</td>
<td>Public</td>
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<tr>
<td>Environmental *</td>
<td>Moderate impact</td>
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<td>High impact</td>
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<tr>
<td>Financial Loss</td>
<td>$100K to $300K</td>
<td>$1M to $3M</td>
<td>$3M to $10M</td>
<td>$10M to $330M</td>
<td>$330M to $1B</td>
<td>$1B to $3B</td>
<td>$3B to $10B</td>
<td>$10B to $30B</td>
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<td>Reputational *</td>
<td>Negative local profile</td>
<td>Small but local minority of customers critical</td>
<td>Many customers critical</td>
<td>Loss of trust-strategic change imposed by regulator and/or shareholders</td>
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<tr>
<td>Reliability</td>
<td>Supply</td>
<td>N/A</td>
<td>Require voluntary load reduction</td>
<td>Localized load shedding</td>
<td>Significant load shedding required</td>
<td>BC load shedding spreads to WECC</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Customer (hours lost per event)</td>
<td>5K to 15K</td>
<td>15K to 50K</td>
<td>50K to 150K</td>
<td>150K to 500K</td>
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* This matrix is consistent with the Corporate Risk Matrix. Additional cells shown as bifurcated and consequence level 8 has been added.
<table>
<thead>
<tr>
<th>FREQUENCY (YEARLY)</th>
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<tr>
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</tr>
<tr>
<td>1/10000 ≤ f &lt; 1/1000</td>
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*This matrix is consistent with the Corporate Risk Matrix. Additional colors are shown as outlined and consequence level 8 has been added.*
Quantitative:
Financial Reliability Metrics

Qualitative:
Environmental Reputational

Mixed:
Accidents/Life Loss
Corporate Risk Matrices

How to equate consequences??
moral and ethical issues…
And how to put them in logarithmic buckets?

YOU DON’T! Consequences Corporate Response

<table>
<thead>
<tr>
<th>Try to avoid, but Business as Usual</th>
<th>Major Crisis</th>
<th>Insurability Limit : Change of Corporate Leadership</th>
<th>Complete Corporate Restructuring</th>
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Corporate Risk Matrices

How to equate consequences??
  moral and ethical issues...
And how to put them in logarithmic buckets?

Great for broadbrush representations to a Board, but

Someone will eventually have to make the hard tradeoffs on the basis of corporate values
After the tradeoffs... we can’t do it all...

Reduce the Hazard
Reservoir lowered Nmax in effect at LAJ

Reduce the Consequences
Restricted Land Use underway at JOR

Interim Risk Management
Enhanced emergency preparedness
Public Education
But what about the justification?

- VI not the right tool
- Corporate Risk Matrix simply not granular enough

.....must discuss Tolerability of Risk

CDA Revised Guidelines
Figure 6-2: *Example* Societal Risk Levels for Dam Safety
A quick history of Risk

1967 – The Farmer curves - Nuclear

Fig. 1.

Fig. 2.
1980’s: UK and Netherlands – other hazardous industries

Different slopes based on different “anchor points”

UK : chemical/nuclear industries

Netherlands : dykes/large scale flooding

Documented/ defensible - adopted nationally

1986: USBR “Guidelines to Decision Analysis” - no criteria
By 1993... move into hydro industry

Early ANCOLD lines....

BC Hydro: Significant interaction with USBR

Specific Risk and Cost Criteria for a single dam:

1 x 10^-3 /yr

$10,000/yr
BC Hydro use of Probability of Failure

Use of Event Trees and the $10^{-3}$ line throughout the latter 1990’s:

Concrete dam and spillway stability
- Alouette, Ruskin, 7Mile, Stave Falls, Wahleach

Debris Passage, Spill Capacity
- LaJoie,

Rip Rap Erosion
- Terzaghi

Internal Erosion
- Coursier

Liquifaction
- Coquitlam
- Hugh Keenleyside (>1 yr, > $1M !)
2 years later....

