BUREAU OF RECLAMATION

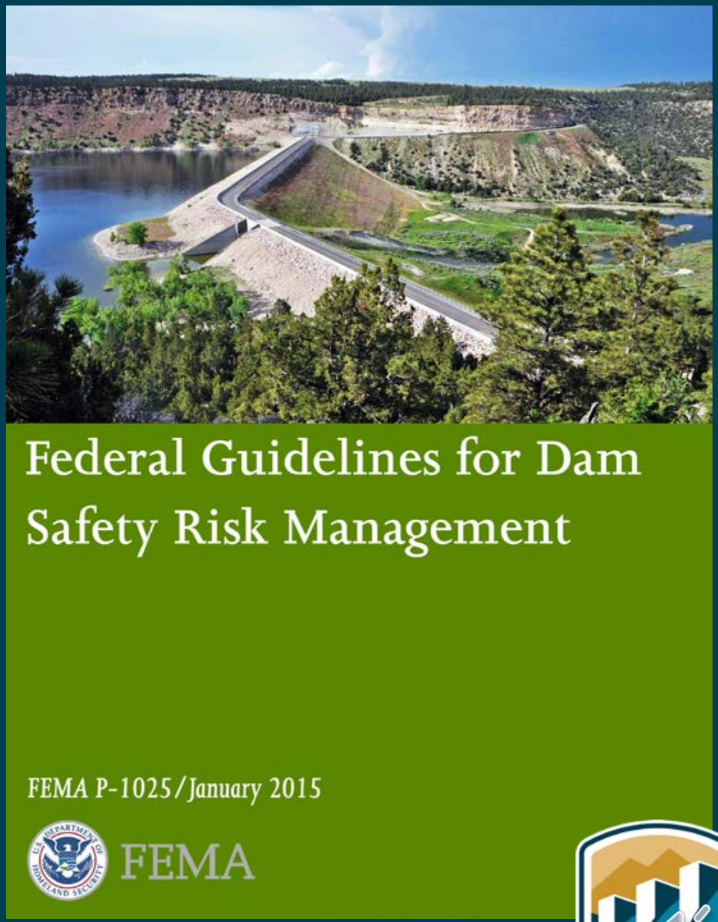
Dam Safety Risk Analysis and Risk Management Practices at the Bureau of Reclamation

Scott Stevens, P.E.

Technical Specialist, Technical Service Center
Denver Colorado

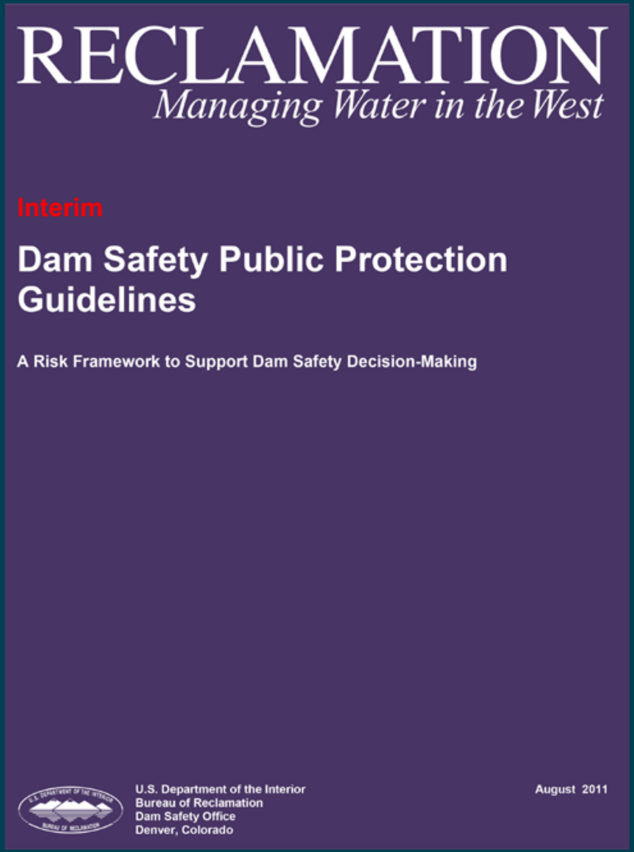
Overview of U.S. inventory of dams

- U.S. inventory consists of federally regulated, state regulated, and unregulated (typically small, low-hazard) dams
- Requirements for state regulated dams vary by jurisdiction
- Dam safety risk management for federally regulated dams is governed by Federal Emergency Management (FEMA) 1025. (Federal Dam Safety Guidelines)



Federal Dam Safety Guidelines

- FEMA 1025 calls for risk informed decision making (RIDM) to be used to manage risks posed by dams, but does not prescribe any specific methodology
- As a result, each Federal agency with administrative dam safety responsibility has its own RIDM guidelines
- Examples include the 2011 Public Protection Guidelines (Reclamation), ER 1110-2-1156 (U.S. Army Corps of Engineers), and the Federal Energy Regulating Commission (FERC) RIDM guidelines.


RECLAMATION
Managing Water in the West

Interim

Dam Safety Public Protection Guidelines

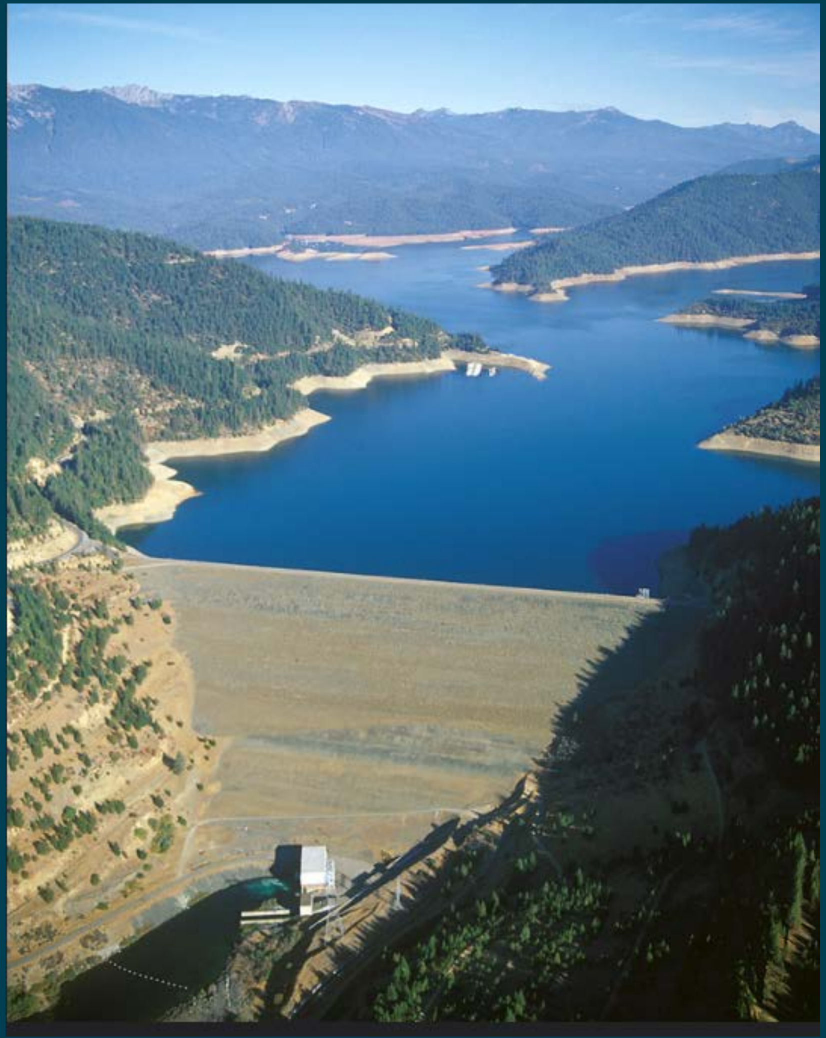
A Risk Framework to Support Dam Safety Decision-Making

U.S. Department of the Interior
Bureau of Reclamation
Dam Safety Office
Denver, Colorado

August 2011

Definitions

- RIDM: A decision making process that considers design information, field data, performance observations, and analysis results, as well as the estimated risk of adverse performance
  - The RIDM processes used by the major federal agencies are very similar (to the extent that joint risk analysis training is held for Best Practices)
  - Reclamation's RIDM process consists of <u>risk analysis</u>, <u>risk assessment</u>, and <u>risk management</u>



Definitions

- Risk: The estimated likelihood of adverse performance (dam failure) or the likelihood of adverse societal consequences (life loss)
  - Basic unit of meaning is the individual facility (as defined in authorization)
  - Basic unit of time is a typical project year (risks are annualized)

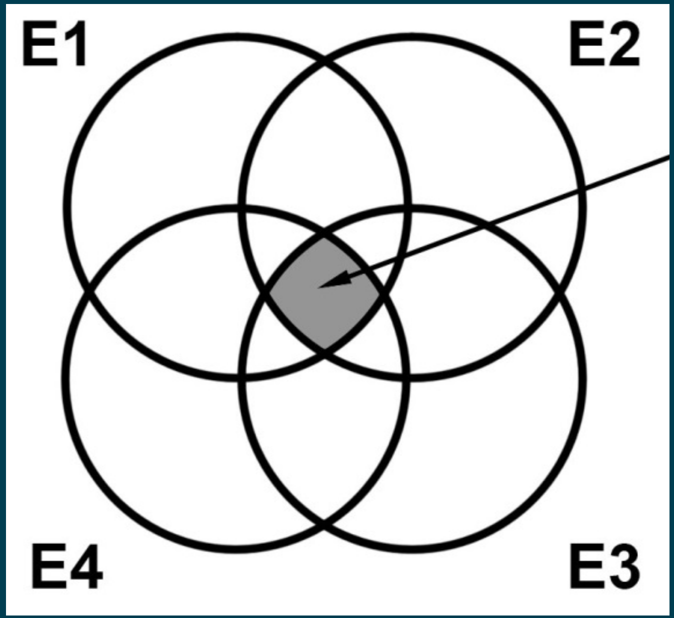
RIDM at Reclamation

RIDM process consists of:

1. Risk Analysis
2. Risk Assessment
3. Risk Management

Risk Analysis

- Risk analysis is the quantitative component of the RIDM process
- Philosophical basis for our risk analysis approach is the idea that a failure process can be conceptualized in the form of a narrative called a Potential Failure Mode (PFM)
- Mathematical basis is the multiplication rule of elementary probability theory, with probability of failure interpreted as the intersection probability of the *n* events of the PFM



Risk Analysis

- Typically performed in a facilitated team setting
- Participants represent various areas of technical expertise (including Consequences)
- Expert judgment is converted into subjective probability with the aid of verbal descriptors
- Basic product is a set of quantitative risk estimates
  - Annualized Failure Probability
  - Annualized Life Loss
- Added benefit is an improved understanding of the dam's strengths and weaknesses

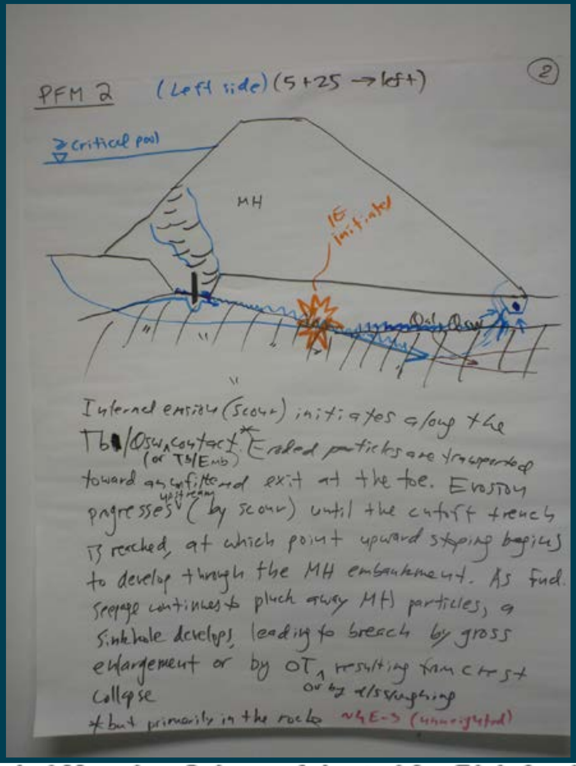
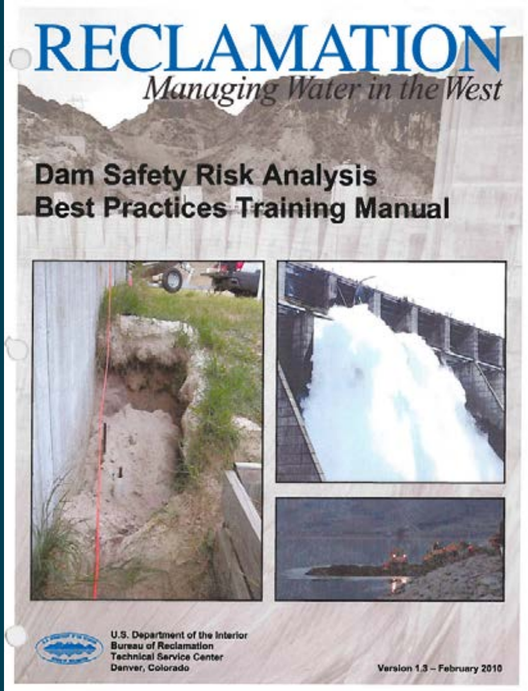
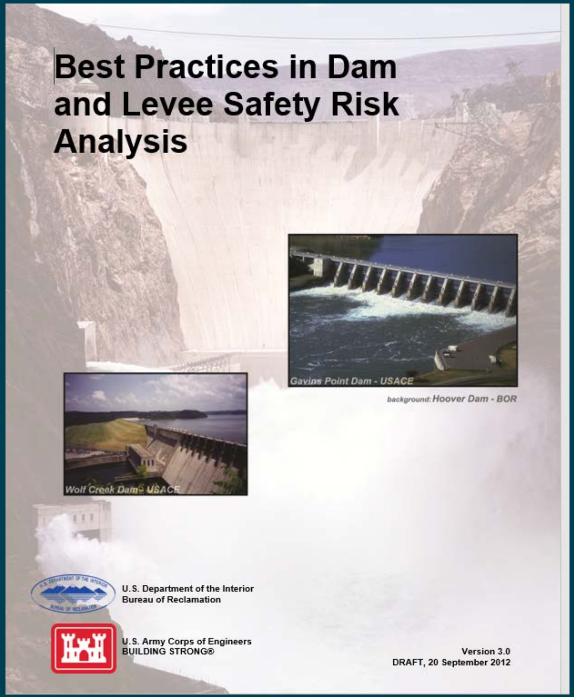


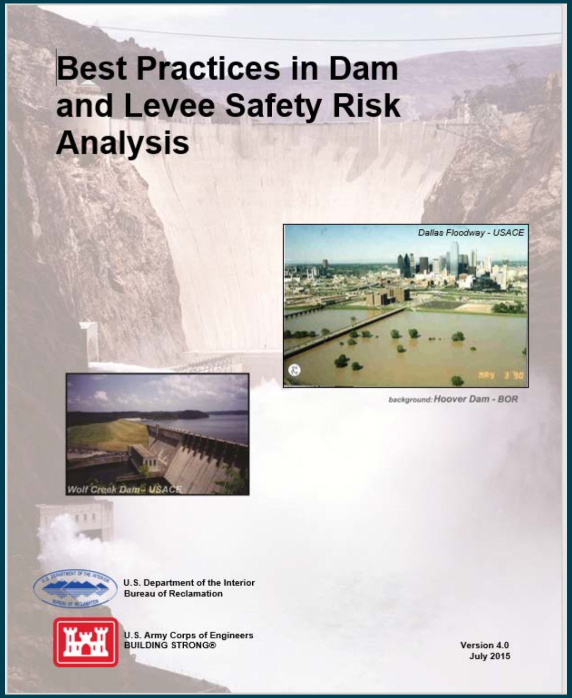
Table A-6-2.—Verbal Mapping Scheme Adopted for Risk Analysis	
Descriptor	**Assigned Probability**
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

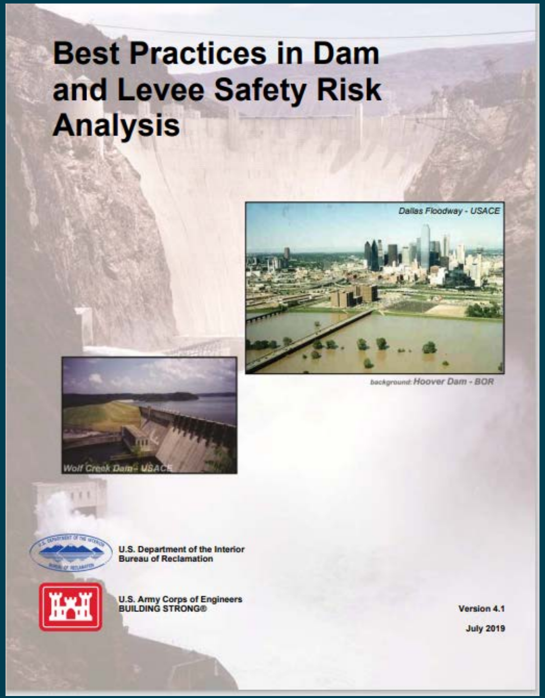
Risk Analysis

Best Practices









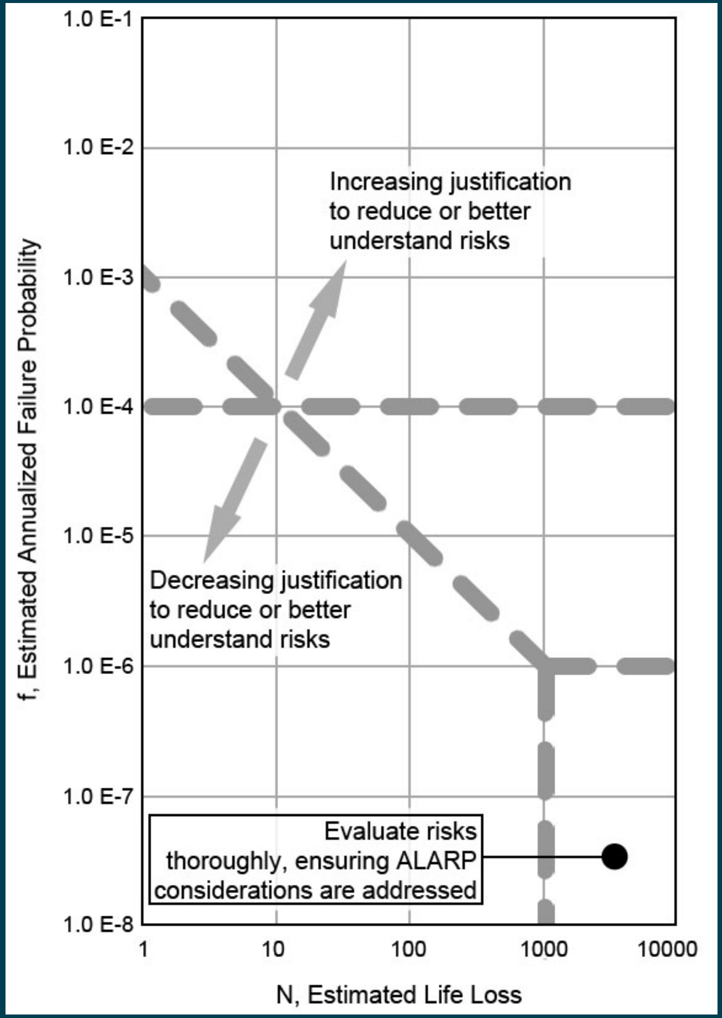
Risk Analysis

Best Practices

- Reviewed and updated periodically to stay current with state of practice, include new topics, incorporate lessons learned, and provide clarification where experience indicates it’s needed.
- Guidance is not a prescriptive approach. Dam Safety risk analyses do not provide accurate or precise estimates.
- Numbers are less important than the identification, understanding, and documentation of the major risk contributors.

