BC Hydro Dam Risk Assessment and Management

JK Lou

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- Canadian Dam Safety Management
- BC Hydro Dam Risk Assessment and Management
- Potential Failure Modes Analysis(PFMA)
- Failure Modes, Effects and Criticality Analysis(FMECA)

Canadian Dam Safety Management

Canadian Water Resource Management

- 10 Provinces, 3 Territories
- Federal government manage border-related water resources
- Each province and territory manages it’s own water resources

Dams in Canada

- **14000 dams (H>2.5 m)**
- **933 large dams H>15m (ICOLD)**

Dams in canada

933 large dams (ICOLD)

• H>**15 m**

Quebec	**333**
Ontario	**149**
British Columbia	**131**
Newfoundland & Labrador	**90**
Alberta	**77**
Saskatchewan	**44**
Manitoba	**41**
Nova Scotia	**37**
New Brunswick	**16**
Territories	**15**

Jones Falls - Rideau Canal -1830 – First system of engineered dams in Canada

Large Dams in Canada

- Multi-purpose
- Most dams hydroelectric

Purpose	Total
Irrigation	64
Hydroelectric	626
Flood Control	43
Water Supply	70
Recreational	8
Other*	122*
Total	933*

* Includes Tailing Dams

Dam Safety Management Framework

- Dam owner responsible for dam safety
- Government
  - Establish dam safety standards
  - Monitoring compliance
  - Power of enforcement

Canadian Dam Safety Guidelines

– Specifies: Principles and What needs to be done

– Does not specify how to do (encourage to use the best technology available)

-- Provides consistent approach nationwide

-- Applies to all dam life cycles

-- Provides risk approach in dam classification, performance goals and in decision making

Dam Classification

- Based on consequences
- Dam classes – low, significant, high, very high and extreme
- Deciding factor in dam design and operation
- Deciding factor in distributing dam safety budget

Canadian Dam Owner

- An engineer responsible for safety of each dam
- Avoid potential consequences of dam failure
  - Use economic and effective technique to reduce risk of dam failure
  - Protect dam owner's investment

Dam Safety Review (DSR)

- Every 5 ~ 10 year
- No need to repeat analysis unless design parameters changed
- Invite experienced expert(s) to perform DSR – value expert's personal experience, not reputation of expert's company
- Recommend deficiency investigation, if required

Dam Deficiency Investigation (DI)

- Based on DSR recommendations to carry out deficiency investigation
- Recommend remediation requirements
- **Identify deficiency of existing instrumentation system, recommend improvement plan to obtain risk information**