A major change in course:

- **Scientific, political and legal difficulties**
  - Societal Risk concepts problematic
  - Vetting had not taken place

- **Use of probability without true understanding of uncertainties could not be justified in the BC Hydro context**
  - Wouldn’t pass a ‘transparency test’ with Public Utilities Commissions

- **Use of both Subjective and Quantitative Probability discontinued**
  - Moved to the Vulnerability Index approach
Why use of specifically defined risk criteria still won’t work...

...at least for public utilities and private dam owners

- Origins vs Current Practice
- Variability in its use
  - Axes, mathematics
  - Definition of zones
- Different Societal Risk Tolerances?
- Ethics, transparency and public acceptance
- Prioritization or Justification?
- How to apply in real situations?
Origins

BC Hydro and USBR (1993)
- Specific Risk and Cost Criteria for a single dam
  - $1 \times 10^{-3}$ /yr
“Needs discussion and vetting…”

USBR (1999)
- Rational for 10-3 line documented, but
- “Logic needs to be re-evaluated…”
Origins

Vetting and discussion STILL has not taken place...

- Line ‘justified’ on basis of historical dam failure data set

..until recently: See P. Regan (2016 ASDSO):

- Dam failure data set is now inappropriate for the purpose of evaluating current societal risk tolerance
- Key numerical values based on possibly flawed calculations
- Inconsistent with current guidance given by world-wide risk experts and with data compiled for other industries.

Needs further discussion
Current Practice

Although:
- 1993/1999 thinking has not yet been tested/revisited
- rarely if ever stated in laws and regulation for any other industry…

- **Approach is used in Dam Safety by various parties:**
  - USBR, USACE, ANCOLD: NSW, HYDROTAZ…

All show the 10-3 line, all look the same, but…
Definition of Axes

Probability of more than $N$ fatalities vs Probability of Failure

Risk is broadly acceptable

Risk is tolerable, if ALARP

Additional risk control is required

Number of fatalities, $N$
Definition of Axes

Why fatalities? PAR?

Risk is broaden acceptable
Risk is tolerable, if ALARP
Additional risk control is required

Number of fatalities, $N$

Probability of more than $N$ fatalities

$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
Choosing a Tolerability Line

- Additional risk control is required
- Risk is broadly acceptable
- Risk is tolerable, if ALARP

a) Follow the crowd ....but don’t ask questions
b) Attempt to logically select one?
c) Have a societal debate?
Choosing a Tolerability Line for Canada?

Annual Exceedence Probability (F)

Fatalities (N)

Empress of India
Halifax munitions explosion

Canadian disasters

1918 flu epidemic

Comet strike (10^-7)
Annual Exceedence Probability ($F$) vs. Fatalities ($N$)

Equation: $y = 7.2941x^{-0.834}$

Justification based on contribution to overall FN?
Non-cumulative probability
- completely different results!
Mathematics

ALMOST 2 ORDERS MAGNITUDE DIFFERENCE IN RISK TOLERANCE!

Figure 2: Tolerability criteria on an f-N and F-N charts

See various publications by Zielinski – needs verification/discussion
Mathematics - Uncertainty

![Graph showing probability of more than N fatalities against number of fatalities, N. Likely uncertainty bounds, additional risk control is required, risk is tolerable if ALARP, and risk is broadly acceptable are indicated.](image-url)
Terminology

Sometimes changing between publications …and with entirely different inferences

<table>
<thead>
<tr>
<th>Number of fatalities, $N$</th>
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</thead>
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Terminology

Sometimes changing between publications …and with entirely different inferences

- Increasing justification
- Intolerable
- Must take action
- Additional risk control required
- Unacceptable except in exceptional circumstances

Risk is broadly acceptable

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<thead>
<tr>
<th>Number of fatalities, N</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>10</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>100</td>
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<td>1000</td>
<td>$10^{-4}$</td>
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</table>
Different Risk Tolerances?