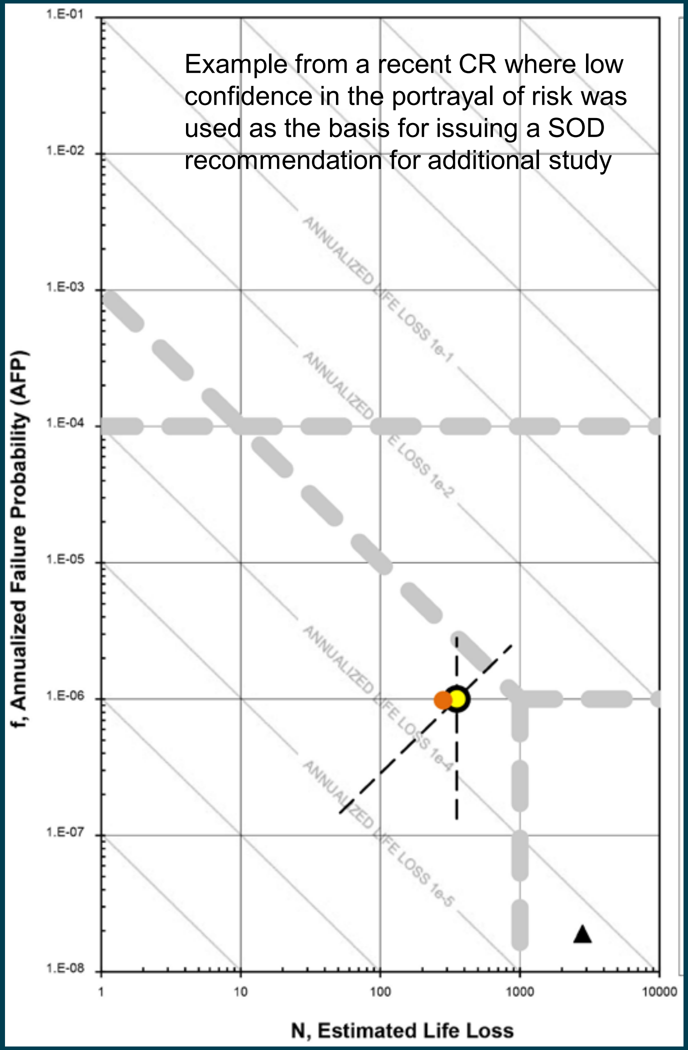
Risk Assessment

- The interpretation of the numbers
- Risks of each PFM are plotted on fN chart and compared to the visual guidelines
  - Total AFP is calculated as the probability of the union of the individual PFMs
  - Total ALL is the normalized “expected” life loss
- Basic objective of PPG is that our dams not significantly increase background risk of death
- When there is the potential for very high life loss, goal is for the risk of failure to be even lower



Risk Assessment

- Important to identify key risk driving PFMs, but also to consider the overall risk picture
- Uncertainty, and its potential impact on the portrayal or risk (confidence), are important
- Guidelines are not intended to serve as hard decision criteria (room for interpretation)
- Not attempting to model or "predict" failure, only to determine if there is a dam safety case to reduce or better understand the risk



Risk Assessment

- Risk analysis package: a report describing the results and a decision/summary document presenting the dam safety case
- Overall dam safety case goes beyond the risk estimates, and must reconcile them with design information, field data, performance observations, analysis results, and overall condition
- This takes experience, which is why key roles on dam safety projects are usually assigned to senior staff
- However, the team approach also provides a way for entry level staff to become involved and gain RIDM experience

Risk Management

- Risk management is the programmatic element of the RIDM process
- Risk analysis and assessment are typically performed by the Technical Service Center
- Risk management is the responsibility of the Dam Safety Office
  - A dedicated dam safety Program Manager is assigned to each of the five Regions
  - Track and prioritize the implementation of Safety of Dams (SOD) recommendations
  - Prepare budget estimates and requests

Region	Dam Name	Issue ID	Actual Status Date	Issue Description/Last Status
MP	BOCA	1984-SOD-B	Deleted:	Determine whether the riprap cover provides adequate upstream slope protection. Last Status: Upstream riprap appears to have performed satisfactorily, and remained in place during high reservoir winds/waves and flooding since 1984.
MP	BOCA	1996-SOD-A	Deleted:	Upgrade the seepage measurement installations by designing the toe drain measurement system to prevent backwater from interfering with measurements. Last Status: The Issue Evaluation Report of Findings, TM No. BO-8312-6, dated 2/26/2004, found this recommendation did not reduce risk imposed by the structure or improve understanding of key failure modes. Based on Decision Memo No. IE-Boca-2004-DP3 Boca Dam can continue to operate in normal fashion.
MP	BOCA	1998-SOD-A	Deleted:	Institute quantitative flow monitoring at the following locations (1) at the toe drain outfalls at the saddle dike, (2) at the wet area to the left of the spillway, (3) at the wet area at the right abutment groin, (4) at the right abutment drain, and (5) at the toe drain outfalls at the maximum section of the dam. Excavation to locate the toe drain outfalls at the saddle dike needs to be performed as part of this work. (Denver) Last Status: The Issue Evaluation Report of Findings, TM No. BO-8312-6, dated 2/26/2004, found this recommendation did not reduce risk imposed by the structure or improve understanding of key failure modes. Based on Decision Memo No. IE-Boca-2004-DP3 Boca Dam can coontinue to operate in normal fashion.
MP	BOCA	1998-SOD-B	Completed:	Install or scribe measurement points on the top of the parapet wall at 100-foot intervals, and also at any apparent low points, for the full length of the dam, and institute routine surveying of them. (Denver) Last Status: 5 additional deflection points were installed on the top center of the parapet wall and surveyed for baseline measurements on November 26, 2002. The baseline deflection measurement data was forwarded to the Denver instrumentation group (D-8460) on December 3, 2002 including a comment requesting revision of the L-23 for Boca Dam to reflect these additional 5 points.
MP	BOCA	1999-SOD-A	Completed:	Conduct a more detailed, comprehensive risk analysis to better define the expected loss of life and corresponding risks due to a failure of Boca Dam. Last Status: The Issue Evaluation Report of Findings, TM No. BO-8312-6, dated 2/26/2004, completed this recommendation. Based on Decision Memo No. IE-Boca-2004-DP3 Boca Dam can coontinue to operate in normal fashion.
MP	BOCA	2004-SOD-A	Completed:	Conduct additional analyses to better estimate the response of the dam to seismic loading and the consequences of dam failure. Upon completion, reassess the risk. Last Status: Per Issue Evaluation Decision Document dated 6/9/2006, Decision:Revise status of this recommendation to "Completed." The analysis completed indicates that significant deformations could occur as a result of foundation liquefaction, in the event of significant earthquake loading. Risk reevaluation of the seismic failure modes has been completed using available data. With this analysis, the probability of failure resulting from seismic loading was re-evaluated to be 2.7x10-5 and the annualized loss of life 4.7x10-3. Based on the risk, there may justification to implement risk reduction actions, however, additional data is needed to further confirm the need for risk reduction.
MP	BOCA	2005-SOD-A	Completed:	Perform a thorough investigation of the void in the right abutment of Boca Dam to determine the extent of the void. Last Status: Per CFR Decision Document dated 5/9/2007, Discussion: The status of this recommendation has been revised to "Completed." A void investigation report titled Boca Dam Void Investigation was transmitted from the Regional Engineer, Mid –Pacific Regional Office to the Dam Safety Office on June 14, 2005. Findings are that the void in question was a preconstruction exploration test pit that was poorly backfilled. That implies that other such test pits may also be poorly backfilled. That conclusion led to recommendation 2005-SOD-B to learn more about test pits that underlie the dam or are within the abutments.
MP	BOCA	2005-SOD-B	Completed:	Perform a thorough search of historical records to determine the method of excavation of the preconstruction test pits at Boca Dam, and develop an investigation program, if warranted by risk, for other test pits underlying the dam or located in its abutments. Last Status: Per Issue Evaluation Decision Document dated 6/9/2006, Decision:Revise status of this recommendation to "Completed." A search of historical records has been completed and the risk associated with preconstruction explorations does not warrant further action.
MP	BOCA	2006-SOD-A	Completed:	Conduct an exploration program to better define the properties and extents of the foundation alluvium. Re-analyze the risk with the results of the exploration program to determine if additional risk reduction actions are warranted. Last Status: Revise status of this recommendation to "Completed". This recommendation is considered complete with the finalization of the Issue Evaluation documentaiton. The exploration program consisting of 16 Becker Penetration Test and 4 Becker Sample holes was completed in 2008. This data from that program was utilized in the reevaluation of the seismic risks at Boca Dam. The risk analysis determined that the total annual probability of failure resulitng from seismic loading is 5.6 X 10-5 and the total annualized loss of life is 5.6 X 10-3.
MP	BOCA	2008-SOD-A	Completed: 12/22/2014	Conduct a Corrective Action Study to address risks to the embankment, foundation, and spillway under seismic loading. Last Status: Three alternatives for the main embankment and five alternatives for the spillway, and dike modification alternative were analyzed in the CAS to reduce the risks for seismic potential failure modes. A security enhanced technically preferred alternative was identified at the end of CAS. The security enhanced technically preferred alternative will be carried forward for final design and construction.
MP	BOCA	2014-SOD-A	Incomplete:	Perform final design and construction of the security enhanced technically preferred alternative identified in the corrective action study to reduce seismic risks at Boca Dam. Last Status: This recommendation is incomplete pending the completion of construction of the SOD modifications. Based on the results of the updated risk analysis for baseline, post-modification and reservoir restriction conditions for Boca Dam, the SOD modification with the security enhanced technically preferred alternative would result in an estimated post-modification total annualized life loss risk of 2.0x10 -4 , which is close to one order of magnitude below the threshold in the 2011 Interim Public Protection Guidelines.

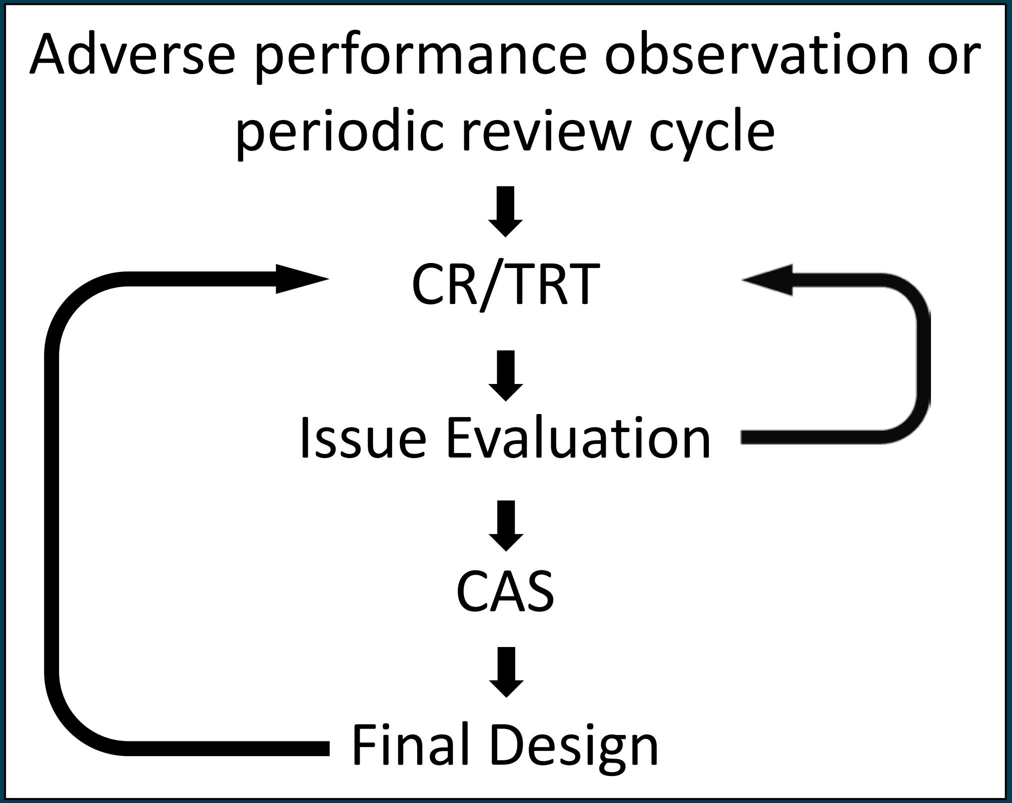
Risk Management

- Dam Safety recommendations must be prioritized
- Dam Safety Priority Rating (DSPR) system used to assess urgency based on factors such as condition of the dam, the controlling loading condition, the total estimated risk, and confidence
- The Dam Safety Office also has an internal prioritization scheme to help differentiate between dams in the same DSPR category

DSPR 1 – IMMEDIATE PRIORITY Immediate actions are necessary to reduce the risk of failure, including both interim actions and the implementation of long-term risk reduction alternatives.	Several of the following factors would typically apply at the DSPR 1 level: • There is direct evidence that a failure is in progress and that the dam could potentially fail if action is not taken quickly. • Risks are extremely high with respect to the applicable portion of the fN-chart guideline. • The high risk is driven by a potential failure mode manifesting under normal operating conditions. • The failure mechanism of concern has been observed in practice and/or the dam is in poor condition. • Confidence in the portrayal of risk is high.
DSPR 2 – URGENT PRIORITY Expedited actions are likely needed to reduce the risk of failure, including the implementation of long-term risk reduction alternatives and serious consideration of interim actions.	Several of the following factors would typically apply at the DSPR 2 level: • Risks are very high with respect to the applicable portion of the fN-chart guideline. • While there may be evidence that a PFM has initiated, there is no direct evidence of advanced progression or a failure in progress. • The high risk is driven by a potential failure mode associated with a relatively frequent (per the interpretation of the team) loading condition. • The risk is driven by a single potential failure mode, but the residual risk (collective risk of the remaining potential failure modes) is also relatively high. • Although the estimated risk is very high, the overall condition of the dam is good, the performance is relatively well understood (and not expected to deteriorate under the loading conditions anticipated in the near future), and most of the DSPR 1 considerations above would not realistically apply. • Confidence in the portrayal of risk is high.
DSPR 3 – HIGH PRIORITY The identified dam safety deficiencies are a concern, and interim action may need to be considered while ways of addressing the long-term risks are being evaluated.	Several of the following factors would typically apply at the DSPR 3 level: • The risks are relatively high with respect to the applicable portion of the fN-chart guideline. • The high risk is driven by a potential failure mode(s) associated with a relatively remote loading condition. • The high risk is driven by a potential failure mode(s) associated with a normal operating condition or relatively frequent loading, but there is no clear or direct evidence of a PFM in progress. • Confidence in the portrayal of risk is moderate to high.
DSPR 4 – MODERATE PRIORITY The risks as portrayed indicate a potential concern, but interim action beyond routine monitoring may not be needed to effectively manage them.	Several of the following factors would typically apply at the DSPR 4 level: • The plotting position of the total risk marker places it near the applicable portion of the fN chart guideline, but there are multiple PFMs contributing to the plotting position. • The estimated risks are relatively high with respect to the applicable portion of the fN-chart guideline, but with low or low to moderate confidence in the portrayal of risk. • The estimated risks are relatively low and confidence in the portrayal of risk is high or moderate to high, but most of the DSPR 5 considerations below would not realistically apply. • The dam is in good condition and has performed well to date. • The response of the dam to reservoir loading is predictable, and conditions do not appear to be changing.
DSPR 5 – LOW PRIORITY The potential failure modes identified at the facility do not present a significant concern, and risks can be effectively managed via routine monitoring.	Several of the following factors would typically apply at the DSPR 5 level: • The risks are relatively low with respect to the applicable portion of the fN-chart guideline. • The seismic and hydrologic loadings are reasonably up to date. • The design of the dam is considered state-of-the-art, or the dam has been recently modified to address any previously identified dam safety issues. • Confidence in the portrayal of risk is high.

Risk Management

- Comprehensive Reviews (CRs) are performed on an 8-year cycle
- Periodic Facility Reviews (PFRs) are performed between CRs
  - Supported by the Technical Response Team (TRT), basically the CR team
- Annual Site Inspections (ASIs) are performed once a year
- Monthly (or more frequent) visual and instrumentation monitoring



Overview of Reclamation's inventory of dams

- Reclamation has 367 high/significant hazard dams spread over 243 facilities
- About half of these dams were built before 1950
- State of the practice and understanding of potential loading conditions (e.g., flood and seismic) have changed since many of these dams were built
- Changes in downstream populations have occurred
- Dam Safety program was established to ensure our dams do not present an unreasonable risk

Overview of Dam Safety Program

- Current focus of the program is on conditions that could lead to a life-threatening, uncontrolled release of water
- Key Developments:
  - Numerous dam failures in the 1970s (non-Reclamation)
  - 1976 failure of Teton Dam
  - 1978 Reclamation Safety of Dams Act
  - 1979 Federal Guidelines for Dam Safety (last updated in 2015)
  - 1997 Public Protection Guidelines (updated 2011 and 2022 update under review)

Track record

- Risk informed decision making process began to be implemented in the 1990s
- Since that time, there have been
  - Three-plus CR cycles for each facility (over 1000 CR-level quantitative risk analyses)
  - Over 230 Issue Evaluation-level risk analyses
  - Over 120 CAS-level risk analyses
- About 100 modifications have been (or are being) performed under the authority of the Reclamation Safety of Dams Act

Track record

- First set of dams modified under the Act had objective performance concerns or did not meet deterministic hydrologic design criteria
  - 1980s, typical of pre-RIDM approach
- Second set of mods (1990s) was evenly split between dams with static, seismic, and hydrologic issues
- Third set of mods (since 2000) is dominated by dams with internal erosion related concerns
- The RIDM process has been particularly helpful in evaluating the significance of threats for which there are no deterministic safety criteria, such as those associated with excessive seepage

Example: Modification of Hyatt Dam, Oregon

- Small embankment dam constructed in 1922 by the local irrigation district (title eventually transferred to Reclamation)
- Generally constructed as a homogeneous rolled earth embankment
  - Some use of puddled fill
- Design included a concrete-pipe toe drain surrounded by "loose rock"
- Design included a small cast-in-place core wall along the base of the cutoff trench

Example: Modification of Hyatt Dam, Oregon

- No adverse performance observations were reported over the first 50 years
- Seepage along the left abutment began to be observed in the 1970s
- Toe drain flows dropped abruptly in 2009, with new seepage areas subsequently reported
- An inspection was performed and revealed that the toe drain pipe was damaged and deteriorated in some places

Example: Modification of Hyatt Dam, Oregon

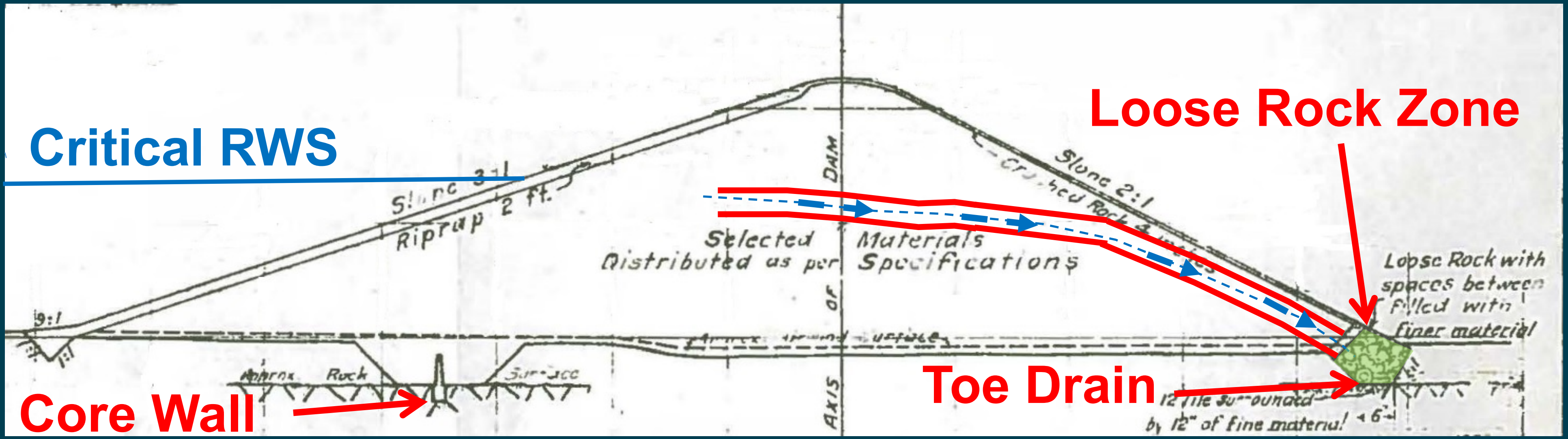
- The standards-based solution at this point would have been to replace the toe drain
- However, based on low confidence in its interpretation of the overall risk, the 2009 CR team recommended an Issue Evaluation study
- The Issue Evaluation was focused on data collection to reduce the uncertainty of the risk estimates, including geotechnical investigations of the embankment and foundation

Example: Modification of Hyatt Dam, Oregon

- The investigations revealed wet seams in the embankment as well as fractured rock in contact with the overburden beneath the downstream shell
- The elevations of these features corresponded to reservoir water surface (RWS) elevations where seepage changes occurred
- The Issue Evaluation risk team concluded that while the damaged toe drain was a contributor, the risks of the key PFMs would remain high if the toe drain was simply replaced

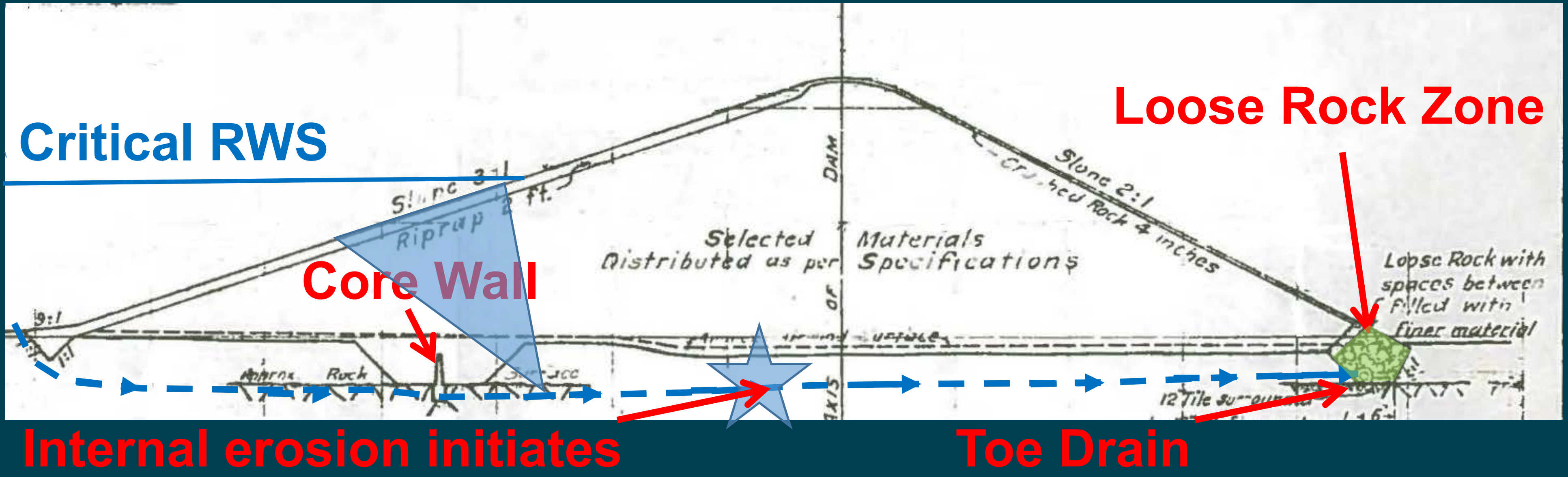
Example: Modification of Hyatt Dam, Oregon