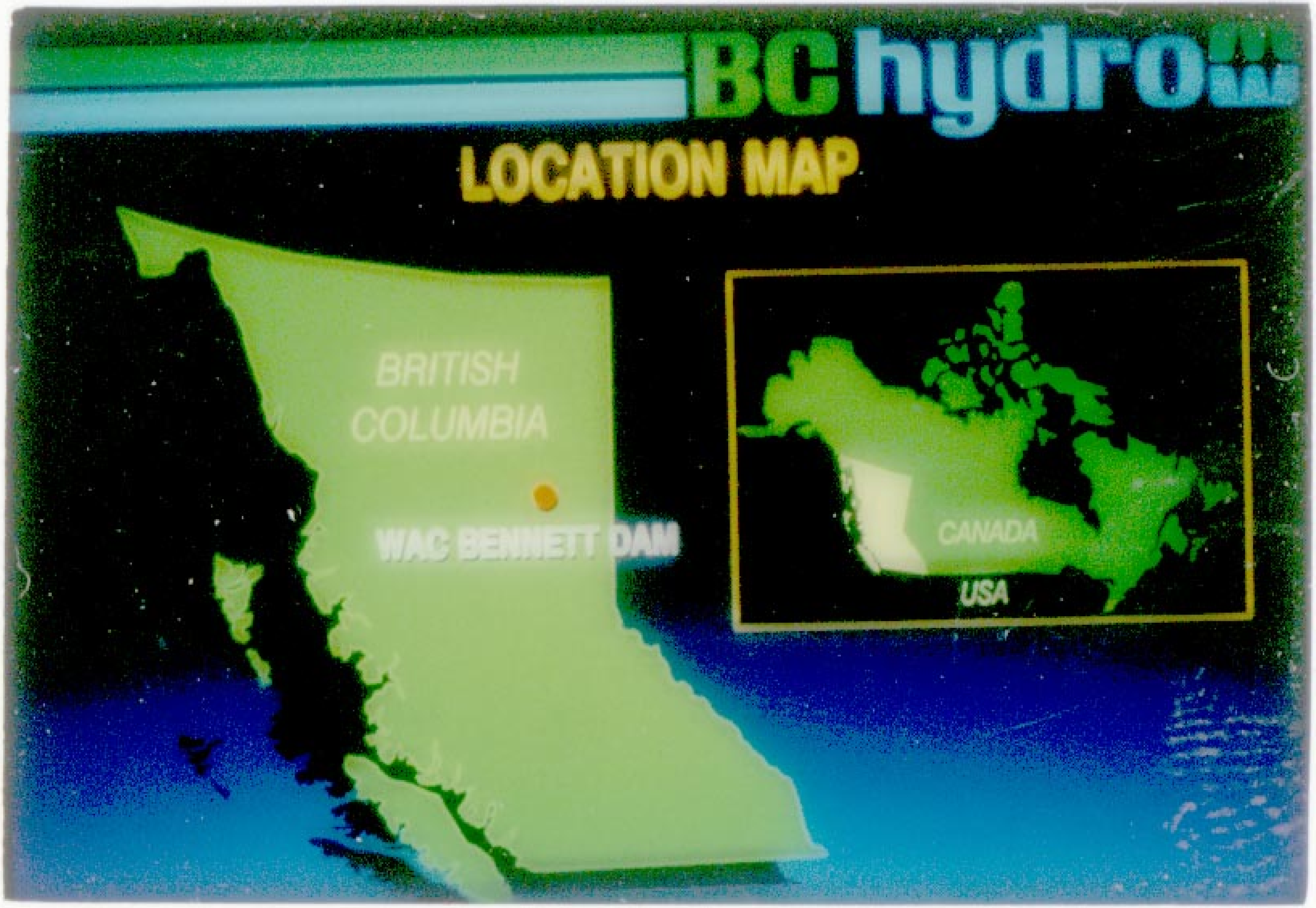
Dam Remediation

- Dam owner compares cost of remediation with dam’s financial returns, decide remediation or decommission the dam

Distribution of Dam Safety Budget for Dam Remediation

Portfolio Risk Assessment (PRA) provides reasonable and transparent recommendations for dam owner to distribute dam safety budget for dam deficiency investigations and remediations

BC Hydro
Dam Risk Assessment
and Management

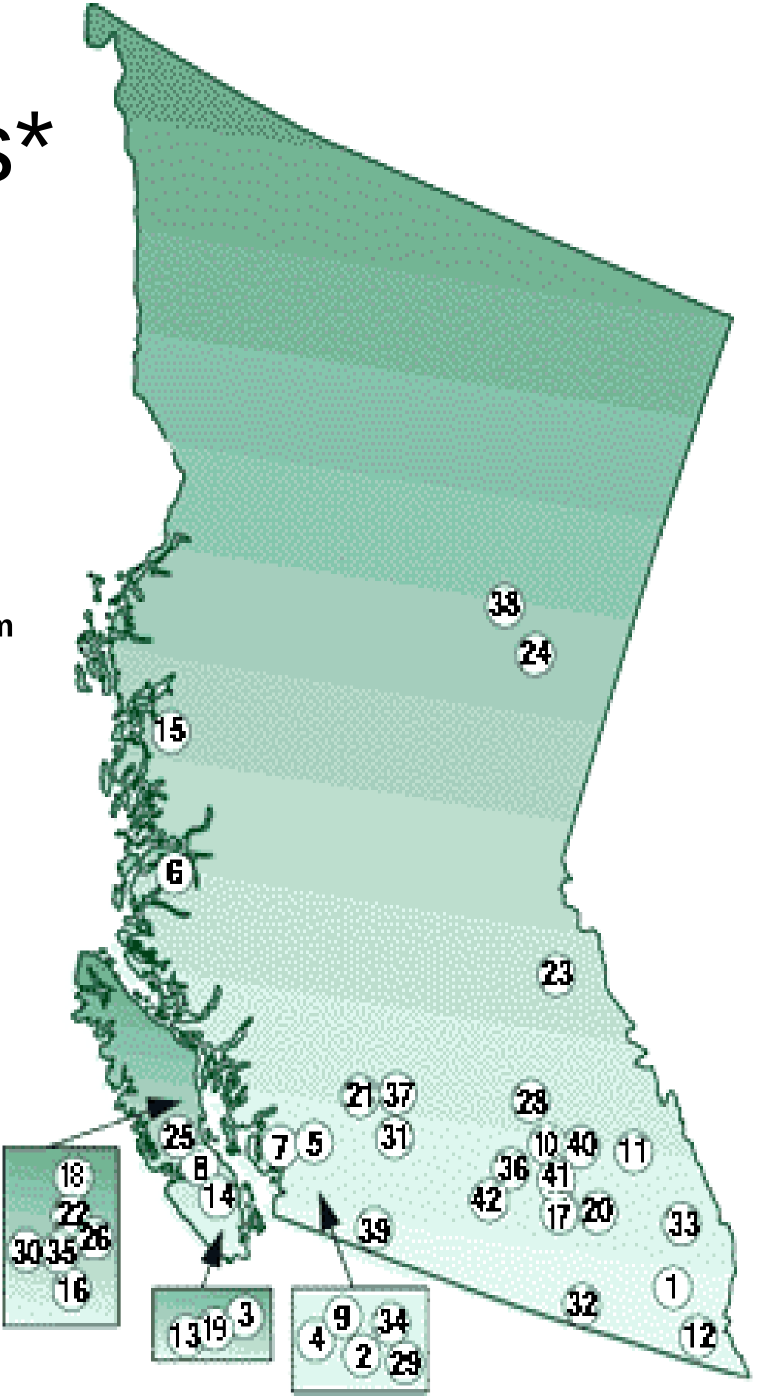

BC hydro
LOCATION MAP
BRITISH COLUMBIA
WAC BENNETT DAM
CANADA
USA

BC Hydro Dam Sites*

1. Aberfeldie Dam
2. Alouette Dam
3. Bear Creek Dam
4. Buntzen Dam
5. Cheakamus Dam
6. Clayton Falls Dam
7. Clowhom Dam
8. Comox Dam
9. Coquitlam Dam
10. Coursier Dam**
11. Duncan Dam
12. Elko Dam
13. Elliott Dam
14. Elsie Dam
15. Falls River Dam
16. Heber Diversion Dam
17. Hugh Keenleyside Dam
18. John Hart Dam
19. Jordan Diversion Dam
20. Kootenay Canal Dam
21. La Joie Dam
22. Ladore Dam
23. Mica Dam
24. Peace Canyon Dam
25. Puntledge Diversion Dam
26. Quinsam Diversion Dam
27. Quinsam Storage Dam
28. Revelstoke Dam
29. Ruskin Dam
30. Salmon River Diversion Dam
31. Seton Dam
32. Seven Mile Dam
33. Spillimacheen Dam
34. Stave Falls Dam
35. Strathcona Dam
36. Sugar Lake Dam
37. Terzaghi Dam
38. W.A.C. Bennett Dam
39. Wahleach Dam
40. Walter Hardman Dam
41. Whatshan Dam
42. Wilsey Dam