Politicians
Engineers
Economists
Public
  ▪ Different locations often have different perceptions

All look at risk differently

The discussions have not taken place!
  ▪ Transposing criteria between industries or jurisdictions?
  ▪ Engineers alone cannot dictate acceptable levels
Ethics and VOSL / CBA

- Additional risk control is required
- Risk is broadly acceptable
- Risk is tolerable, if ALARP

Number of fatalities, $N$

Probability of more than $N$ fatalities

- $10^{-7}$
- $10^{-6}$
- $10^{-5}$
- $10^{-4}$
- $10^{-3}$
Ethics and VOSL / CBA

Possibly for large, general populations, but…

Defined populations are not statistics!

When does your child become a statistic?

“There's nothing more we can do. Your condition has become too expensive”
Application: Recent Example

Campbell River

Jordan River

M7.4
Two societies – two safety cases

- Very High: 1:2500
- Extreme: 1:10000

Number of fatalities, $N$

Probability of more than $N$ fatalities

- Risk is broadly acceptable: $10^{-7}$
- Risk is tolerable, if ALARP: $10^{-4}$ to $10^{-6}$
- Additional risk control is required: $10^{-5}$

Guidelines for seismic withstand.
Two societies – two safety cases

No Upgrades; Property Purchase Offer:
- Minimal incremental damages
- Public awareness of the risk,
- Emergency Exercises involving entire permanent PAR
- Personal choice to accept, or not accept the risk

Both sites: 1:500 AEP seismic withstand

25-30 yr Upgrade Program
- Rate of risk reduction as fast as practicable
- Public awareness
- Inundation mapping etc...

Very High
1:2500

Risk is broadly acceptable

Risk is tolerable, if ALARP

Both sites: 1:10000

Campbell

Jordan

Risk is broadly acceptable
Challenges from the public

Reduce PAR by 1 or 2 households?

Risk is tolerable, if ALARP

Risk is broadly acceptable

Additional risk control is required

Number of fatalities, $N$

Probability of more than $N$ fatalities

1:2500 → 1:10000

Guideline for seismic withstand

1:2500

1:10000
Challenges from the public

Why is it ok for me to be 100x less safe?

Risk is broadly acceptable

Risk is tolerable, if ALARP

Additional risk control is required

Number of fatalities, $N$

Probability of more than $N$ fatalities

Guideline for seismic withstand

BC Hydro
Power smart
Challenges from the public

1:2500 1:10000

Probability of more than $N$ fatalities

Number of fatalities, $N$

1 10 100 1000

10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7}

Risk is broadly acceptable

Risk is tolerable, if ALARP

Additional risk control is required

Guideline for seismic withstand

“You have to be joking…”
Challenges from the public

Personal choice to accept, or not accept the risk

Same result if it had been a retirement home rather than a surfing community?

Guideline for seismic withstand

- Probability of more than $N$ fatalities

- Number of fatalities, $N$

- Additional risk control is required

- Risk is broadly acceptable

- Risk is tolerable, if ALARP

- Personal choice to accept, or not accept the risk
Quantified societal risk criteria cannot withstand public scrutiny

Crown Corporation must justify all expenditures as a Public Necessity in a very public forum
  - Can’t hide behind “national security”

UK: “a retreat from CBA” Hopkins, McQuaid

Netherlands – abandoning societal risk criteria for individual risk

NSW Dam Safety Bill 2015

The current approach to dam safety does not clearly establish the point at which compliance has been reached and has contributed to a strong focus on engineering measures over alternative approaches to risk reduction. The lack of a clear minimum standard and the focus on engineering
Some questions for your Board to ponder....

• How to proceed in such murky waters?
  • no framework even to determine how to determine tolerability of risk!

• In today’s society, is there an *obligation* to formally consider the views of those exposed to the hazard?
  • If so, to what degree does perception-based judgements enter into the decision-making process?

• **When defending yourself against negligence:**
  ▪ Does neglecting to account for ethical risk issues open the door for a strong legal argument that acceptable risk has not been demonstrated?
There’s a LOT of thinking we need to do....

We need better ways to characterize and communicate risk in the context of local jurisdiction:

Answer to be found in the domain of social politics and economics, not engineering

D. Hartford
Legal Framework Considerations in the development of risk acceptance criteria
Structural Safety, 2008
END