- Controlling PFM 1: Internal erosion of the embankment (by backward erosion piping)



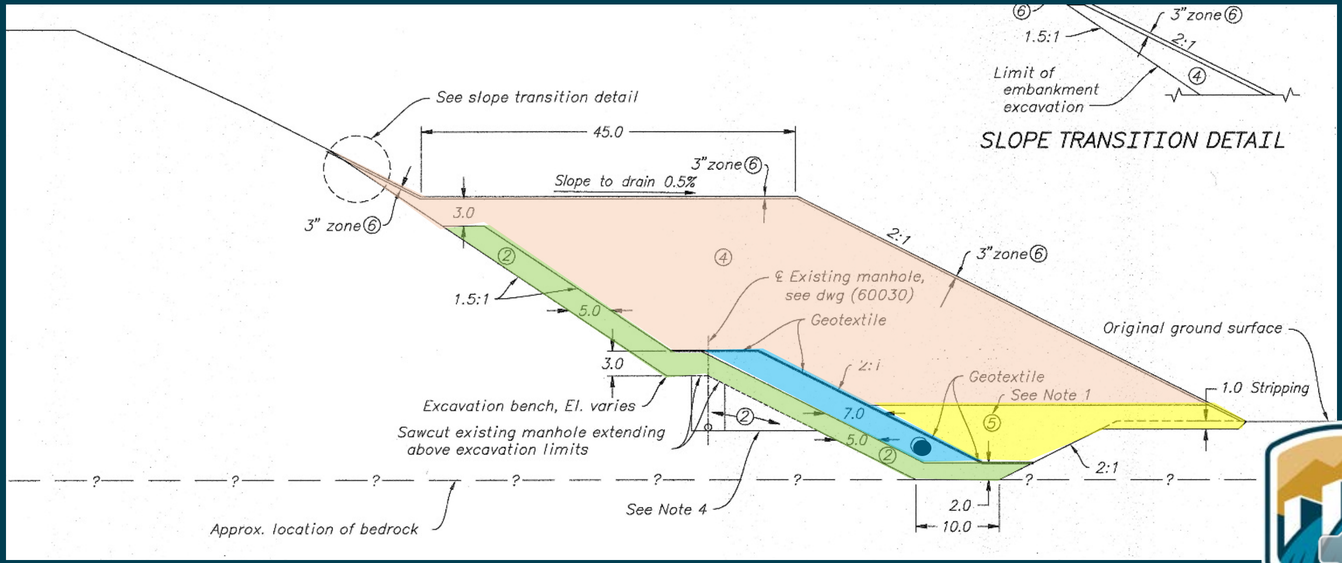
Example: Modification of Hyatt Dam, Oregon

- Controlling PFM 2: Internal erosion of the foundation along the contact between the rock and the overburden (by scour)



Example: Modification of Hyatt Dam, Oregon

- The Issue Evaluation indicated a relatively high risk of failure, with relatively high confidence in the overall portrayal of risk
- Recommendation was made to proceed into a corrective action study
- Dam was modified in 2017 to reduce the risk of internal erosion



RIDM and the Dam Safety Program

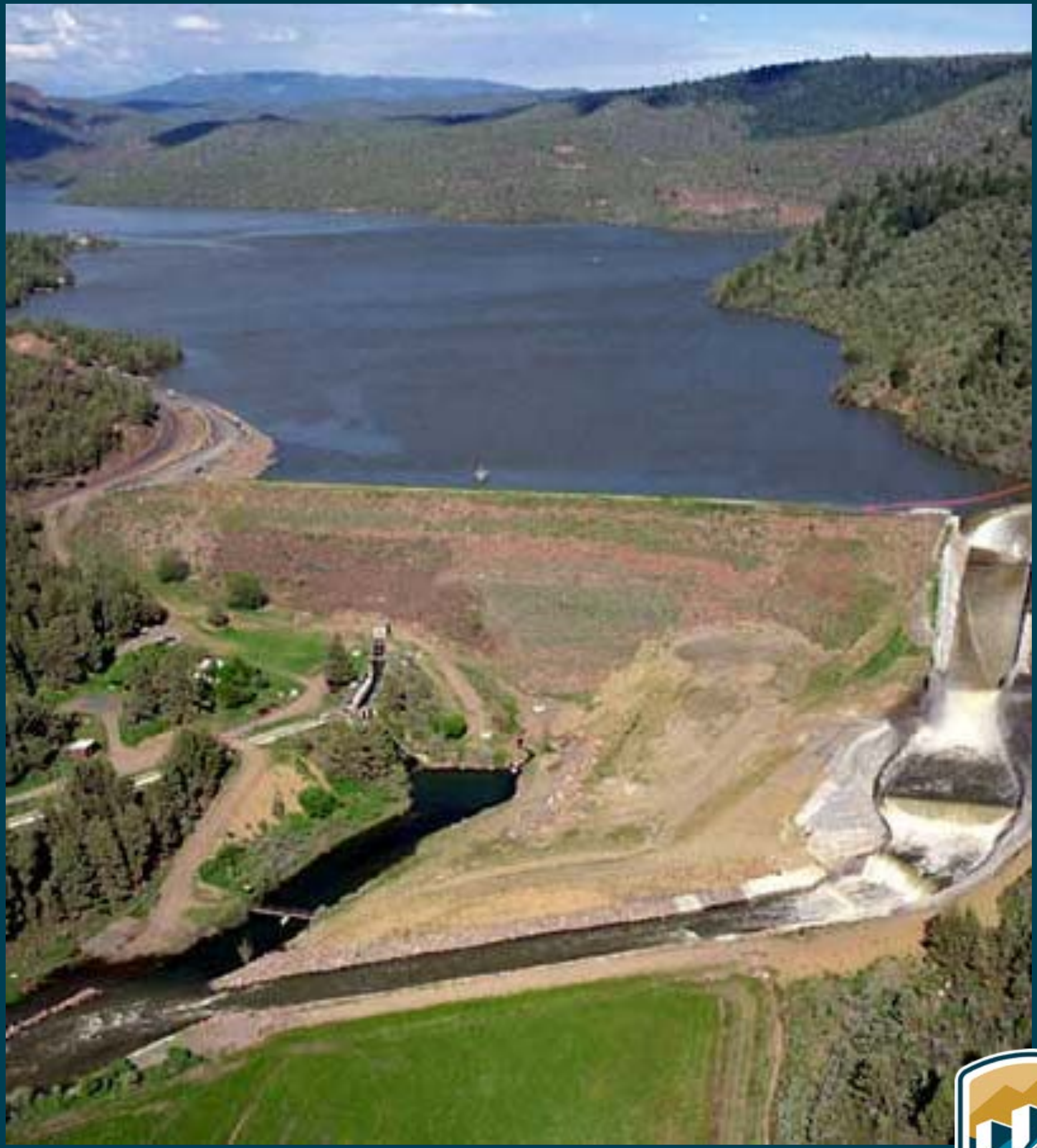
- Limited funding for dam safety work, must be approved by Congress
  - The budget for the Dam Safety Program represents only a percentage of Reclamation's overall operating budget
- We believe that the use of the RIDM process has resulted in limited dam safety funding being spent in a way that maximizes its impact
  - Don't spend it on non-dam safety issues
  - Address the most urgent issues first

Incorporating RIDM into a new dam safety program

- RIDM allows for a systematic way of prioritizing resources
- A key benefit of doing a risk analysis is that it helps improve a team's overall understanding of the dam's strengths and weaknesses
- However, the numbers generated in a risk analysis would be difficult to interpret in the absence of public protection guidelines
- Before introducing RIDM into a new dam safety program, it would be necessary to establish a similar set of guidelines
- Reclamation's PPG were developed specifically for the social, political and regulatory environment of the jurisdiction in which we operate. They may not be applicable to other jurisdictions

Future Challenges

- Reclamation is in the process of updating its Public Protection Guidelines
  - RIDM process continues to evolve
- Some of the topics on which new guidance is being prepared include:
  - Risk-informed design
  - Construction risk
  - Incident risk



Risk Informed Design

- Modifications to Reclamation dams are performed for a variety of reasons other than high estimated risk.
- Modifications can also involve increasing storage capacity or hydropower development. In these cases, Reclamation dams must be risk neutral (no net increase to the baseline risk).
- Regardless of who is designing the modification, Reclamation's design standards are considered, however; meeting the letter and spirit of the design standards does not in itself assure a risk neutral modification – risk analysis usually required before approval

Construction Risk

- Reasons why risk exposure might be different during construction:
  - Modification involves a temporary reduction in the minimum crest elevation, reduction in the spillway or outlet capacity, or excavation at the toe of the dam
- Risk management options:
  - Impose a temporary reservoir restriction
  - Schedule construction to minimize the time of critical excavation work
  - Updating the emergency Action Plan (EAP)
  - Select alternative with a relatively low construction risk

Incident Risk

- The February 2017 spillway incident at Oroville Dam (CA DWR) has had repercussions throughout the industry
- Although the incident did not involve a breach, there were major downstream impacts
- This had led to questions about what kinds of events should fall under the purview of a dam safety program

Incident Risk

- In the future, incident threats that are highly visible and with the potential to result in public disruption may fall under the Dam Safety Program
- However, since such incidents are not necessarily associated with a risk of life loss, so difficult to use the existing PPG to evaluate
  - Goal of the PPG is that our dams not increase the background risk of death for those downstream

Conclusions

- Our use of the RIDM process results in limited dam safety funding being spent in a way that maximizes its impact
- Our risk analysis methodology is philosophically transparent and mathematically simple
- RIDM process must continue to evolve in order to remain relevant
- A key challenge we face is ensuring that any changes we make to PPG are value added
- Proposed new guidance on incident risk will help both risk estimators and decision makers adapt to changing views on the role of our dam safety program

Thank you for your time and interest!

sstevens@usbr.gov

BC Hydro Dam Risk Assessment and Management

JK Lou

October 2021 Taipei

- 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**

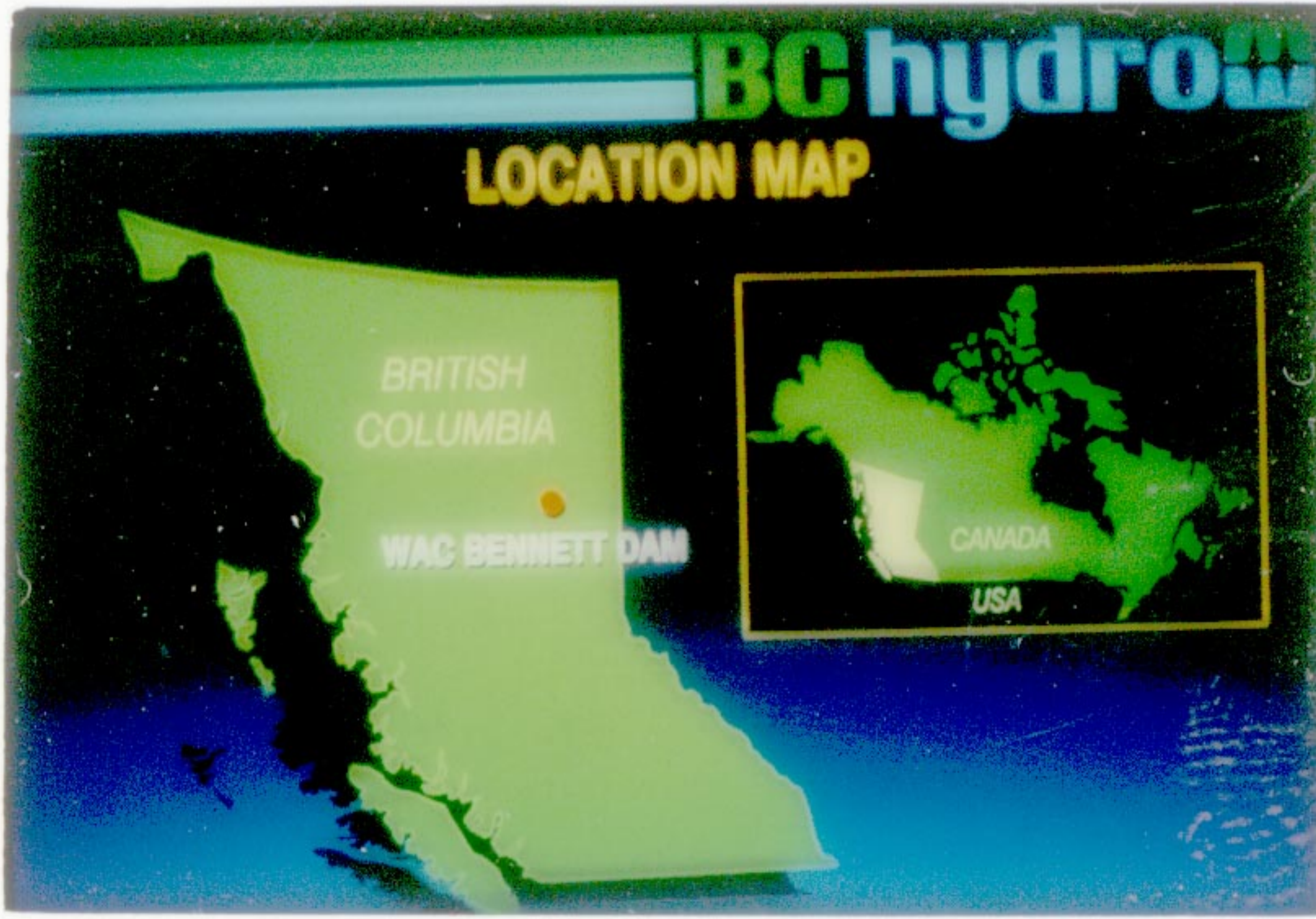
Dam Remediation

- 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

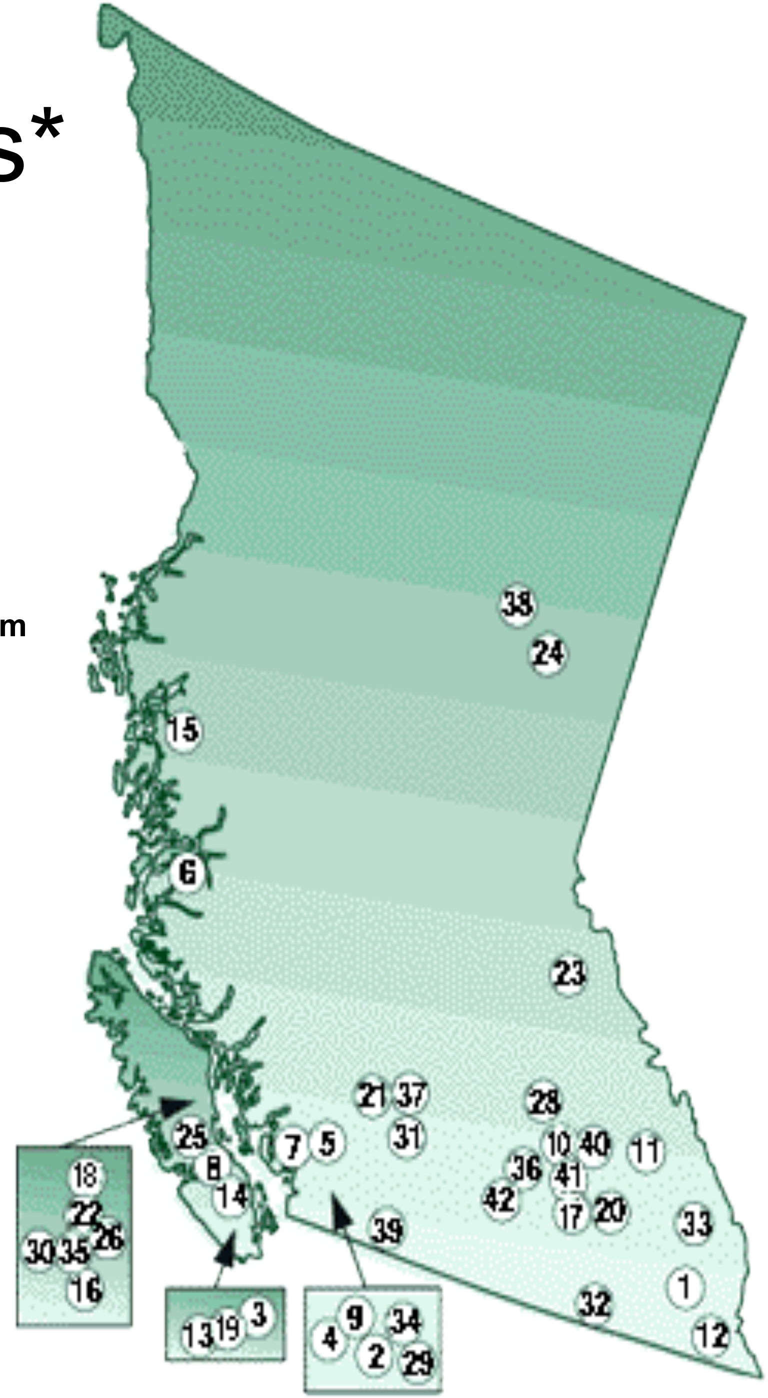
BC Hydro
Dam Risk Assessment
and Management