* - Some sites have several dams (75 total)

** - Decommissioned in 2003



BC Hydro

- **Vancouver, British Columbia**
- **4,500 employees，400 engineer stuff**
- **Manage 41 dams in BC**
- **Mica Dam 244m high，Bennett Dam reservoir 74 x1,000,000,000 m^3**
- **Total generating capacity 11,298MW**
- **BC population 5 million,**

  area 950,000 km^2


W.A.C. Bennett Dam

BC Hydro Dam Risk Management

- World leader
- First company use risk analysis in dam safety management(1991)

BC Hydro Dam Safety and Risk Management

- 1979–1991   Standards-Based (traditional)
- 1991–2006   Risk-Based
- After 2006   Risk-Informed

Standards-Based Dam Safety Management (1979-1991)

- Traditional management based on Standards and Regulations
- Concern only common failure modes
- Neglect unique characteristics of each dam
- No risk concept
- Downstream consequence not considered

Risk-Based Dam Safety Management (1991-2006)

- Potential failure modes
- Consequence-based dam classification
- Quantitative risk assessment – uncertainty in deciding probability
- Better than traditional in finding dam deficiencies

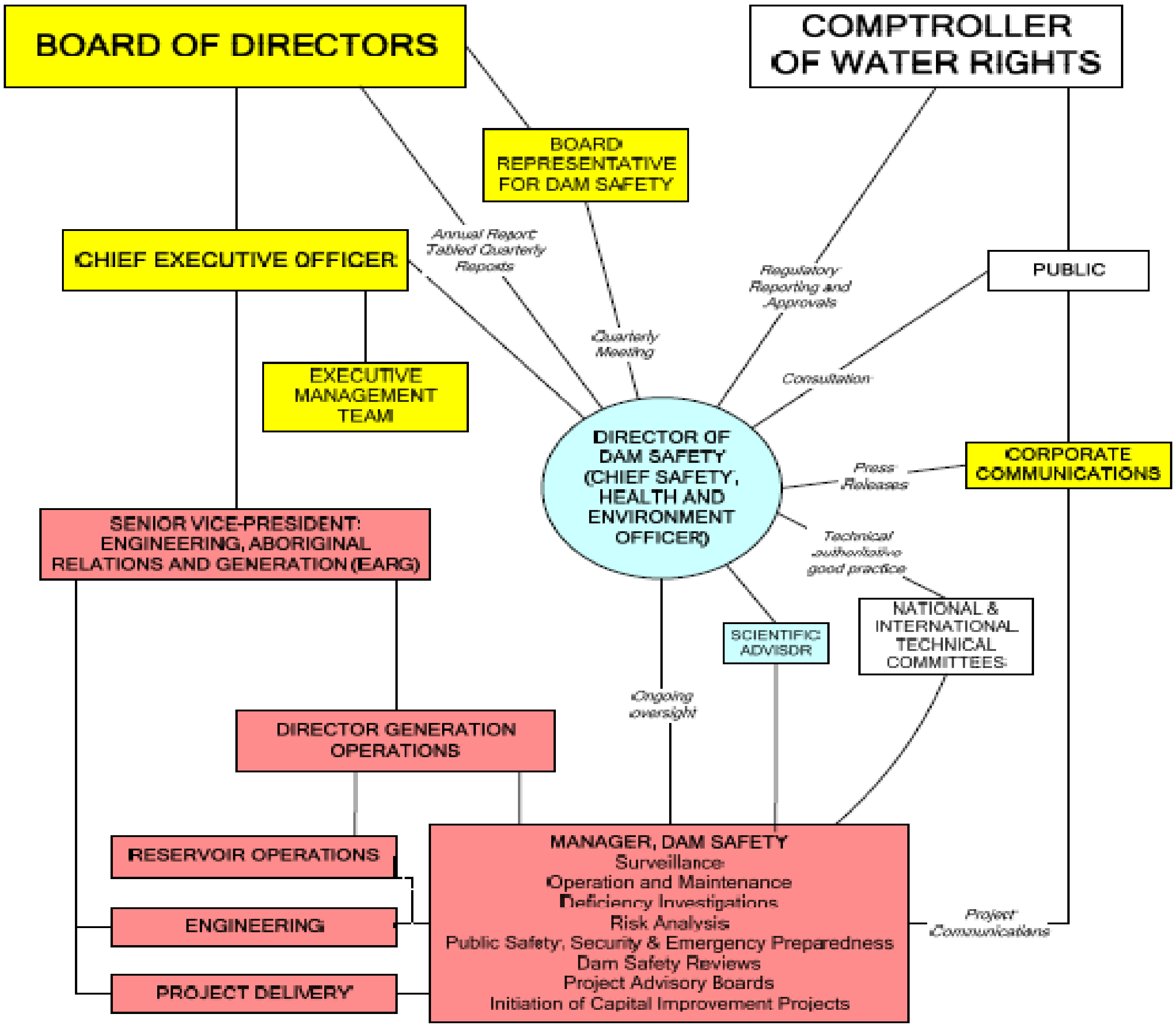
Risk-Informed Dam Safety Management

- Based on traditional and risk-based dam safety management
- Dam safety review, OMS and PFM –assess dam deficiencies and risk information
- Pay high attention to risk info from instruments
- Assess effectiveness of existing instrumentation and necessity of adding new instruments
- Semi-quantitative risk assessment, relative risk value, dam owner rationalize distribution of dam safety budget

Dam Risk Management

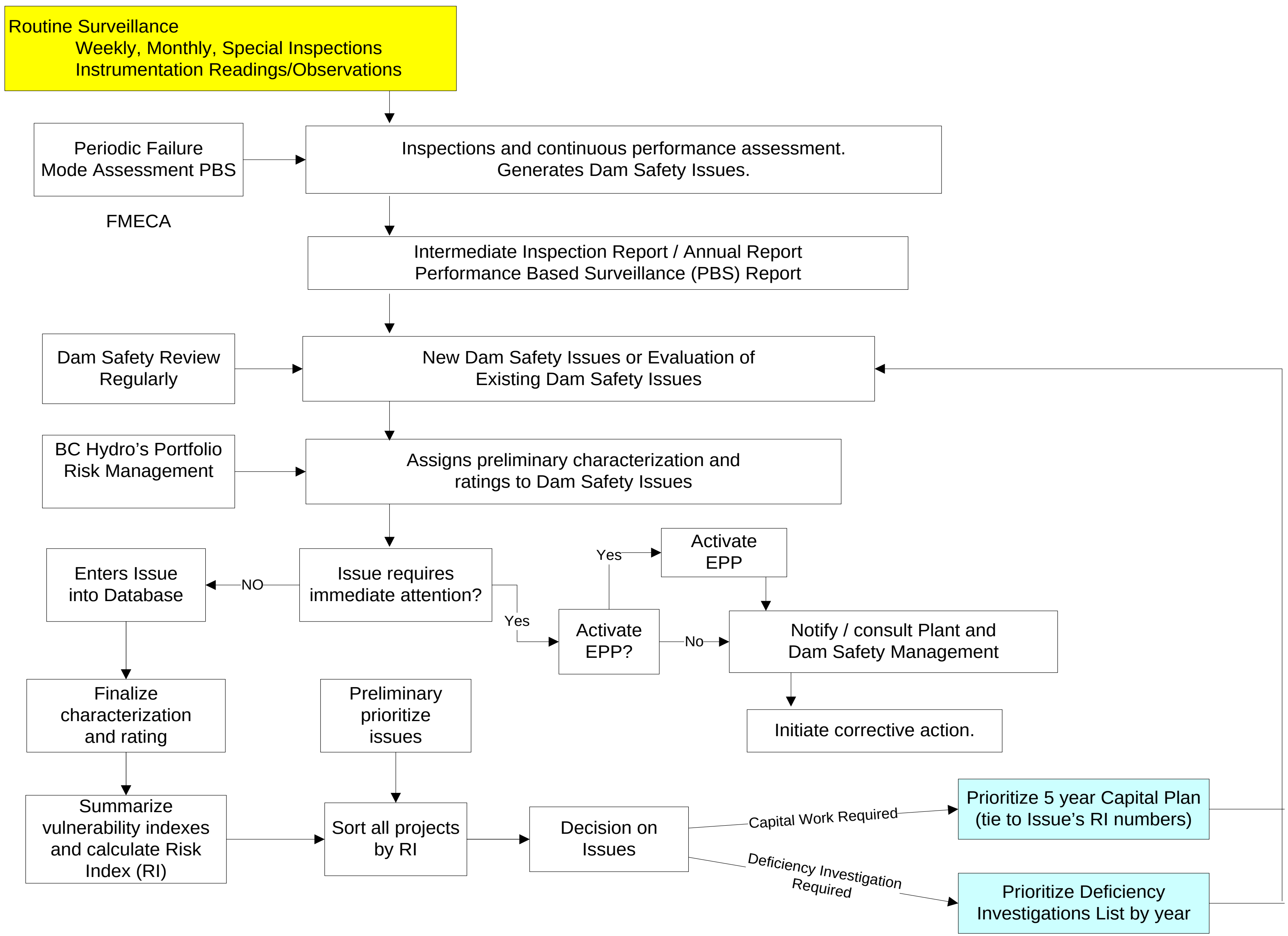
- The rule of business economy is to avoid catastrophic loss, not to make a lot of profit
- Invisible administrative achievement – the better the risk management, the less the problems occur – **NO INCENTIVES** for government officials to do dam risk management
- Private dam owner has to perform risk management to protect his investment (avoid consequences of dam failure)

Attachment A1-1: Dam Safety Governance Framework



Portfolio Risk Management
BC Hydro

- Developed in 1998
- Founded on risk assessment principles anchored by guidance provided by Canadian Dam Safety Guidelines
- The Canadian Dam Safety Guidelines provide the basis for assessing actual and potential dam safety deficiencies



LIFE CYCLE OF A DAM SAFETY ISSUE

Portfolio Risk Assessment (PRA)

- Based on dam deficiencies and completeness of dam safety management
- Semi-quantitative
- Info from dam inspection, FMECA and Dam Safety Review (DSR)
- Rational, transparent assessment

群壩風險管理
Portfolio Risk Management

破壞模式關鍵值分析（FMECA）
設施檢查（Inspections）
壩安全複核(Dam safety reviews)