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

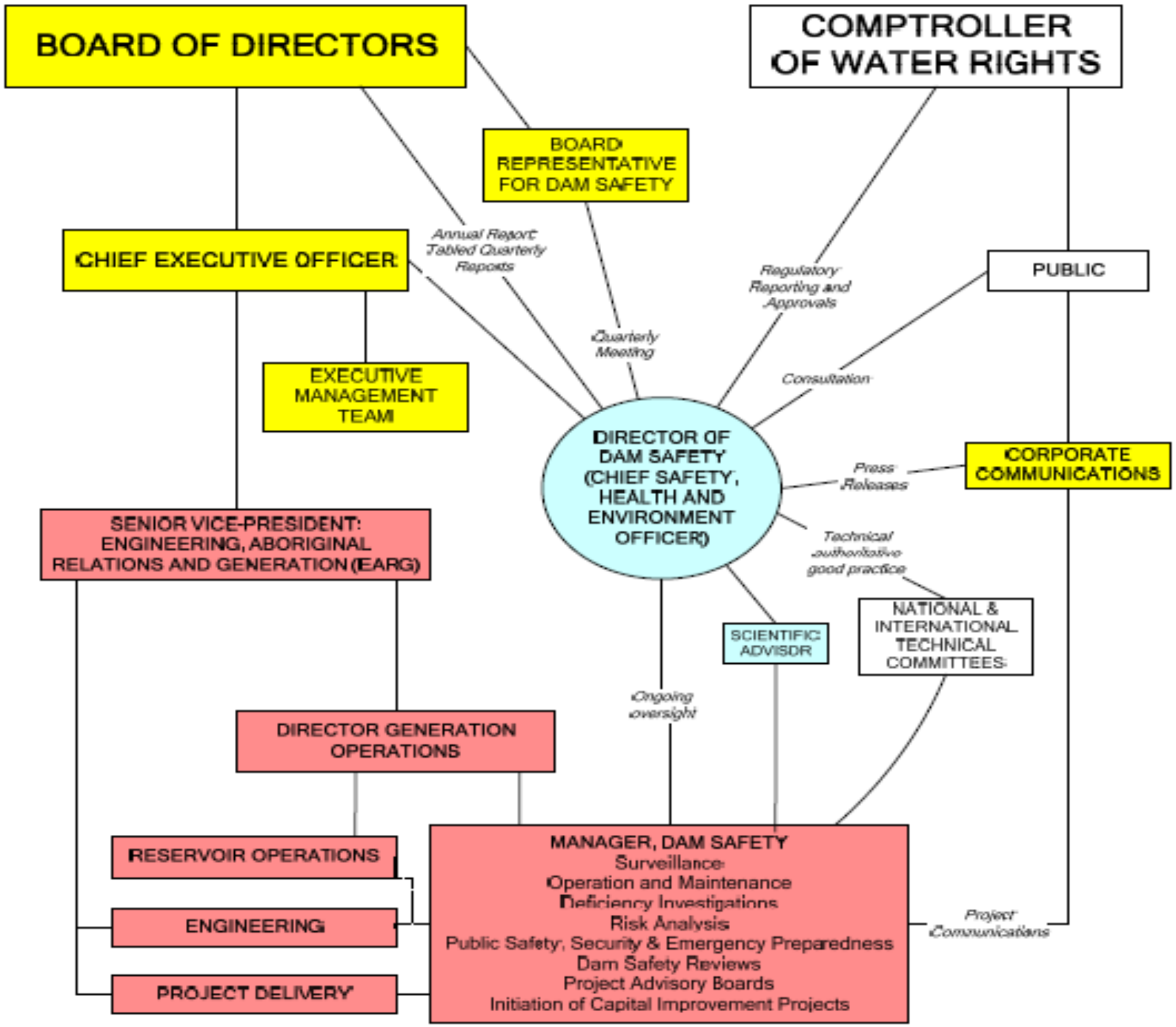
Risk-Informed Dam Safety Management

- 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

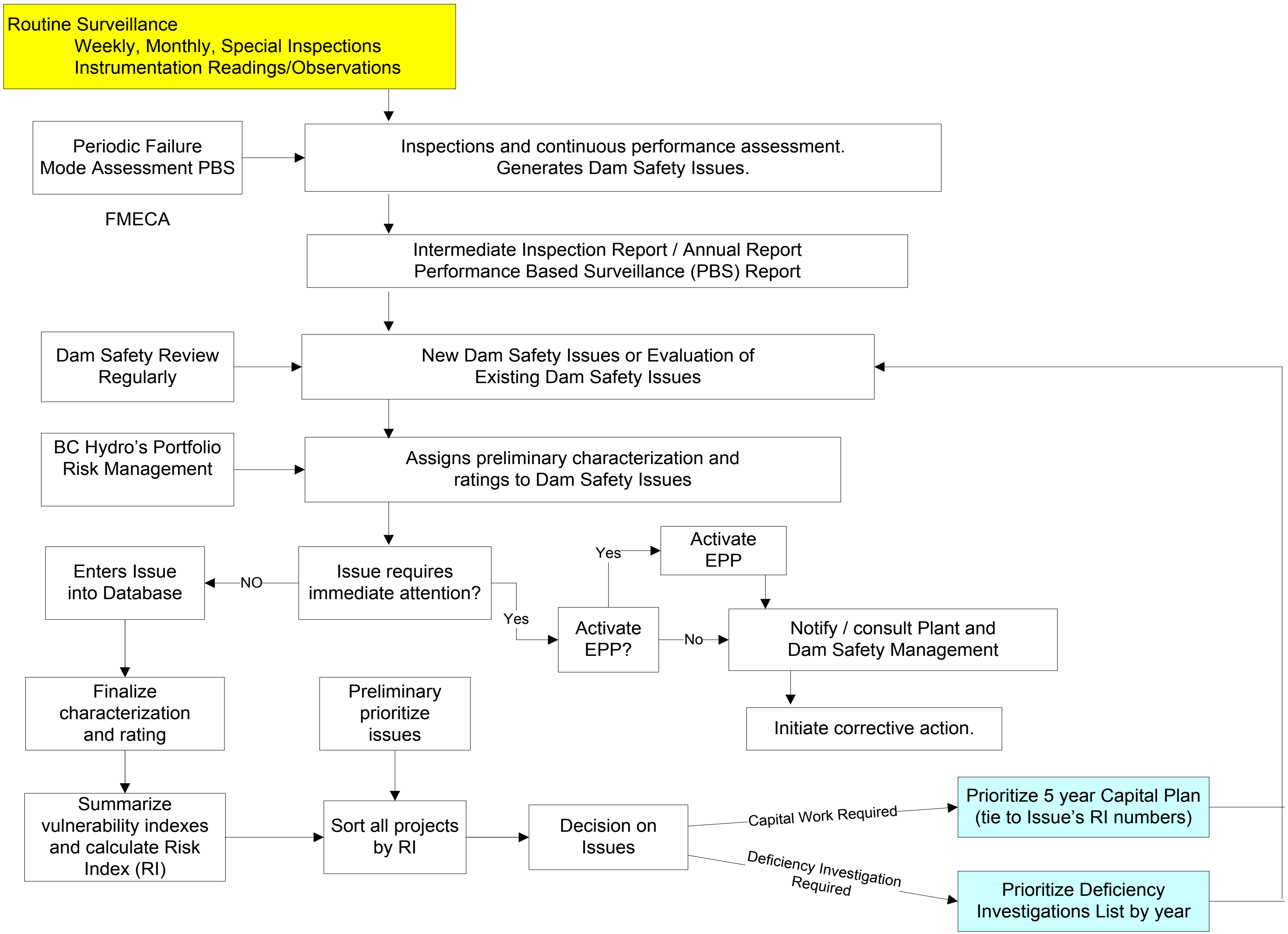
- The rule of business economy is to avoid catastrophic loss, not to make a lot of profit
- Invisible administrative achievement – the better the risk management, the less the problems occur – **NO INCENTIVES** for government officials to do dam risk management
- Private dam owner has to perform risk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

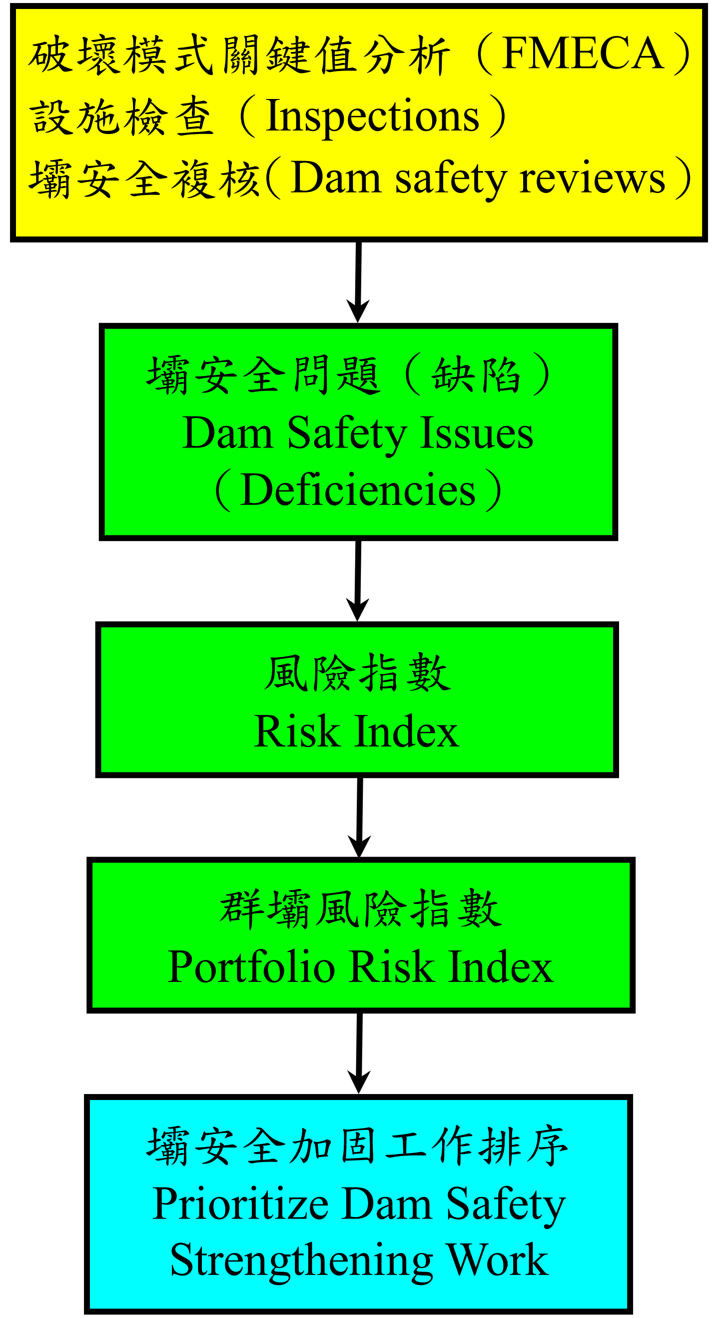


LIFE CYCLE OF A DAM SAFETY ISSUE

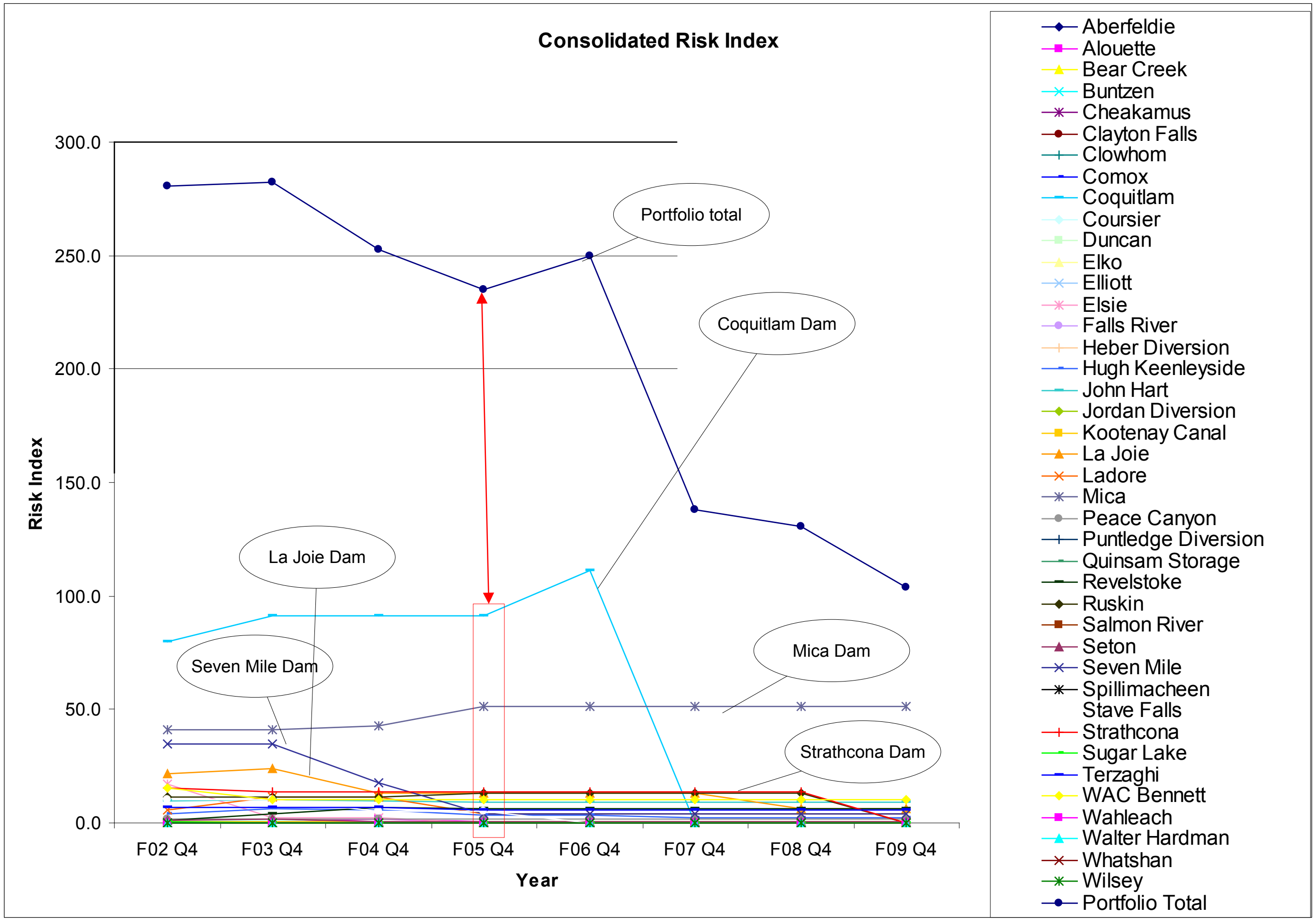
Portfolio Risk Assessment (PRA)

- 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



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

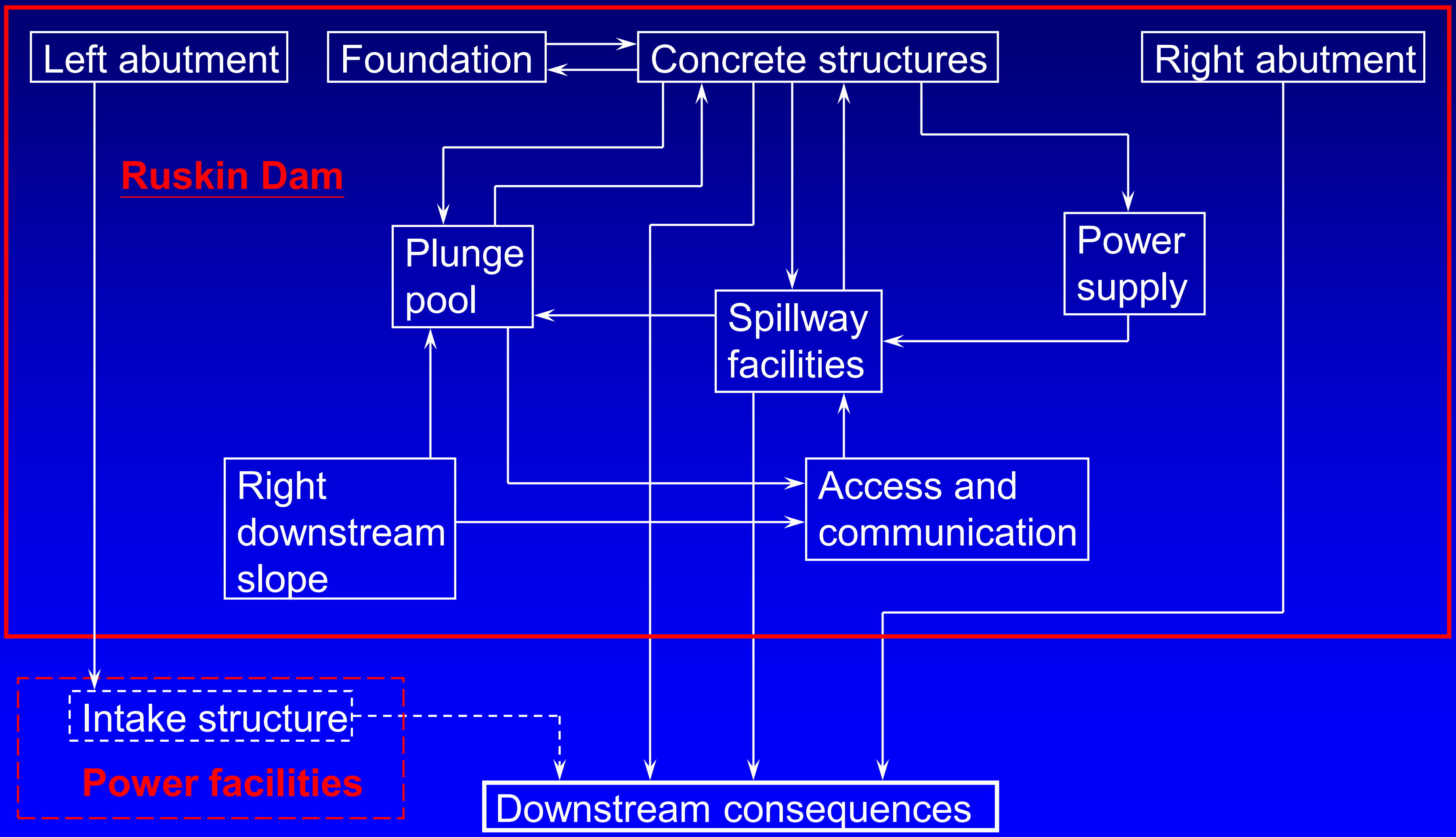


Table 2 sheet 3 of 31

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

THE IMPLEMENTATION OF ZENGWEN RESERVOIR RISK ANALYSIS (PFMA AND BEST PRACTICE)

HSUAN-MEI HSIAO (SUNNY)

Associate Engineer, Southern Region Water Resources Office, Water Resources Agency, MOEA

OUTLINE

01. About Zengwen Reservoir

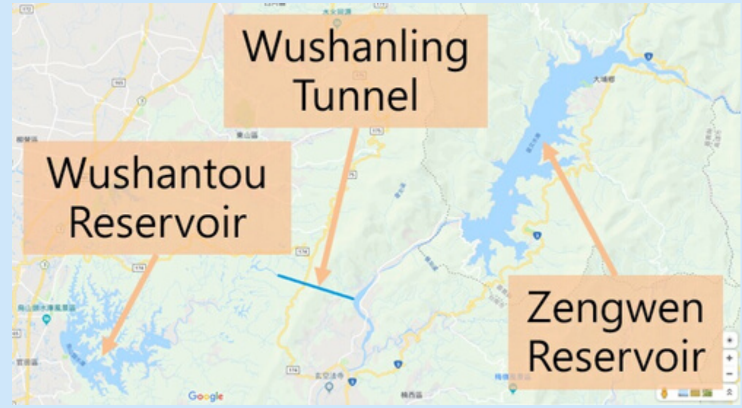
02. Experience in FERC's Methods

03. Experience in USBR's Methods

04. Lessons Learned

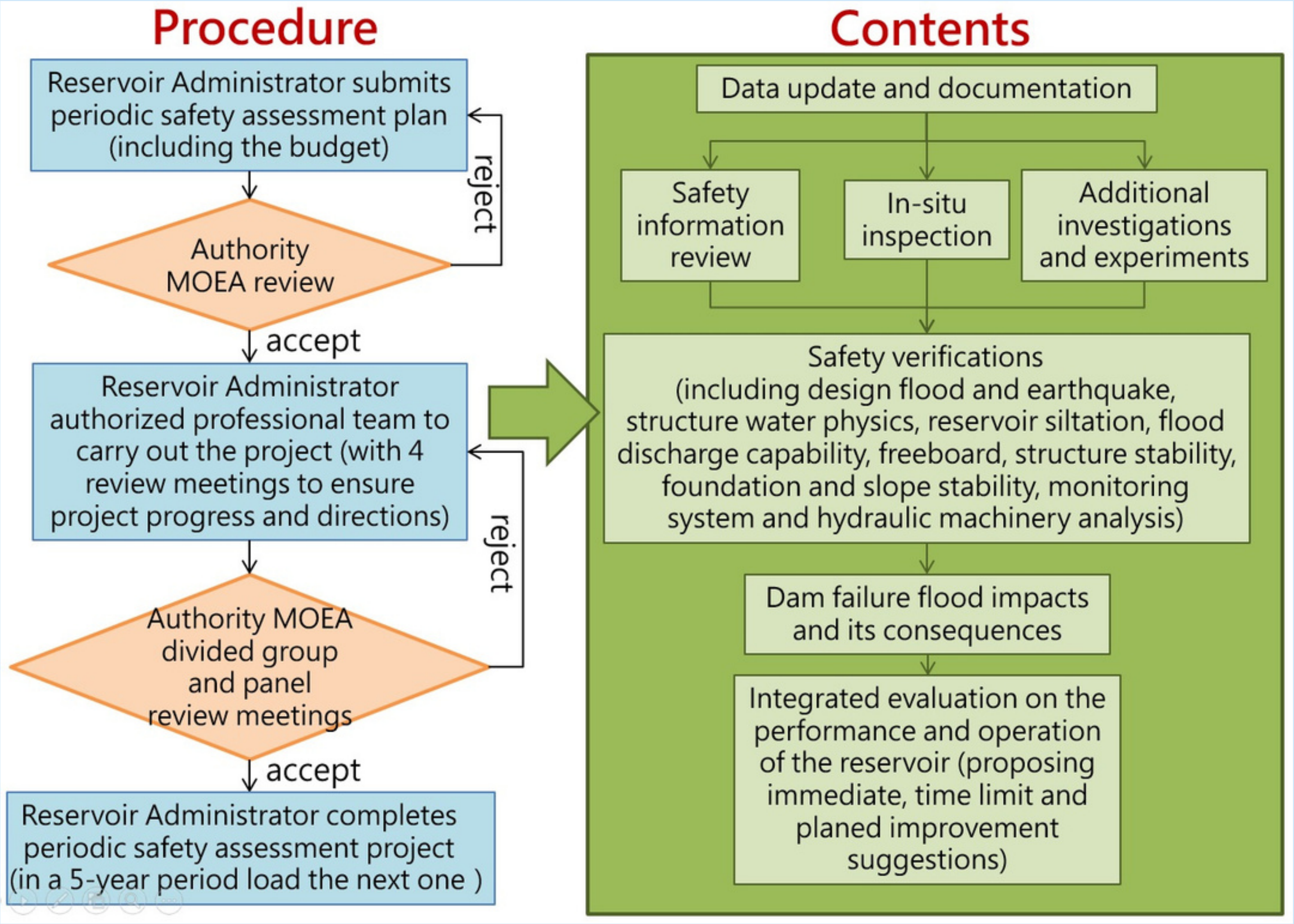
ZENGWEN RESERVOIR

- Irrigation
- Water Supply
- Power Generation
- Flood Mitigation
- Tourism
- Education



Capacity	$509,560,000m^3$
Crest EL.	EL.236m
Dam Height	134m
Crest Length	400m
Water Area	$18.93km^2$
Catchment	$481km^2$

DAM SAFETY REGULATION

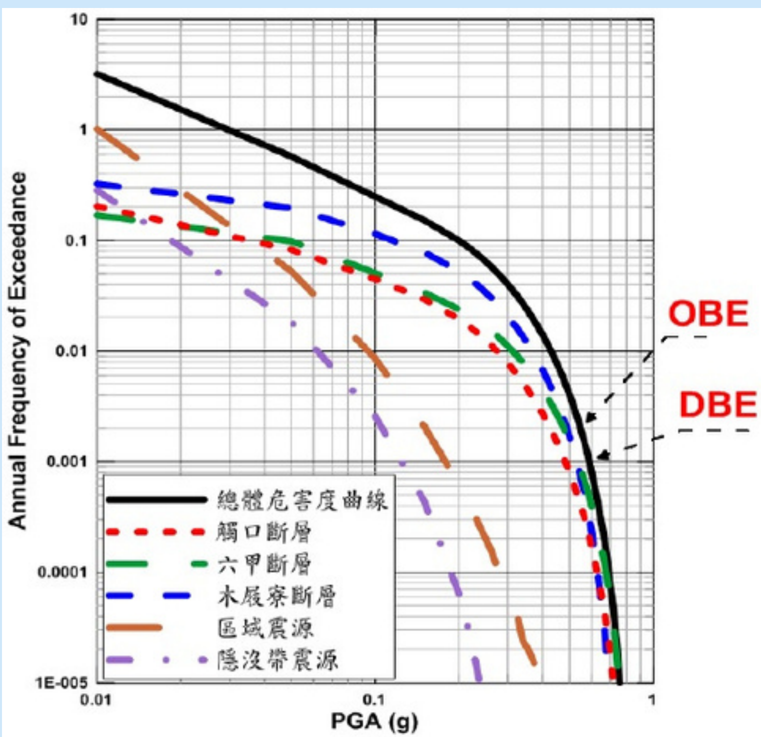


OUR SAFETY ASSESSMENTS

1987	1998	2000	2004	2011	2017
#1	#2	Chichi EQ	#3	#4	#5
PERIODIC	PERIODIC	SPECIAL	PERIODIC	PERIODIC	PERIODIC

#2 PGA=383gal

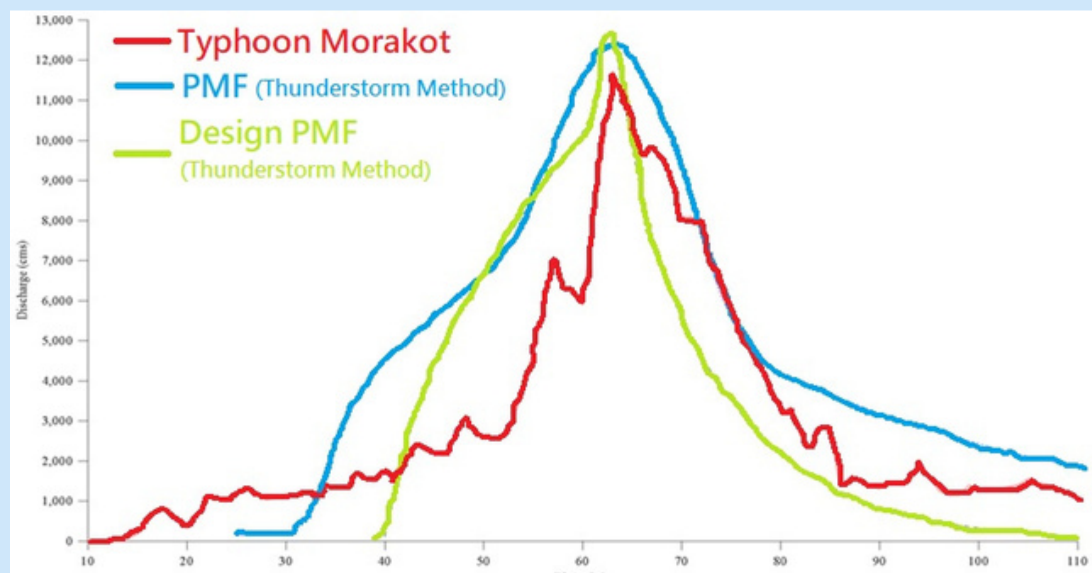
2000 Chichi EQ #5 PGA=628gal



#3 PMF=12,430cms

2009 Typhoon Morakot Qp=11,729cms

#5 PMF=12,958cms



REFORM PROJECTS

CORE HEIGHTENING

EXCAVATION

HYDRAULIC DREDGING

INTERCEPTING

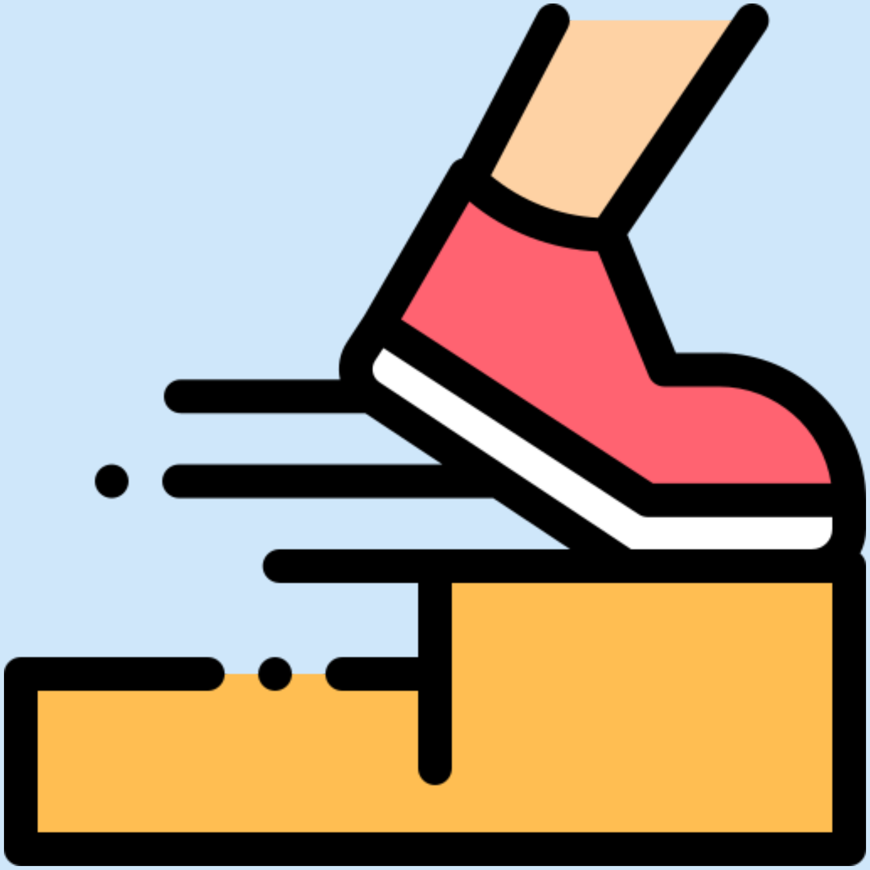
INTAKE EXTENDING

SLUICING/FLUSHING

"Why not go one step further?"

Risk Informed Decision Making

Risk Management



Potential Failure Mode

Event Tree & Risk Matrix

@Freepik

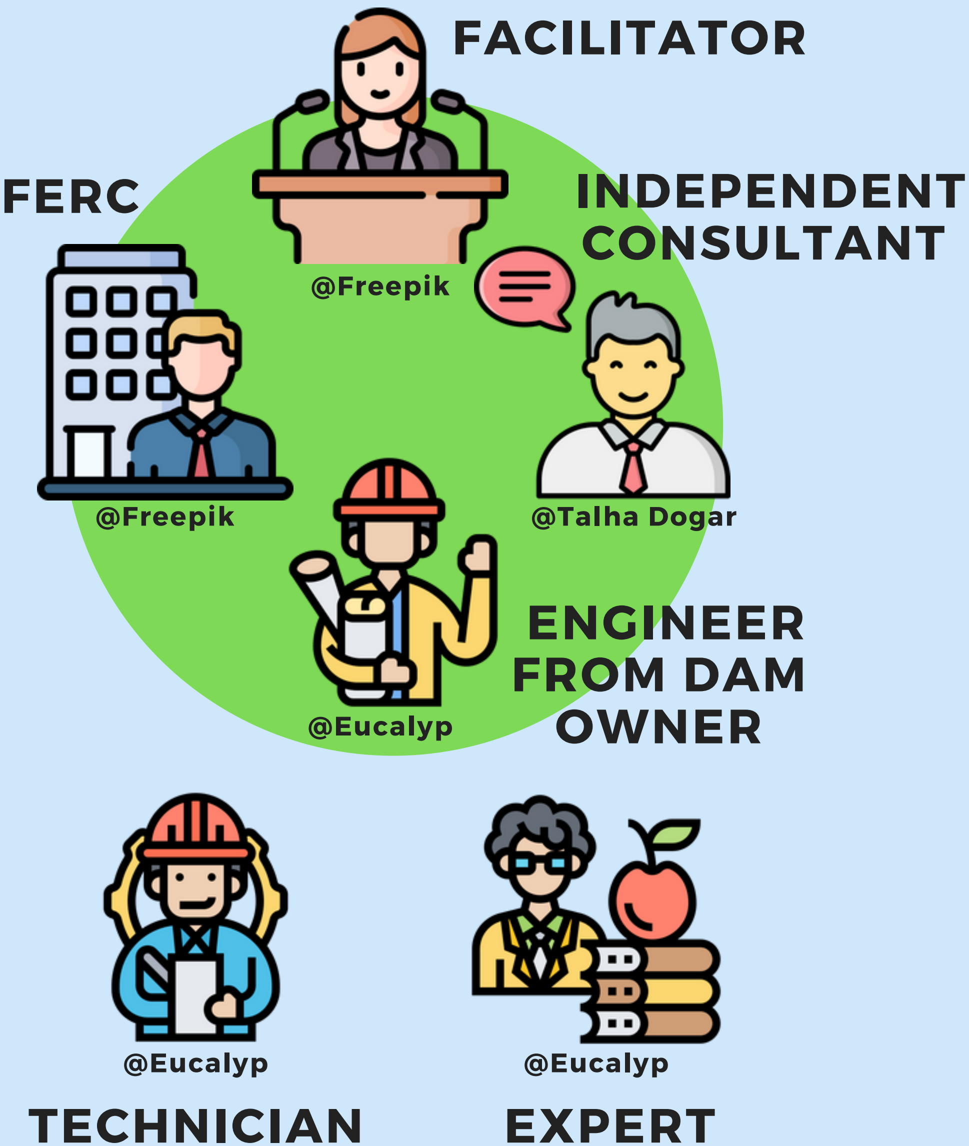
POTENTIAL FAILURE MODE ANALYSIS SEMINAR

BY INDEPENDENT CONSULTANTS

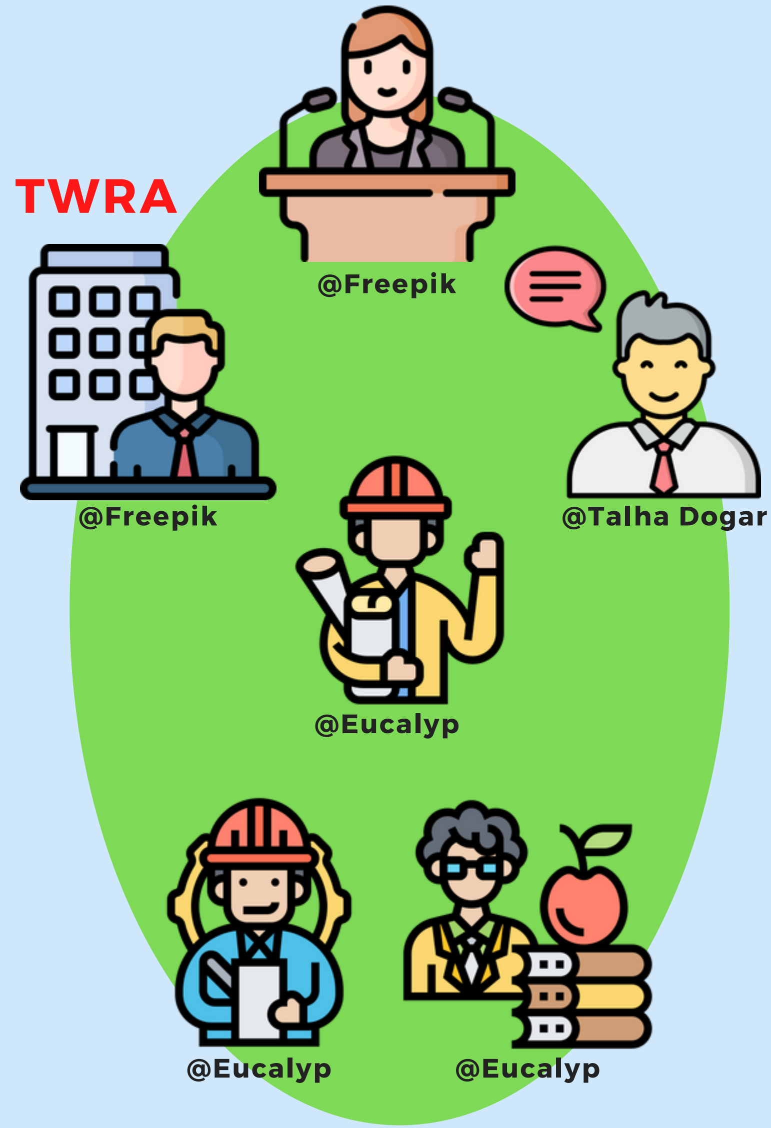
Target: Mudan, Zengwen and Agongdian Reservoir (2016, 2017 and 2019)

PARTICIPANTS

FERC



ZENGWEN CASE



POTENTIAL FAILURE MODE ANALYSIS SHEET

LOAD CASE:	
PFM No.1: (Identify The Failure Process In Detail)	
Facts and Conditions: (List Facts Related To The Process)	
Favorable Conditions: (List Facts And Conditions That Slow Down or Stop the Process)	**Adverse Conditions:** (List Facts And Conditions That Speed Up Or Cause The Process)
Category Voting Result:	
Explanation: (List Reasons to Vote For Each Category)	
Possible Risk Reduction Measures: (List Measures That Can Decrease The Risk)	

SUPPORTING INFORMATION: GRAPHS, SHEETS, PHOTOS

Categories	
I	Highlighted Potential Failure Modes
II	Potential Failure Modes Considered but not Highlighted
III	More Information or Analyses are needed in order to classify
IV	Potential Failure Mode Ruled Out

PFMA PROCESS

Stage One

WRASB form working group

Dec 2016 ~March 2017

↓

Propose candidate PFM & complete PFMA sheets draft

↓

Stage Two

Core team formed

21th ~23th March 2017

↓

Review safety assessment report, PFMA sheets draft and in-situ inspections

↓

Confirm & complete PFMA sheets

↓

Safety assessment project team produce PFMA report

↓

PFMA report included in safety assessment project

PFMA RESULTS (SUMMARY)

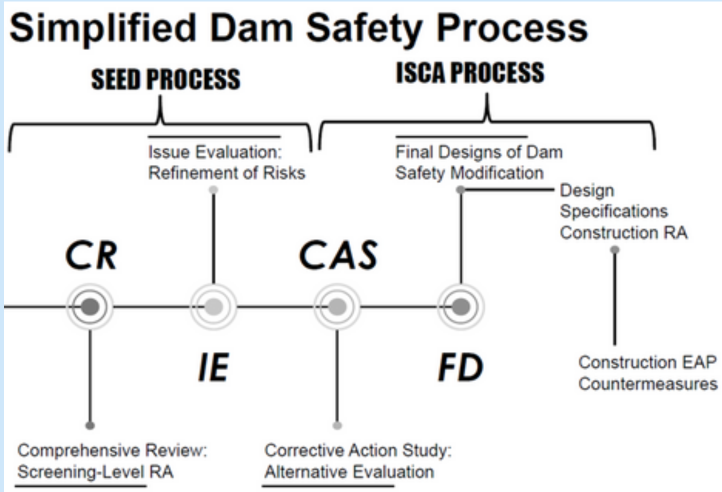
PFM	Failure Process (Summary)	Loading	Category
1	Typhoon → Flood Operation → Water Area Landslide → Storage Capacity Decreased → **Overtopping**	**Flood (PMF)**	**II-8, IV-12**
2	RWL > EL.227m → Downstream Phreatic Surface > EL.215m → Internal Erosion → **Piping**	**Flood**	**II-15, III-3**
3	Water Level > EL.230m → Seepage Increased → Core Material Lost through Shear Zone → **Piping**	**Flood**	**II-18**
4	Typhoon → Flood Operation → Spillway Gate Electric or Mechanic Failure → **Overtopping**	**Flood**	**II-18**
5	EQ Trigger Dam Site Cracks → Displacement → Transverse Cracks → Leakage → **Piping**	**EQ (MCE)**	**II-12, IV-5**
6	Typhoon → Flood Operation → Spillway Chute Cavitation → Spillway Wall Overtopped → Dam eroded → Spillway Gate Shut Down → **Overtopping**	**Flood**	**II-15, IV-3**
7	MCE → Spillway Damaged → Can Not Be Repaired → Flood Operation (PRO) → **Overtopping**	**EQ (MCE) Flood**	**III-18**
8	Typhoon → Flood Operation → Catchment Landslide → Storage Capacity Decreased → **Overtopping**	**Flood (PMF)**	**II-7, IV-9**

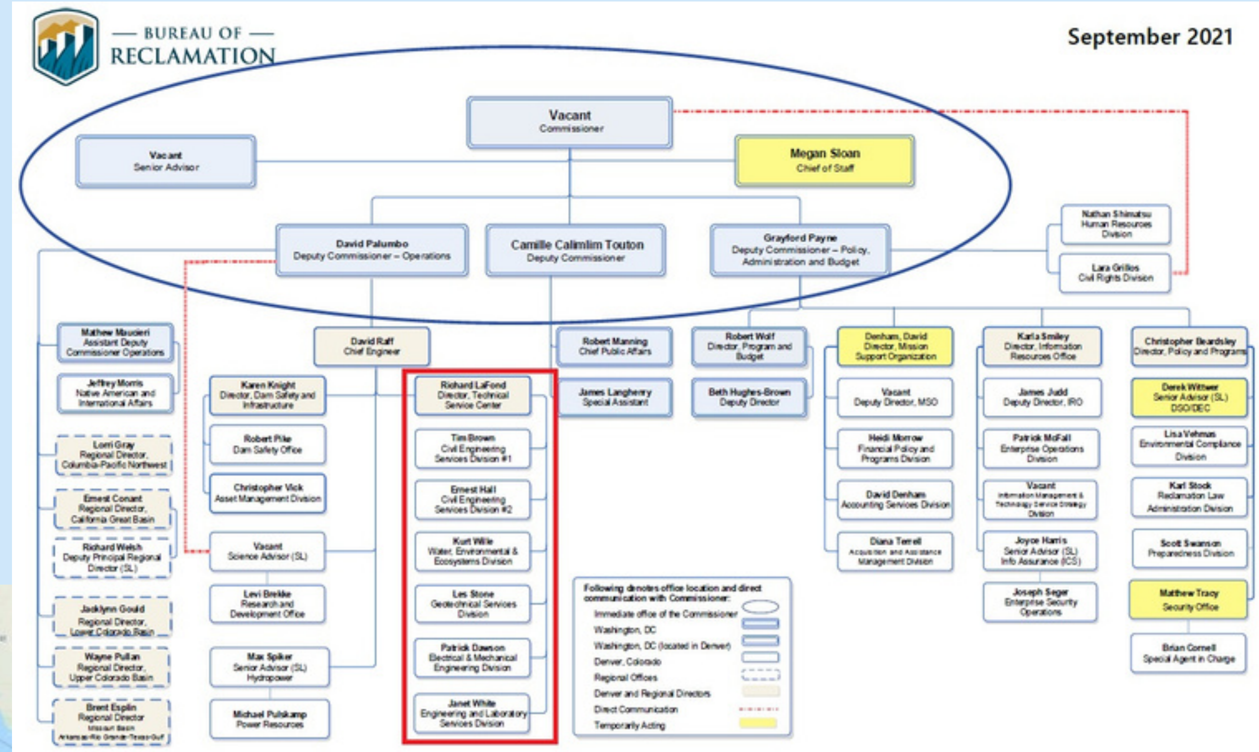
THE TECRO-AIT WATER RESOURCES COOPERATION

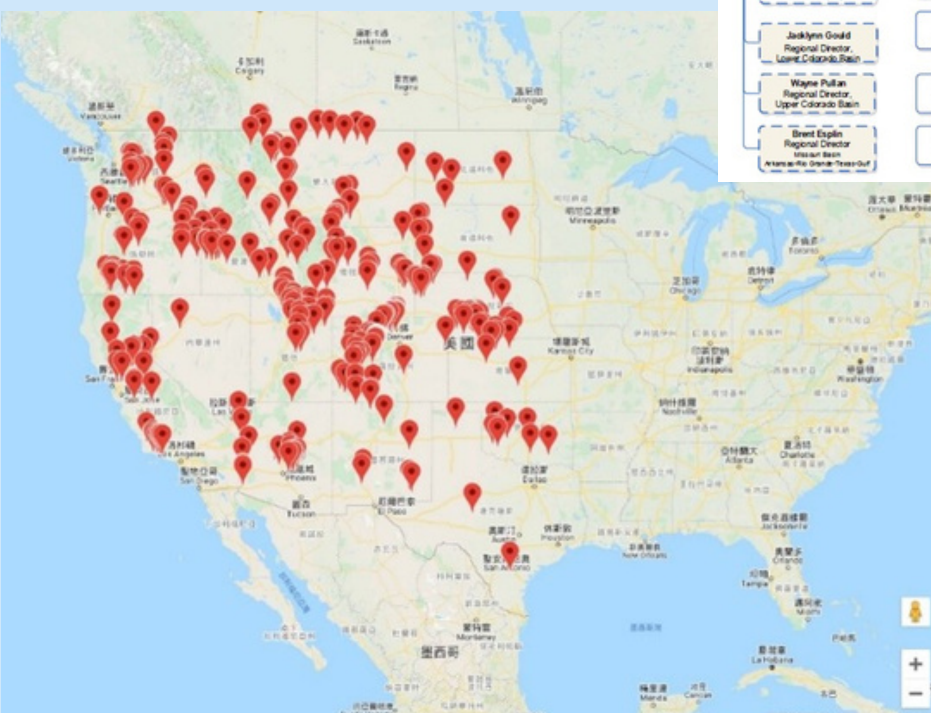
BETWEEN USBR AND TWRA

Appendix 6: The introduction of risk management for dam safety assessment (2019~2021)