↓

壩安全問題（缺陷）
Dam Safety Issues
（Deficiencies）

↓

風險指數
Risk Index

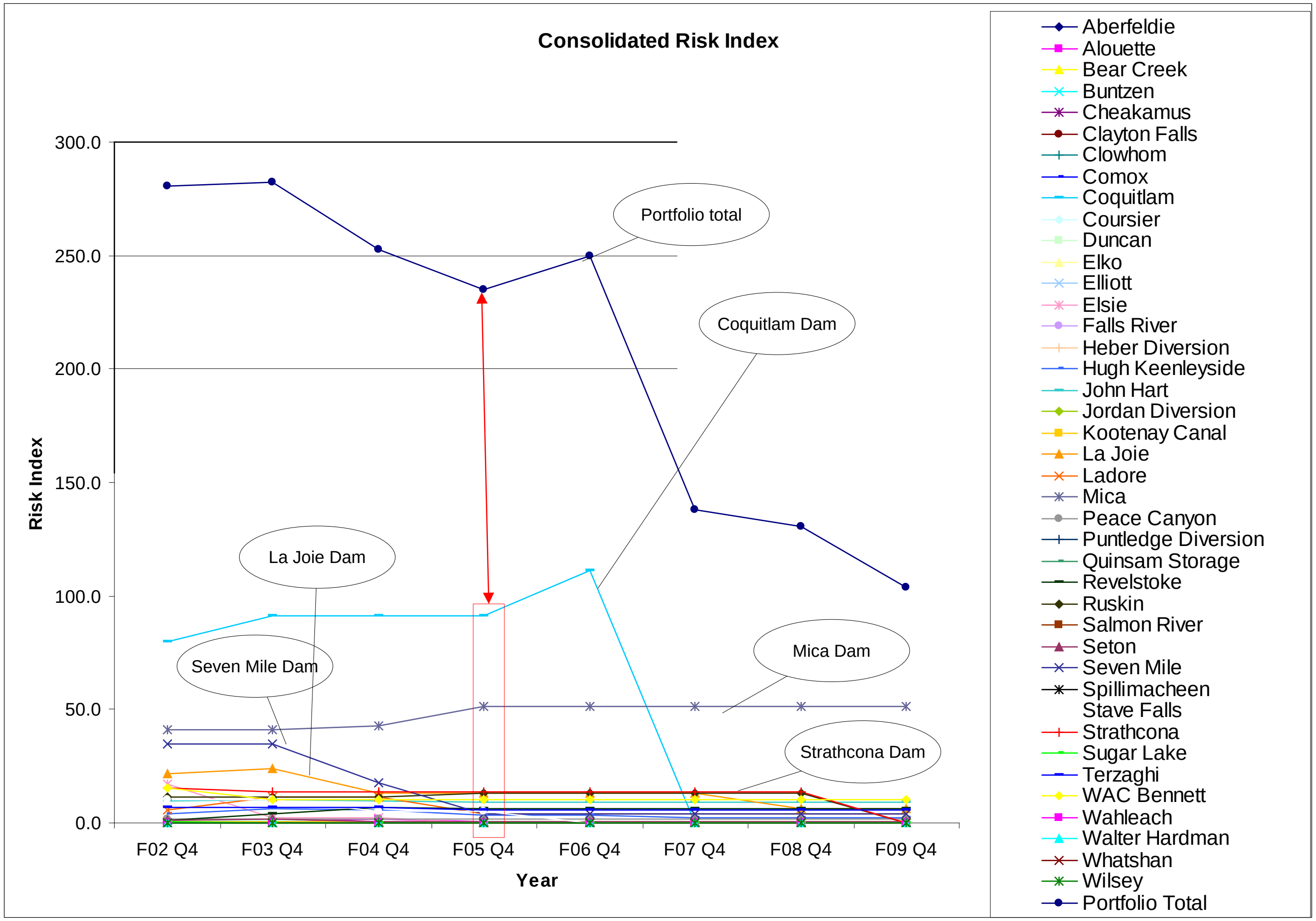
↓

群壩風險指數
Portfolio Risk Index

↓

壩安全加固工作排序
Prioritize Dam Safety Strengthening Work

BC HYDRO 水壩風險管理



Potential Failure Modes(PFM) Identification

- FMECA, Event Tree, Fault Tree
- Experience

Dam Instrumentation / PFM

- Based on PFM, assess capability of existing instrumentation system in providing risk information on dam deterioration/early stage of PFM
- Identify incompleteness of existing instrumentation system, assess requirements for new instrumentation
- Identify existing instruments not able to provide risk information – stop reading or reduce reading frequency

Potential Failure Mode Analysis (PFMA)

PFMA – essential in dam risk management

PFMA

- Assess PMF under normal loading only
- Extreme loadings not considered

PFMA

1. BC Hydro (Canada)
2. USBR/FERC (US)

PFMA (BC Hydro)

- First company use PFMA (1993)
- Obtain basic information from FMECA
- Apply risk-informed technique since 2003
- Invite 2-4 international experts experienced with this type of dam, perform “brain storm” meetings and assess PFMs

PFMA (USBR/FERC)

- Not always invite international experts to participate
- Carry out by personnel familiar with design, construction and operation of the dam, perform “brain storm” meetings and assess PFMs by vote. Decision making is subjective and without experts, could potentially miss some PFMs