PARTICIPANTS





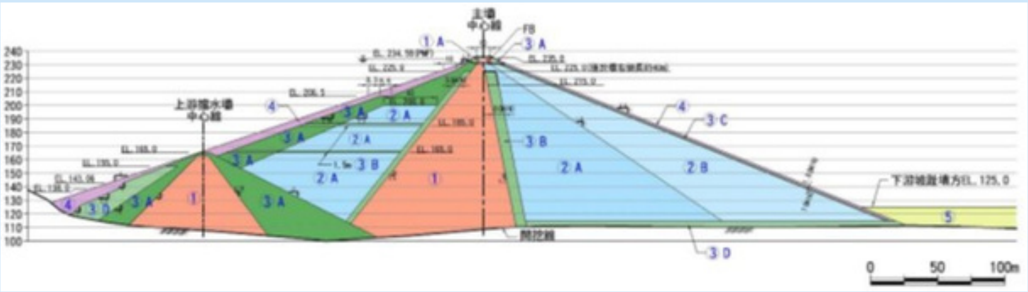


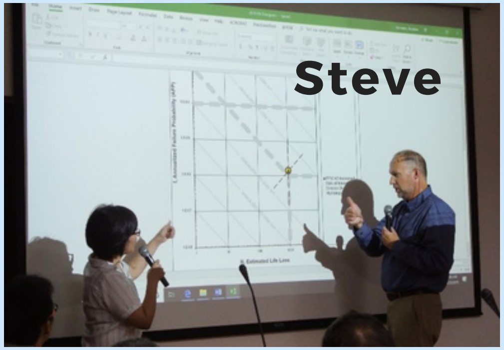
THE RECLAMATION

- MAINTAINS 491 DAMS
- TECHNICAL SERVICE CENTER
- CR: ~30 FACILITIES/YEAR

BEST PRACTICE TOPICS (2020)

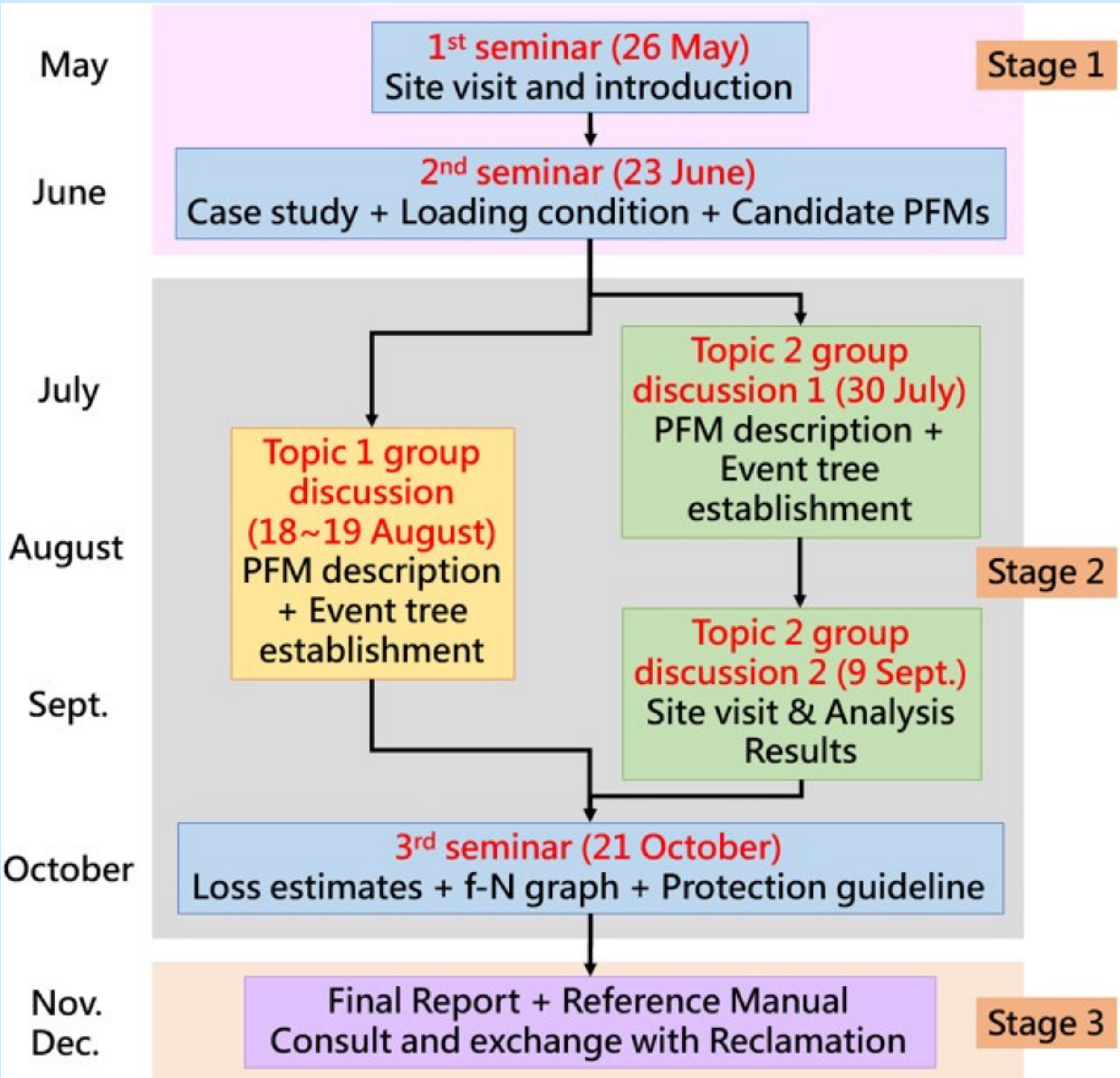
TOPIC 1
INTERNAL EROSION FAILURE



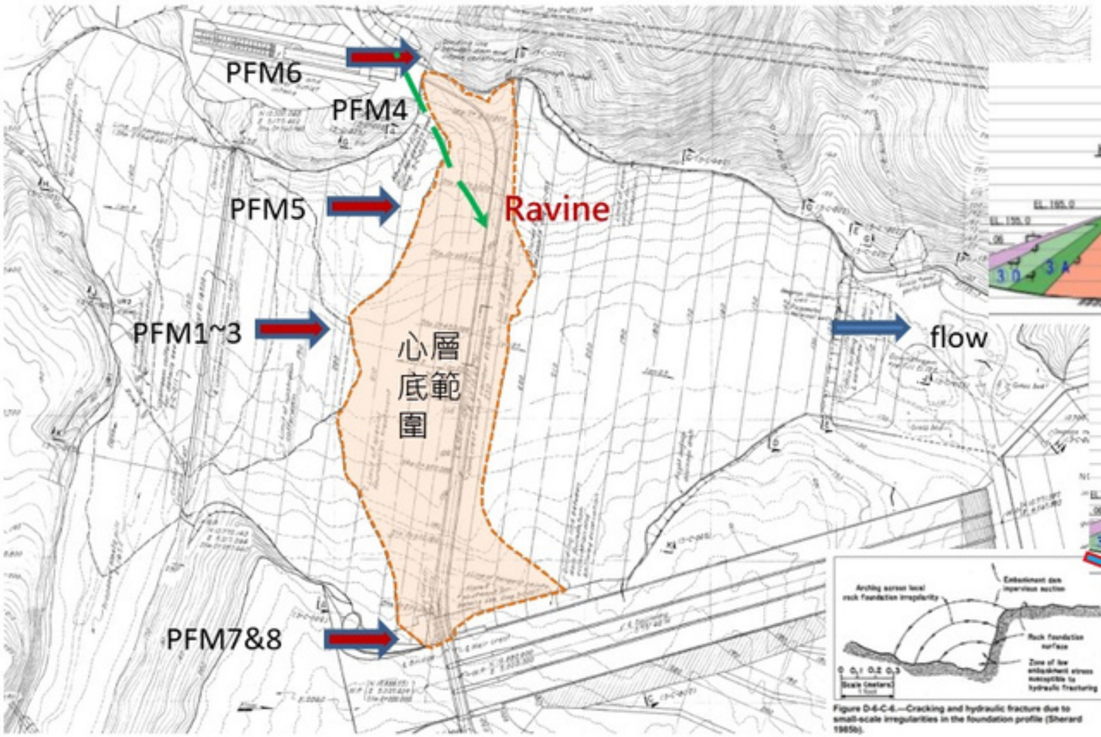


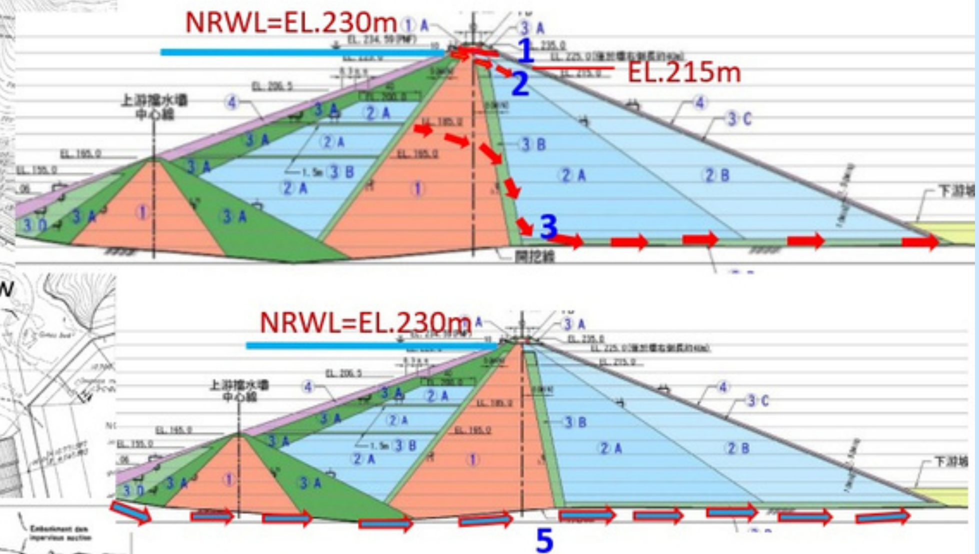
TOPIC 2
RADIAL GATE SEISMIC FAILURE

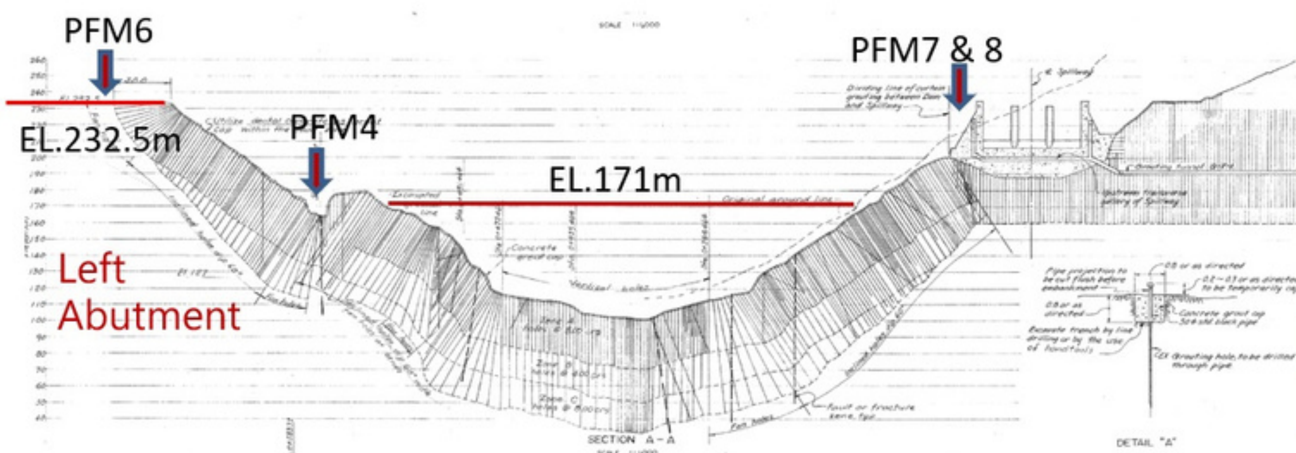
BEST PRACTICE PROCESS (2020)



INTERNAL EROSION PFM (2020)



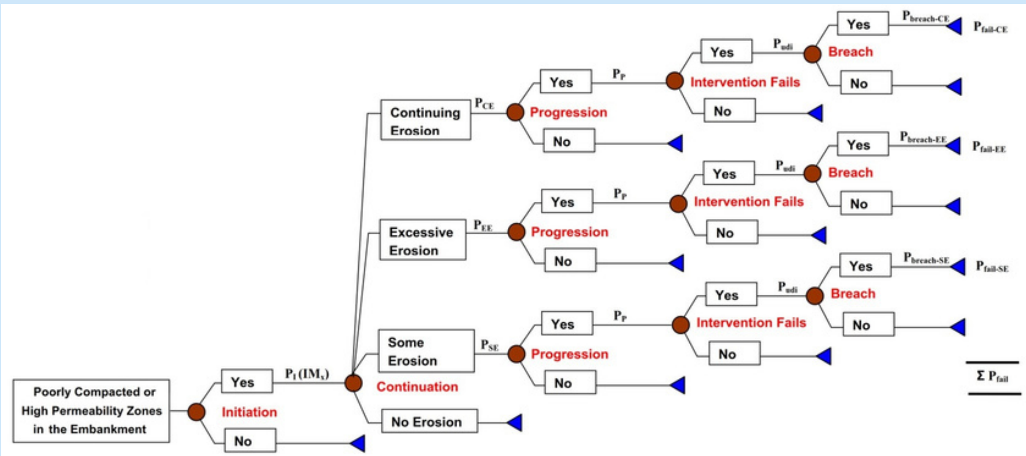




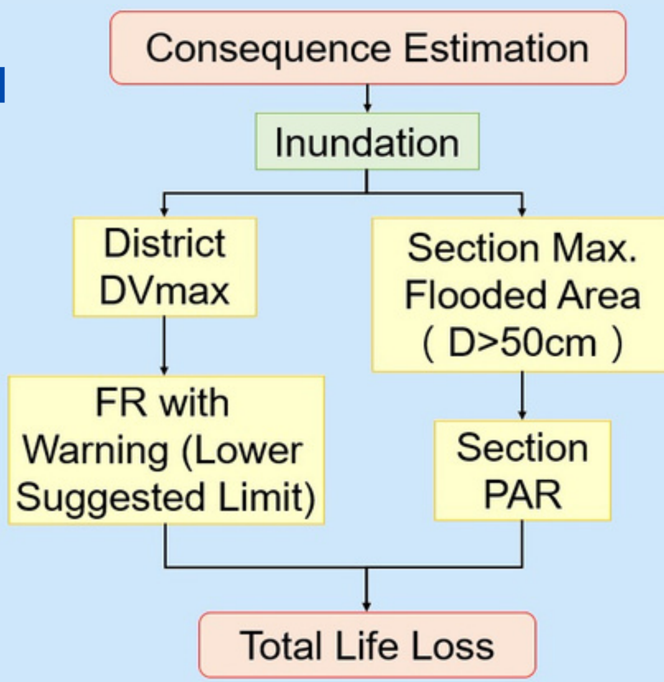
Critical Elevations (EL. m)	
234.59	Max. RWL (PMF)
232.5	Top of Grouting Curtains at Left Abutment
231.3	Boundary of Crest Heighten Construction
230.0	Max. NRWL since 2018
227.0	Max. NRWL during 2001~2017
215.0	Top of Downstream Filter
171.0	Silting Elevation

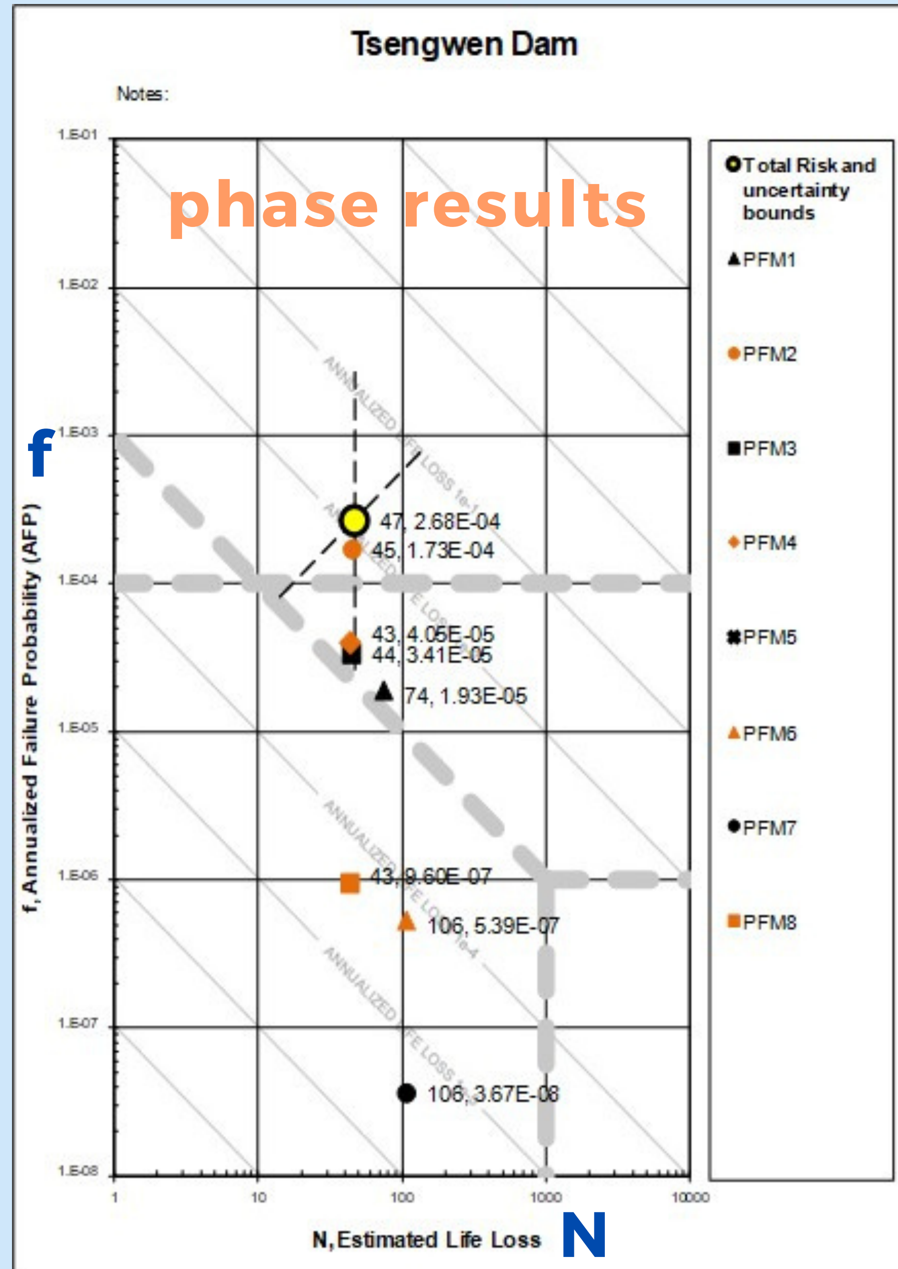
IE RISK ANALYSIS (2020)

f: failure probability

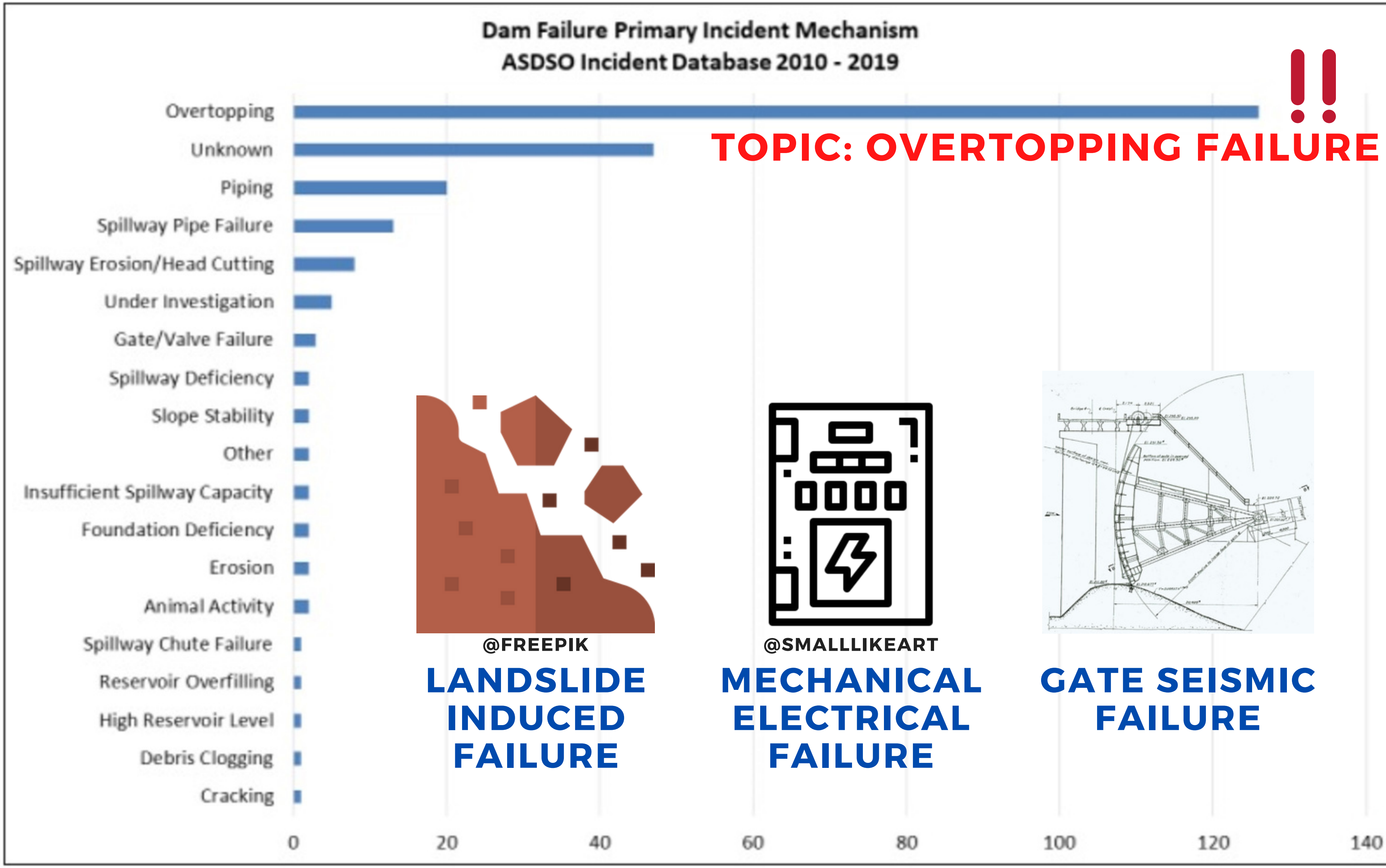


N: estimated life loss





BEST PRACTICE TOPIC (2021)