International Experts

- Provide up-to-date professional expertise, owner’s most cost effective investment
- Owner’s cost effective investment
  - Owner should provide sufficient time for experts get familiar with work(at least 3 days) before meeting, not just provide brief subjective presentation at meeting
  - $5,000-10,000 USD/day/expert
  - Experts provide useful/effective recommendations
  - Could save Owner a lot of unnecessary expenditure on dam design, construction, operation, remediation and management

BC Hydro

Failure Modes, Effects and Criticality Analysis (FMECA)

FMECA

- Analyze criticality of failures of individual dam components to whole dam system
- Identify components affected by failure of an individual component
- Assess likelihood of failure mood, consequences and probability of detection and intervention
- Provide failure mode pathways information for PFM assessment

FMECA

Criticality = (likelihood of the failure mood) x (consequences) x (probability of effective detection and intervention)

Ruskin Dam
Sub-system Interaction Diagram

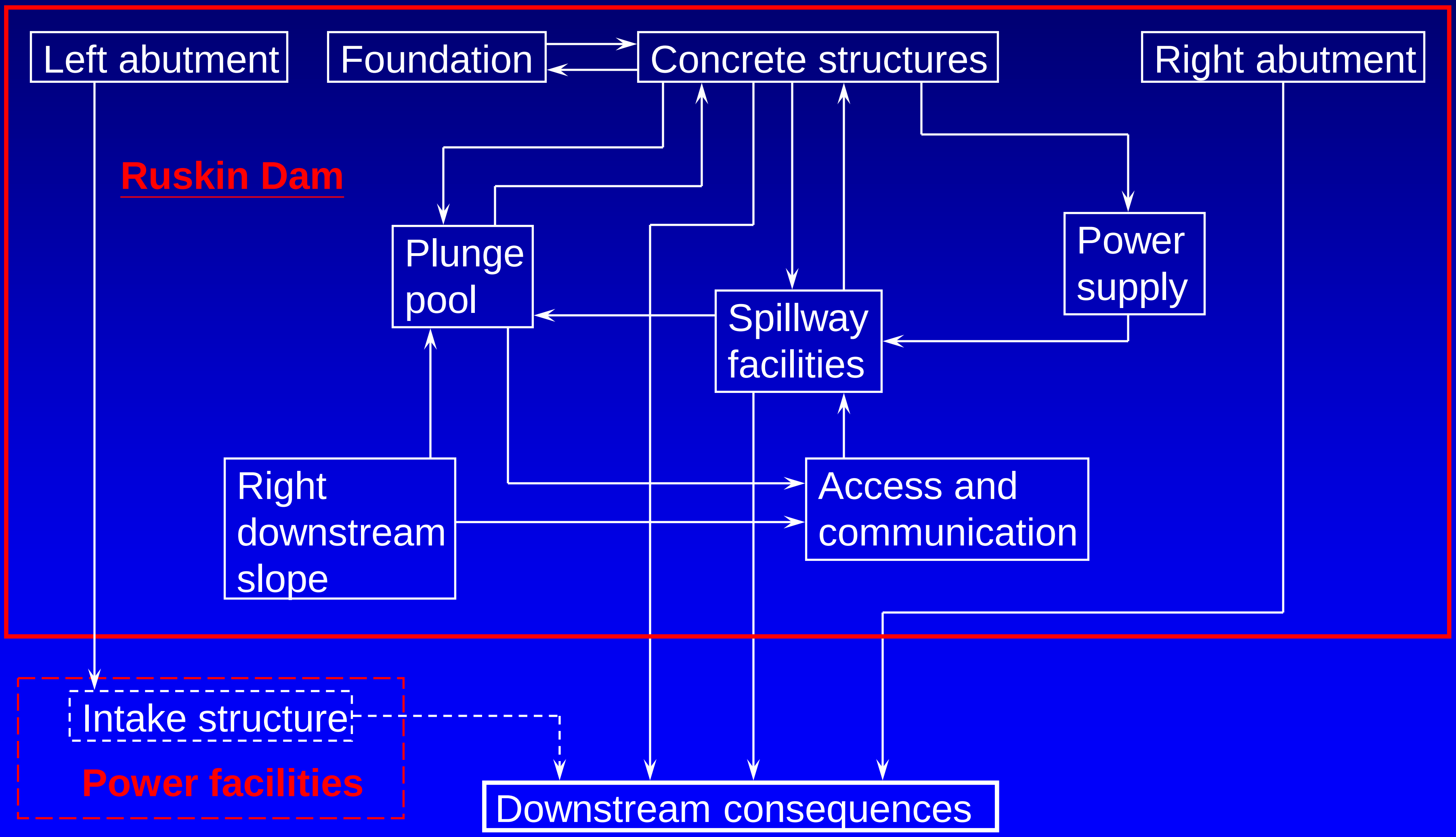


Table 2 sheet 3 of 31

TABLE 2 - Sheet 3 of 31
FAILURE MODES, EFFECTS AND CRITICALITY

Comp. Number/ Fail. Mode Number	Subsystem	Component	Failure Mode	Failure Mode Interaction Affected by Comp.:	Failure Mode Interaction Affects Comp.:	Likeli-hood Factor	Consequence	Conse-quence Factor	Detection/Intervention	D/I Factor	Criticality Index
02	**Blind Slough Dam**										
0201	Foundation										
02010101		Foundation in channel	Displacement of blocks of foundation rock. Sliding along weak bedding planes or joints.		020104 020105 020201 020202 020301 020302 04	1	Likely to result in partial failure of dam. Consequences dependent on the extent of the failure. Estimated that the worst feasible result would be failure of the radial gate section.	5	Failure of the section of the dam expected to be sudden and early detection very unlikely. Intervention not feasible other than evacuation of persons at risk.	4	20
02010102			Localized crushing of rock beneath toe of dam. Considered extremely unlikely.			1	Cracking in foundation, increased seepage and uplift pressures and a corresponding decrease in the stability of the dam. Considered very unlikely to be sufficiently extensive to lead to dam failure.	2	Crushing most likely caused by seismic loading. Increase in uplift pressures likely to be detected and remediation by grouting feasible.	2	4
02010103			Opening of fissures and joints within rock mass by the washing out of fine material.			3	Increased seepage and uplift pressures beneath the dam resulting in increased risk of dam failure. Remediation anticipated before dam stability significantly affected.	2	Likely to be detected through increased drain flows and/or increased piezometer readings.	1	6
02010201		Left abutment	Become unstable upstream of the dam.		020201	1	Potential small rockfall into the forebay. Minimal consequences.	1	Visual detection very likely. Remediation probably unnecessary.	1	1
02010202			Instability of rock downstream of the dam.			1	Potential small rockfall into channel downstream of dam. Very unlikely to damage the concrete of dam. Minimal consequences.	1	Visual detection very likely. Remediation probably unnecessary.	1	1
02010203			Small displacement of blocks resulting in opening of fissures and joints within the rock mass.			2	Seepage through left abutment. Unlikely to significantly affect the general stability of the abutment.	1	Detection possible. Sealing cracks and fissure by grouting possible.	2	4
02010204			Opening of fissures and joints within rock mass by washing out of fine material.			3	Seepage through left abutment. Unlikely to significantly affect the general stability of the abutment.	1		2	6
02010301		Right abutment	Instability of rock slope upstream of dam.		020303 020313	2	Rockfall into approach channel upstream of radial gate section, possibly causing obstruction and potential damage to structure and, especially, the radial gates.	3	Visual detection and rehabilitation very likely.	2	12
02010302			Instability of the vertical rock face downstream of dam.			3	Rockfall into discharge channel immediately downstream of radial gate section. Potential for damage to concrete inverts and piers of water passages.	3	Visual detection certain. Rehabilitation likely.	2	18
02010303			Small displacement of blocks resulting in opening of fissures and joints within the rock mass.			3	Seepage through right abutment. Unlikely to significantly affect the general stability of abutment.	1	Detection possible but not certain. Sealing cracks and fissures by grouting possible.	2	6
02010304			Opening of fissures and joints within the rock mass by washing out of fine material.			3	Seepage through the right abutment. Unlikely to significantly affect the general stability of abutment.	1	Detection and sealing by grouting likely.	2	6