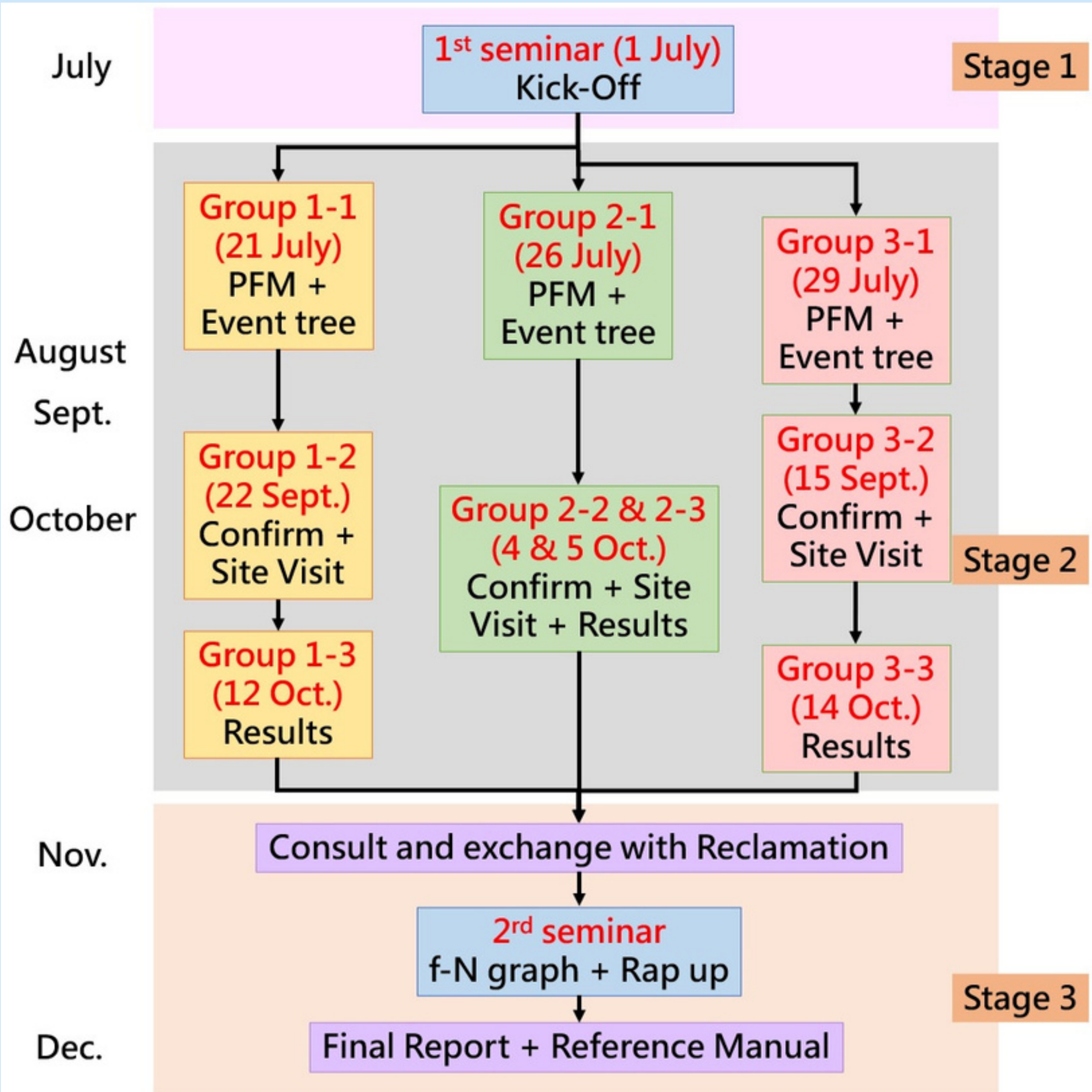
TOPIC: OVERTOPPING FAILURE

LANDSLIDE INDUCED FAILURE

MECHANICAL ELECTRICAL FAILURE

GATE SEISMIC FAILURE

BEST PRACTICE PROCESS (2021)



"What have we learned?"

Risk Informed Decision Making

Risk Management

Potential Failure Mode

Event Tree & Risk Matrix

@Eucalyp

WE LEARNED TO……

@Eucalyp

DISMANTLE THE FAILURE PROCESS

@Smashicons

FIND OUT INFORMATION

@monkik

GET CLOSER TO REALITY

@Freepik

BRAINSTORM TOGETHER

TO GO FURTHER WE NEED......

@Freepik

GUIDANCE FOR IMPLEMENTATION

@Freepik

FACILITATOR TRAINING

@Freepik

PUBLIC AWARENESS

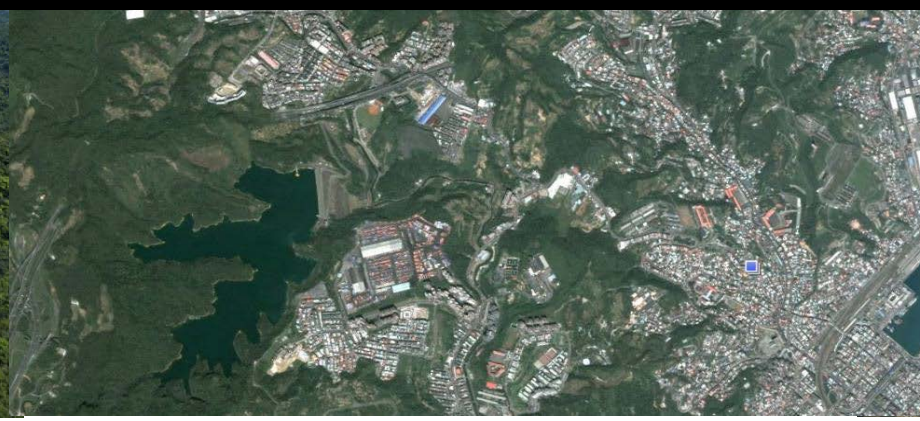
@smalllikeart

TO EXERCISE THE BALANCE

THANK YOU FOR YOUR ATTENTION!

FOR MORE INFORMATION, PLEASE CONTACT:
HMHSIAO@WRASB.GOV.TW

Feitsui dam risk analysis-
PFMA based on FMECA

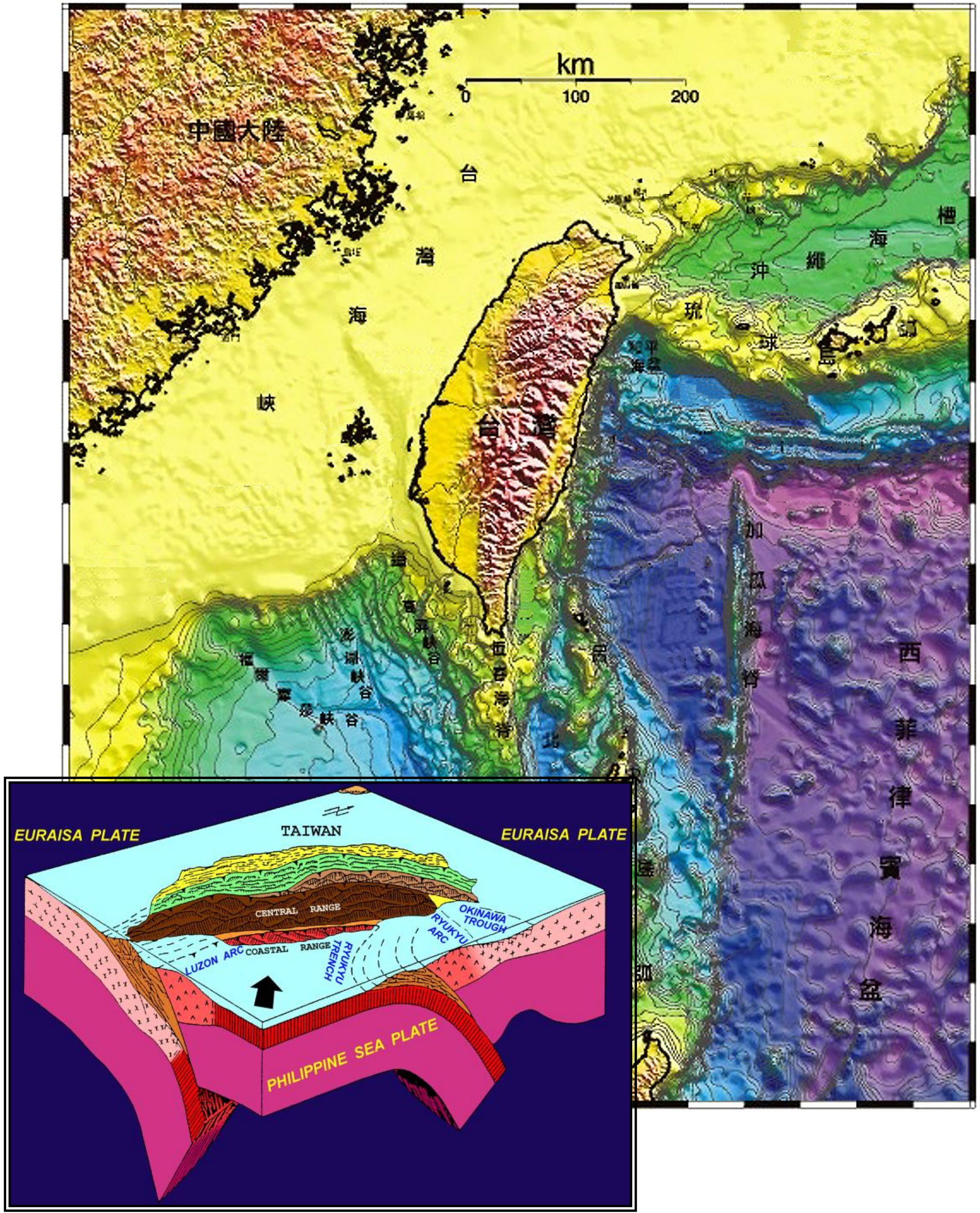

Sinotech Engineering Consultants, Inc.
Hsien-Chang Kao

October 2021

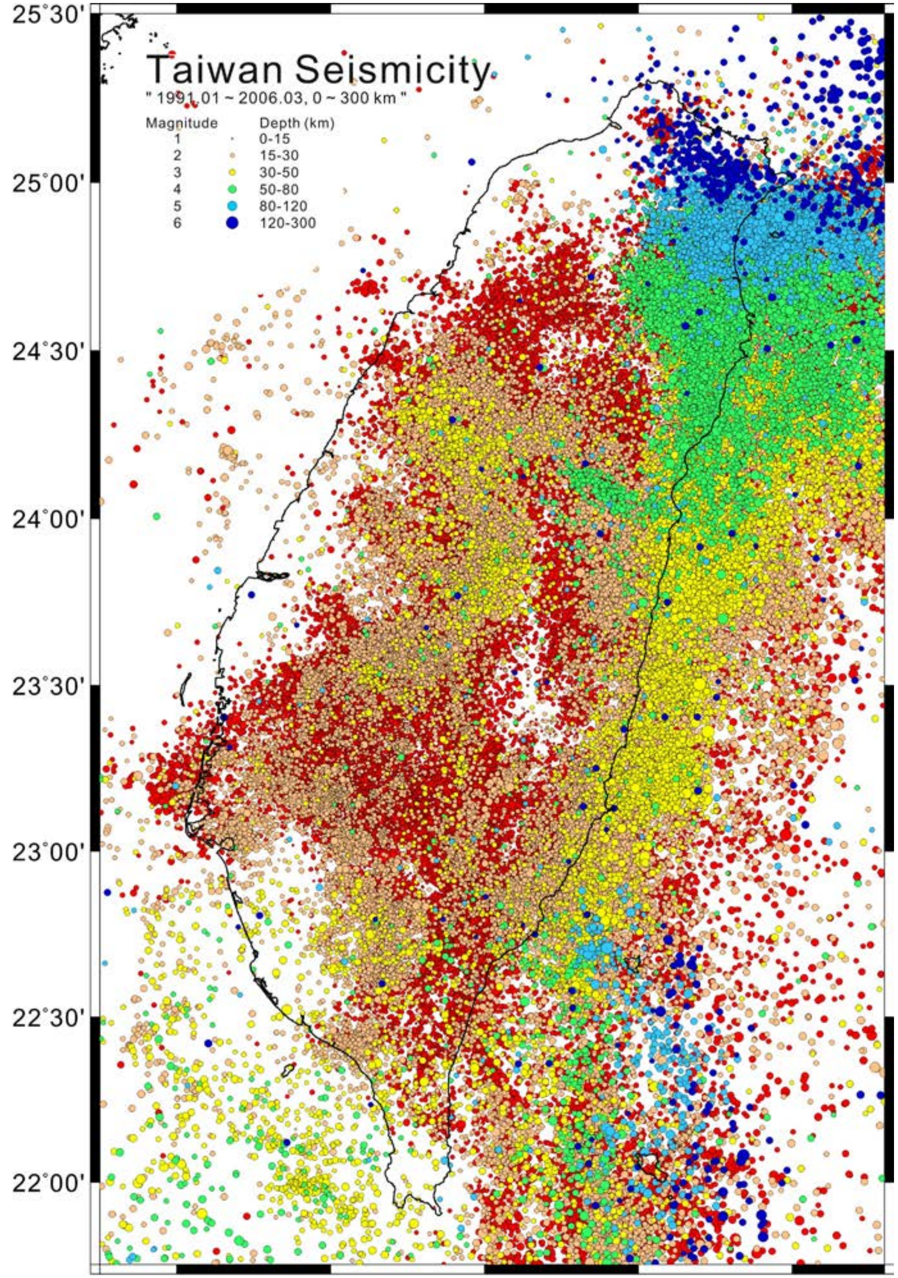
Overview

1. Dams in Taiwan
2. Introduction of Feitsui Dam
3. Dam risk management
4. Why FMECA
5. Potential failure modes identified

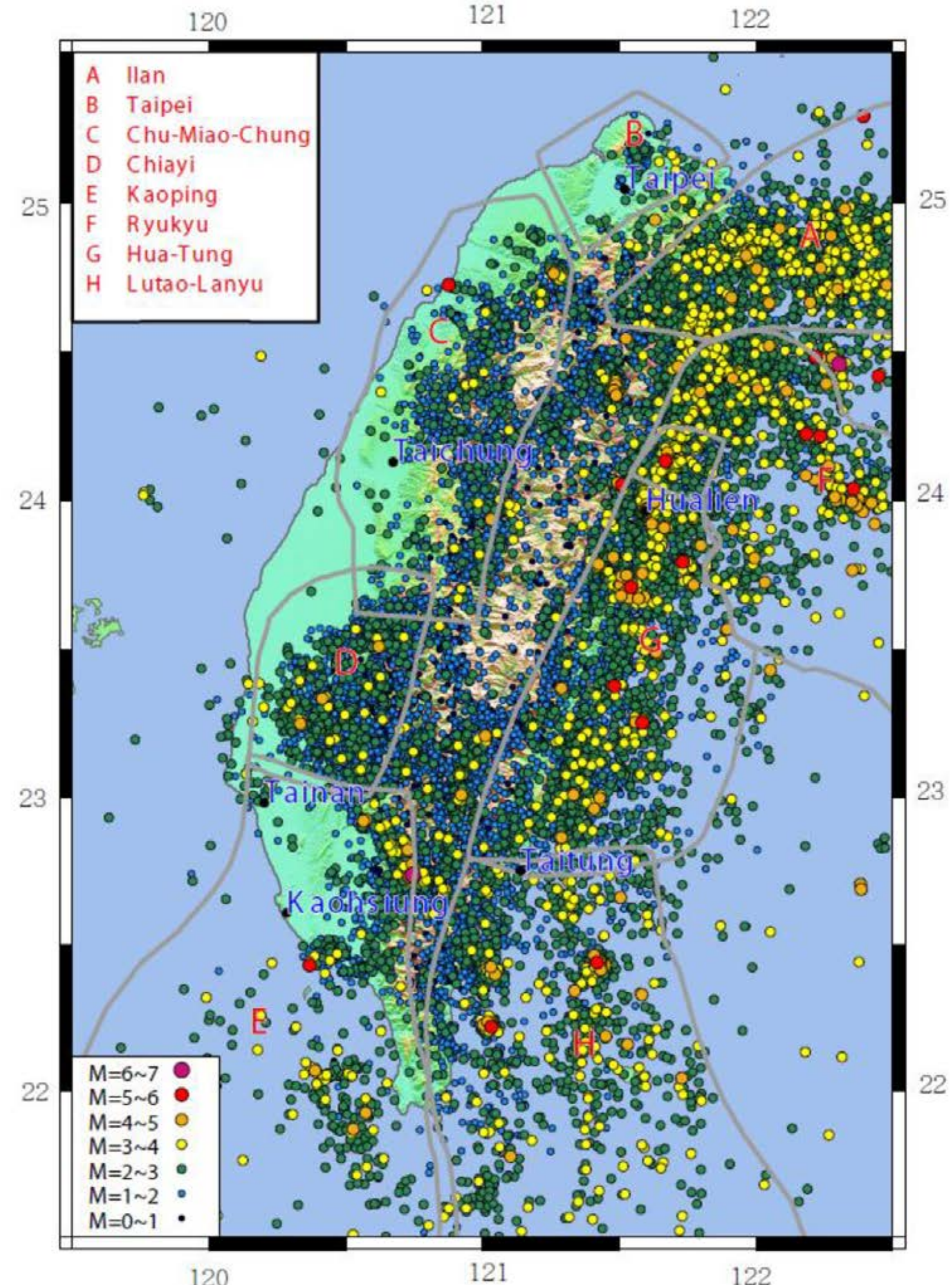
SINOTECH



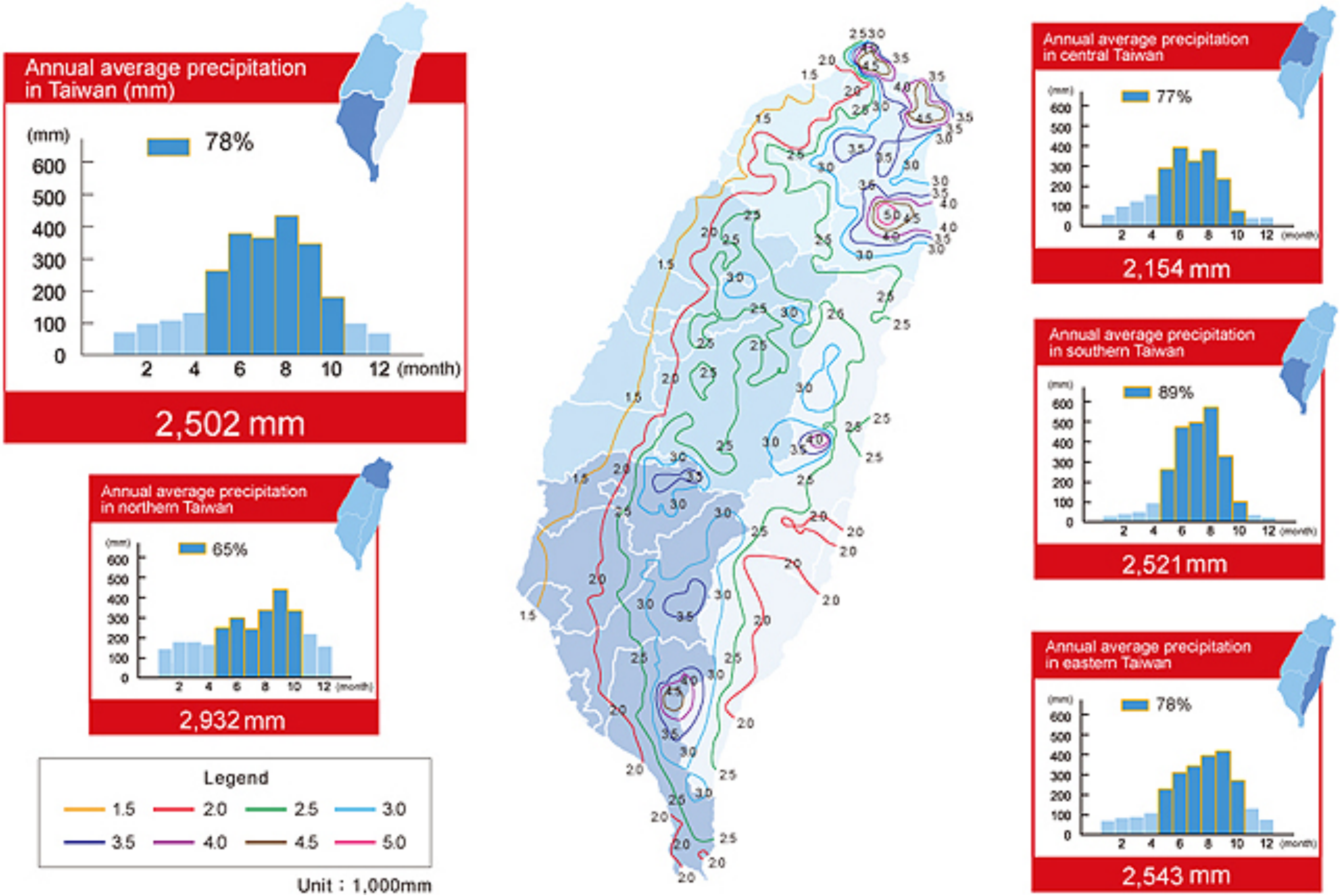
- Taiwan lies on western rim of circum-pacific seismic zone
- Located on convergent and compressive boundary between Eurasian and Philippine Sea Plates
- The rock formations are young and weak