02010401		Drains	Blockage of drains by rock fragments or calcite deposits.	020101	020301 020302	4	Increased uplift pressures beneath dam. If not rectified would significantly affect the stability of dam.	3	Development gradual and detection by monitoring piezometer readings very likely. Clearing drains by high pressure washing or re-drilling likely.	1	12

Table 2 sheet 26 of 31

TABLE 2 - Sheet 26 of 31
FAILURE MODES, EFFECTS AND CRITICALITY

Comp. Number/ Fail. Mode Number	Subsystem	Component	Failure Mode	Failure Mode Interaction Affected by Comp.:	Affects Comp.:	Likeli-hood Factor	Consequence	Conse-quence Factor	Detection/Intervention	D/I Factor	Criticality Index
0406	Ruskin Dam, Power supply										
04060101		Primary power cable	Failure of buried power line between Ruskin powerhouse and the east vault room in the dam.	040413	040509	4	Loss of all electrical power to the spillway hoists, lighting and miscellaneous power outlets on the dam, until back-up power activated. (See Items 04051001 to ..003 and Item 04060201.) Inability to operate spillway gate hoists. Consequences dependent on need to operate gates.	3	Certain to be detected during attempt to operate spillway gate hoists. As this is the only currently operable power cable, and as this cable is also used for the diesel generator unit, quick intervention is mandatory. Twenty four hour delay likely before a temporary cable could be installed.	4	48
04060201		Secondary power cable	Failure of the secondary power line between the powerhouse and the east vault room (this parallels the primary line). Currently inoperative.	040413	040509	5	Provided the primary power cable does not fail or the back-up diesel generating unit is available and operable, consequences minimal.	1	Known to have failed. If considered required, replacing the cable with new cable is feasible but expensive and time consuming.	3	15
0407	Plunge pool										
04070101		Invert	Erosion deepening the plunge pool and creating a bar at the downstream end of the pool.	040411 040501 040702 040801	040411 040702 040703	3	If occurred, formation of a bar expected to take long period resulting in gradual increase in average tailwater level. (If development rapid, see Item 04070102.) Consequences small.	1	Gradual increase in tailwater level and formation of a visible bar certain to be detected. Problem alleviate by dredging.	2	6
04070102			Deep erosion forming a scour hole.			2	Most likely to occur during very large spill. Likely to result in loss of toe support to energy dissipation structure and, in turn, the concrete dam. If severe, would reduce stability of concrete dam.	3	During large spillway discharge, may not be detected and intervention not feasible until spilling stopped. With no spillway discharge, corrective action possible by placing (large quantities) of tremie concrete in plunge pool.	4	24
04070201		Banks	Erosion of the left bank causing rock slides into the plunge pool.	040411 040501 040701	040701	3	Partial blockage of plunge pool and probable formation of a bar. Increased tailwater elevation. Not expected to affect dam abutment.	2	Detection certain and remediation possible by dredging the plunge pool and tailwater area.	2	12
04070202			Erosion of the right bank causing rock slides into the plunge pool.			3	Partial blockage of plunge pool and probable formation of a bar. Increased tailwater elevation. May increase the risk of instability of the natural slope of granular material immediately downstream of the right abutment.	3	Detection certain. Clearing debris by dredging the plunge pool and tailwater area and stabilizing the slope feasible.	2	18
04070301		Powerhouse access bridge pier/abutments	Moderate to severe erosion of the concrete of the pier and abutments. Severe erosion has occurred in the past.	040411 040501 040701	040904	4	Provided support to bridge deck not affected, immediate consequences minimal. However, repairs would be required to prevent more serious deterioration (see Item 04070302).	1	Detection certain. Rehabilitation of pier and abutments possible but expensive.	3	12
04070302			Major erosion of the pier or abutments leading to loss of support to the access bridge.			2	Loss of vehicular access and direct pedestrian access to the powerhouse. Potential for significant blockage of outlet of plunge pool.	3	Detection obvious. Reconstruction of bridge very likely but would take at least six months and may cost in the order of two million dollars.	3	18
0408	Right downstream slope										
04080101		Native granular slope	Shallow surface slide onto the powerhouse access road.	040802	040701 040902 040904	4	Temporary obstruction to or loss of vehicular access to the powerhouse. Would expect debris to be cleared quickly.	2	Certain to be detected and effective corrective action in short time very likely.	1	8

Table 3
sheet 1 of 3

TABLE 3 SUMMARY OF COMPONENT FAILURE MODES WITH CRITICALITY INDICES > 30 Page 1 of 3

Comp./ Fail. Mode Number	Sub-system, Component	Failure Mode	Criticality Index
02020304	Blind Slough Dam, Bulkhead gate section, Concrete piers	Downstream failure of pier(s) due to severe seismic ground motion.	45
02020305	Blind Slough Dam, Bulkhead gate section, Concrete piers	Lateral failure of pier(s) during an earthquake caused by cross-valley seismic motion.	60
02030101	Blind Slough Dam, Radial gate section, Concrete/rock contact	Cracking at interface reducing frictional strength. Most likely caused by very high HWL or seismic loading.	50
02030202	Blind Slough Dam, Radial gate section, Concrete base	Cracking near base of piers and abutments due to excessive stresses caused by high HWL or seismic loading.	75
02030404	Blind Slough Dam, Radial gate section, Piers	Structural failure of piers triggered by cross-valley seismic loading.	75
02030405	Blind Slough Dam, Radial gate section, Piers	Structural failure caused by upstream/downstream seismic loading or high HWL.	75
02030605	Blind Slough Dam, Radial gate section, Road bridge decks	Longitudinal tension or compression failure caused by cross-valley seismic loading.	50
04030102	Ruskin Dam, Right abutment, Concrete gravity wall	During 1/475 yr. earthquake, cracking at the mid-height of the wall. Once it extends through the wall, sliding of section will occur.	60
04030103	Ruskin Dam, Right abutment, Concrete gravity wall	During MDE, cracking at the mid-height of the wall. Once it extends through the wall, sliding of section will occur.	75
04030105	Ruskin Dam, Right abutment, Concrete gravity wall	Instability of the gravity wall by sliding at the rock/concrete interface or overturning into the reservoir caused by MDE.	40
04030202	Ruskin Dam, Right abutment, Concrete core wall	During 1/475 yr. earthquake, shearing of concrete core wall greater than approx. 50 mm will cause rupture of reinforcing steel and sliding of section.	40
04030203	Ruskin Dam, Right abutment, Concrete core wall	During MDE, shearing of concrete core wall greater than approx. 50 mm will cause rupture of reinforcing steel and sliding of section.	60
04030206	Ruskin Dam, Right abutment, Concrete core wall	Instability of wall by toppling into reservoir during MDE.	40
04030302	Ruskin Dam, Right abutment, Fill outside core wall	Sliding failure into reservoir during 1/475 yr. earthquake.	64
04030303	Ruskin Dam, Right abutment, Fill outside core wall	Sliding failure into reservoir during MDE.	80
04030402	Ruskin Dam, Right abutment, Sheet piling	Sheet piling pulling apart at the interlocks during 1/475 yr. earthquake.	36
04030502	Ruskin Dam, Right abutment, Sloping concrete slab	Concrete slab carried with sliding of underlying soils (the sheet pile section) during 1/475 yr. earthquake. Separation along edges and joints due to relative displacement.	36
04030503	Ruskin Dam, Right abutment, Sloping concrete slab	Concrete slab carried with sliding of underlying soils during MDE. Separation along edges and joints due to relative displacement.	48
04030505	Ruskin Dam, Right abutment, Sloping concrete slab	Cracking of the slab at the connection to the gravity or core wall caused by relative displacement initiated by 1/475 yr. earthquake.	64

PFMA Taiwan Dams

- Completed PFMA for Xinshan, Hsishih, Baoshan Second, Zengwen, Feitsui dams and assessed risk-informed requirements for their instrumentation system
- Completed PFMA for Shihmen Dam, but assessment on instrumentation to be done

Taiwan Dam Risk Management

- Mr. Hsien Chang Kao, Deputy Director of Sinotech Consultants Inc. has devoted a lot of time promoting dam risk management in Taiwan, a very difficult task in the environment of traditional dam safety management
- Water Resources Agency concurs importance of dam risk management
- Existing traditional dam safety Standards and Regulations need to be updated to include risk
- Taiwan’s dam risk management level has advanced gradually, now is the leader in Asia

Thank You