List of earthquakes in Taiwan from 1991 to 2006



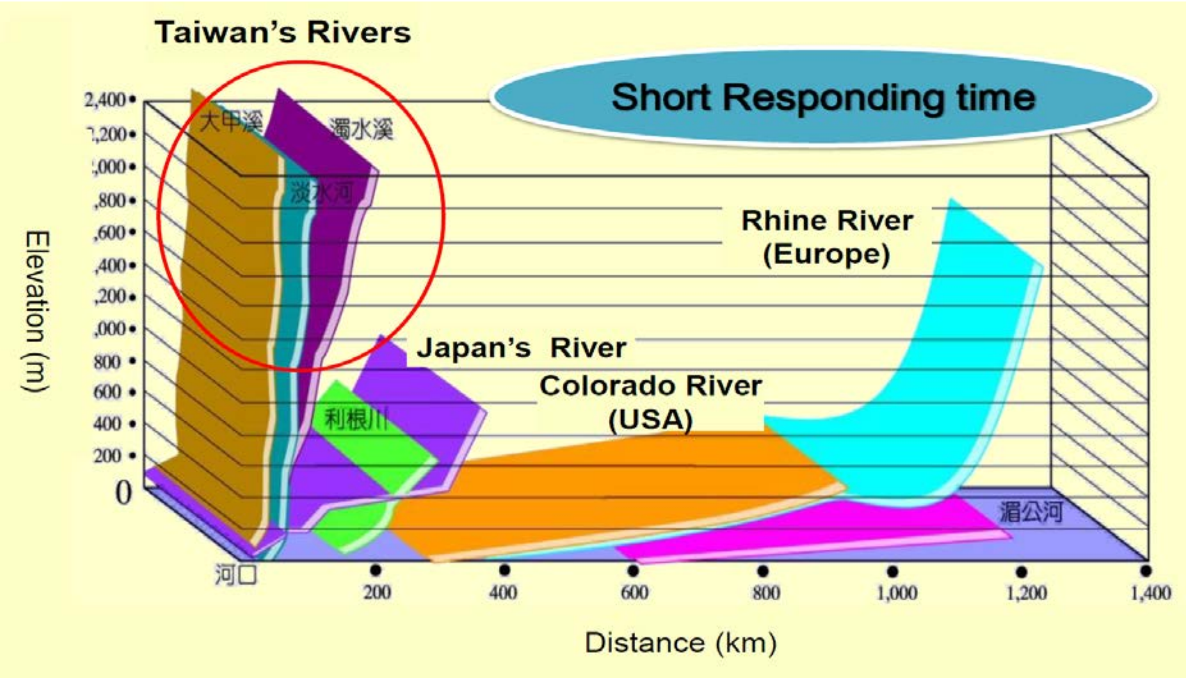
Earthquakes in Taiwan from 2011/11 to 2012/10



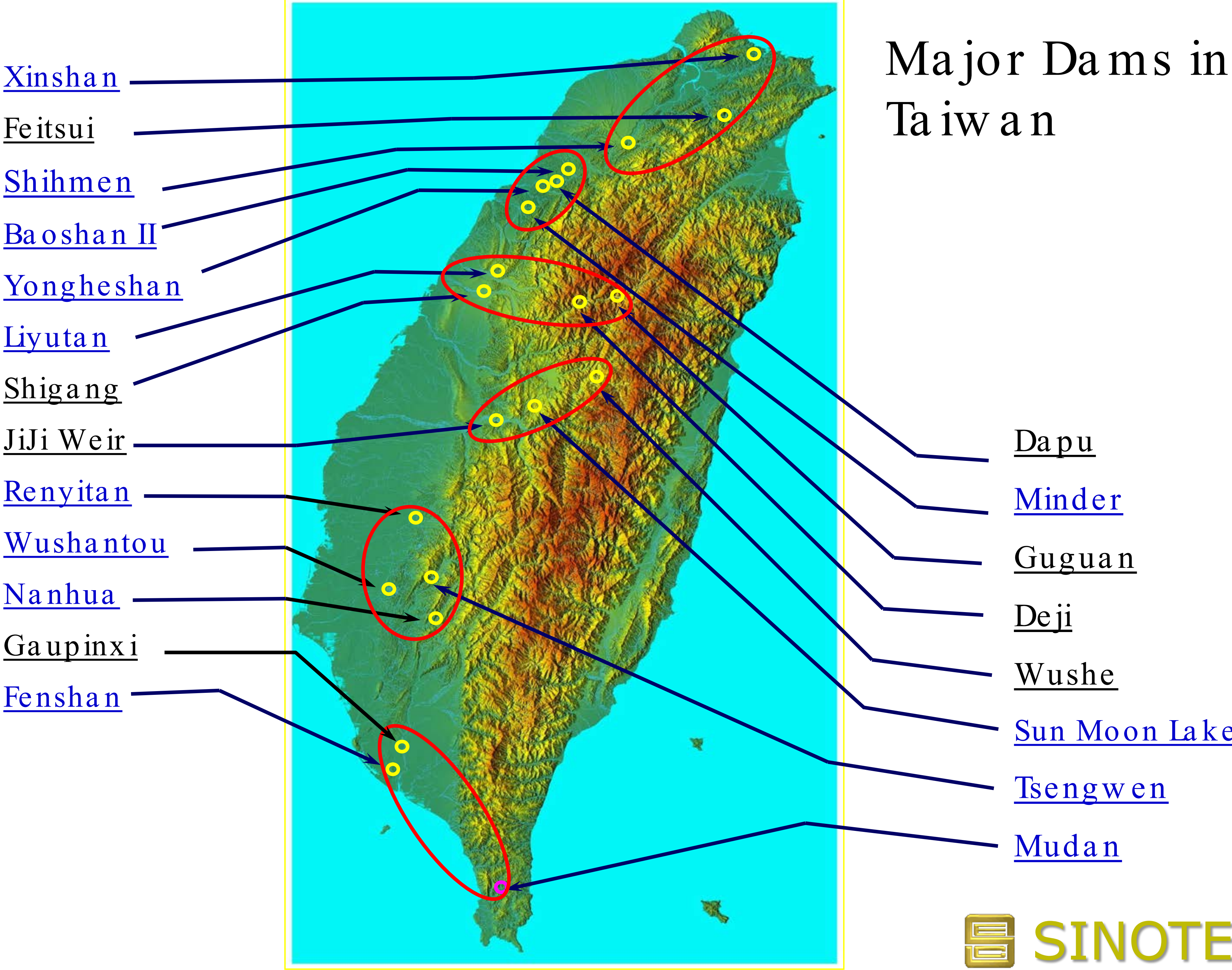
Annual average precipitation in Taiwan (mm)
(mm)
600
500
400
300
200
100
0
78%
2
4
6
8
10
12 (month)
2,502 mm
Annual average precipitation in northern Taiwan
65%
2,932 mm
Legend
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Unit：1,000mm
Annual average precipitation in central Taiwan
77%
2,154 mm
Annual average precipitation in southern Taiwan
89%
2,521 mm
Annual average precipitation in eastern Taiwan
78%
2,543 mm

Landform &Geology

- Short river with steep slopes
- Weak geology of watershed
- Soil poorly Consolidated
- Rapid flow with high sediment concentration



Major Dams in Taiwan

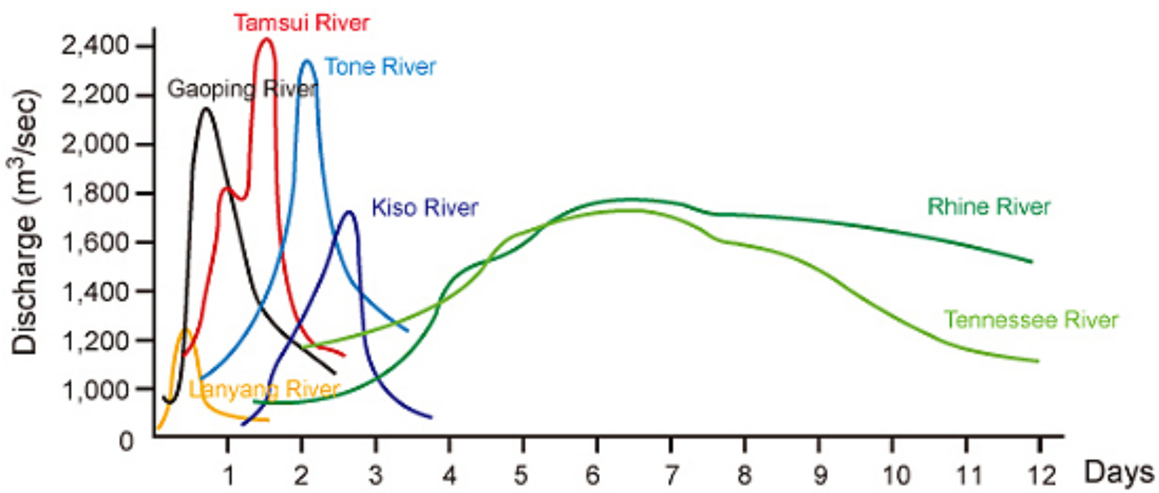


Name	Dam Type	Year of Completion	Gross Capacity of Reservoir $\times 10^8\ m^3$
Wu-Shan-Tou	Earth Dam	1930	1.5
Sun Moon Lake	Earth Dam	1934	1.72
Wu-She	Gravity Dam	1959	1.48
Shih-Men	Earth Dam	1964	3.1
Pai-Ho	Earth Dam	1965	0.25
Tseng-Wen	Earth Dam	1973	7.1
Te-Chi	Arch Dam	1974	2.3
Jong-Hua	Arch Dam	1984	0.12
Ming-Hu	Gravity Dam	1985	0.08
Fei-Tsui	Arch Dam	1987	4.06
Li-Yu-Tan	Earth Dam	1992	1.26
Nan-Hua	Earth Dam	1993	1.58
Mu-Dan	Earth Dam	1995	0.31
Ming-Tan	Gravity Dam	1995	0.12
Bao-Shan II	Earth Dam	2006	0.32
Husan	Earth Dam	2016	0.50


Dense population in the downstream of dam
Feitsui Dam
新北
凯旋门
西门
中正纪念堂
台北市
新北市
中和区
南势角
木栅
新店区
港口
Image © 2021 CNES / Airbus
Image © 2021 Maxar Technologies

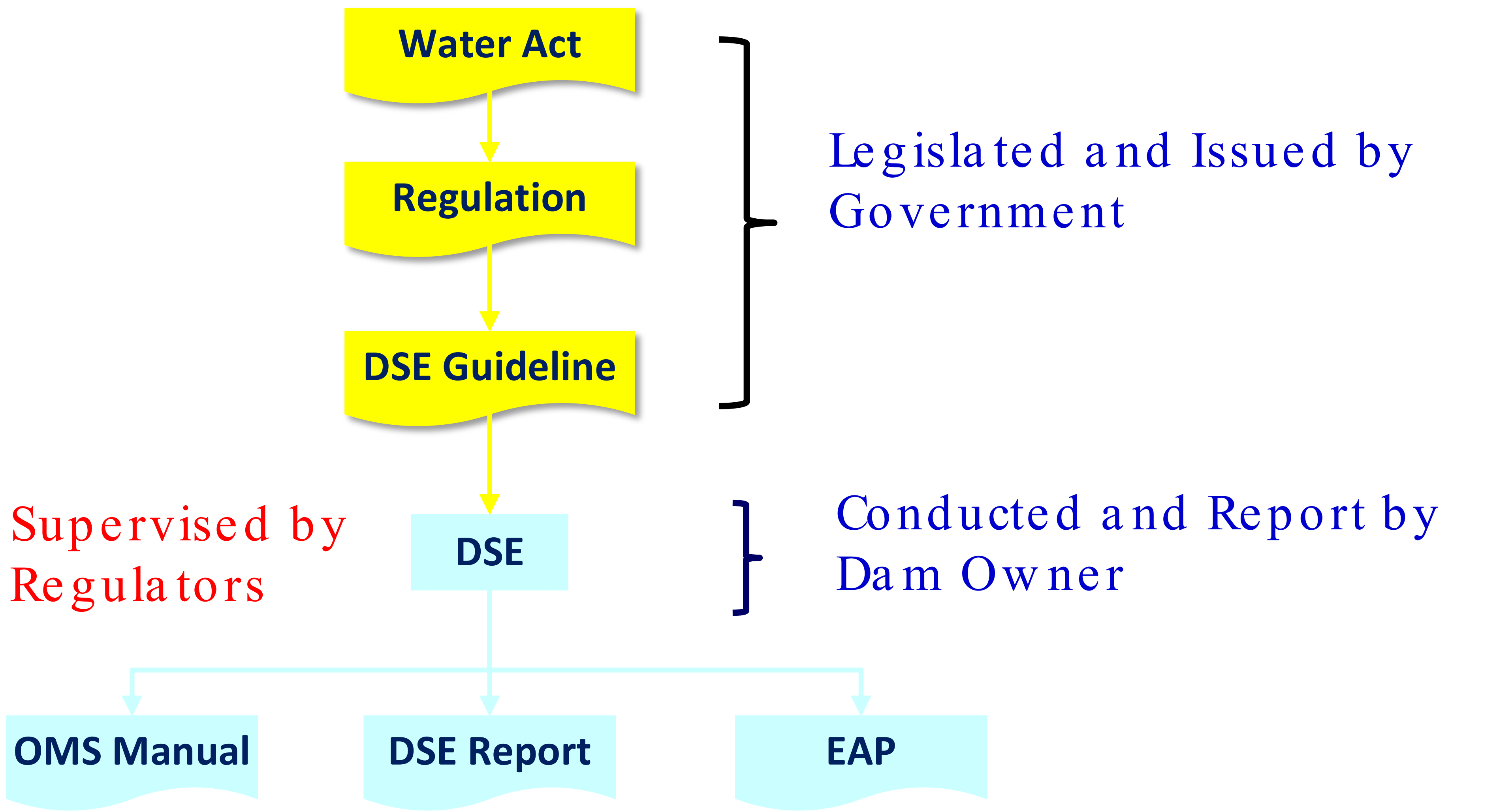
Role and Challenge of Reservoir in Taiwan

- The reservoir can be said the most important and reliable water resource in Taiwan
- High mountain, steep drainage slope, small reservoir volume
  - Young and weak geology, unstable slope
  - Threat of earthquakes
  - Most precipitations come from typhoons, with high rainfall intensity and large erosion

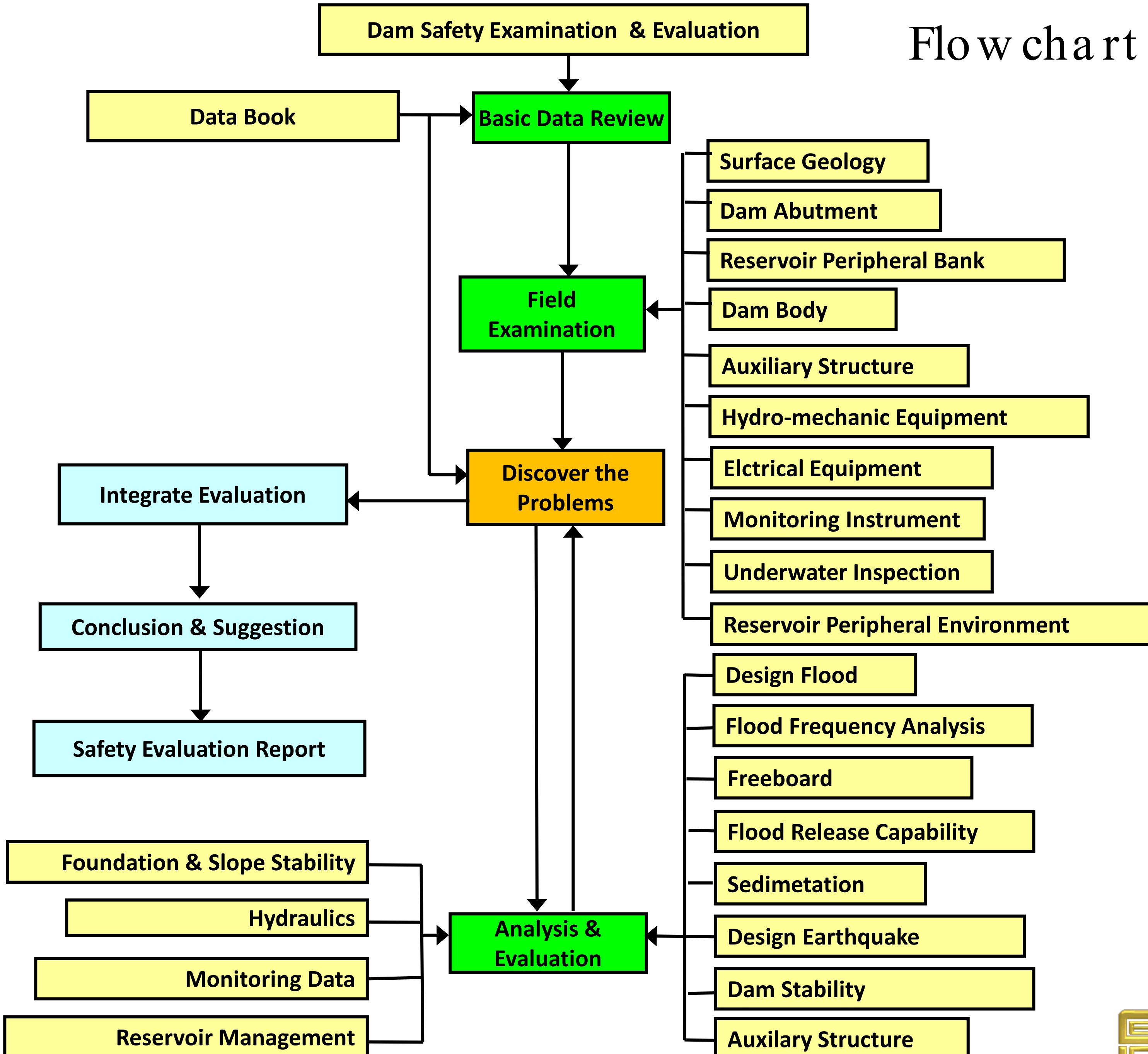


SINOTECH

Framework of Dam Safety Management in Taiwan



Flow chart of dam Safety Evaluation



SINOTECH

Analysis & Evaluation

- Design Seismic Analysis
- Design Flood Analysis
- Hydraulic Analysis
- Reservoir Sediment Analysis
- Flood Releasing capability Analysis
- Freeboard Analysis
- Dam Structure Safety Analysis
- Auxiliary Structure Safety Analysis
- Tunnel Structure Safety Analysis
- Dam Abutment & Reservoir Peripheral Slope Stability Analysis
- Monitoring data Analysis
- Hydro-mechanical Equipment Analysis

Standard-Based Approach

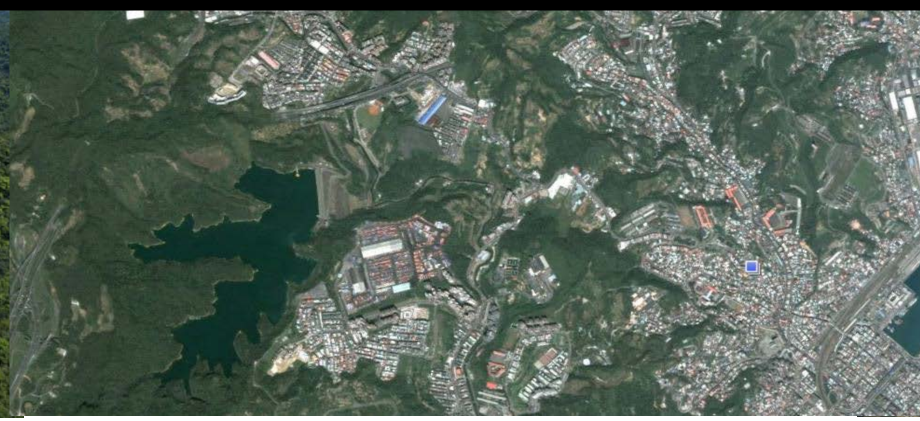
SINOTECH

Evolution of Dam Safety Management in the World

- **Standard-Based**
- **Risk-Based**
- **Risk-Informed**

SINOTECH

Introduction of Feitsui Dam

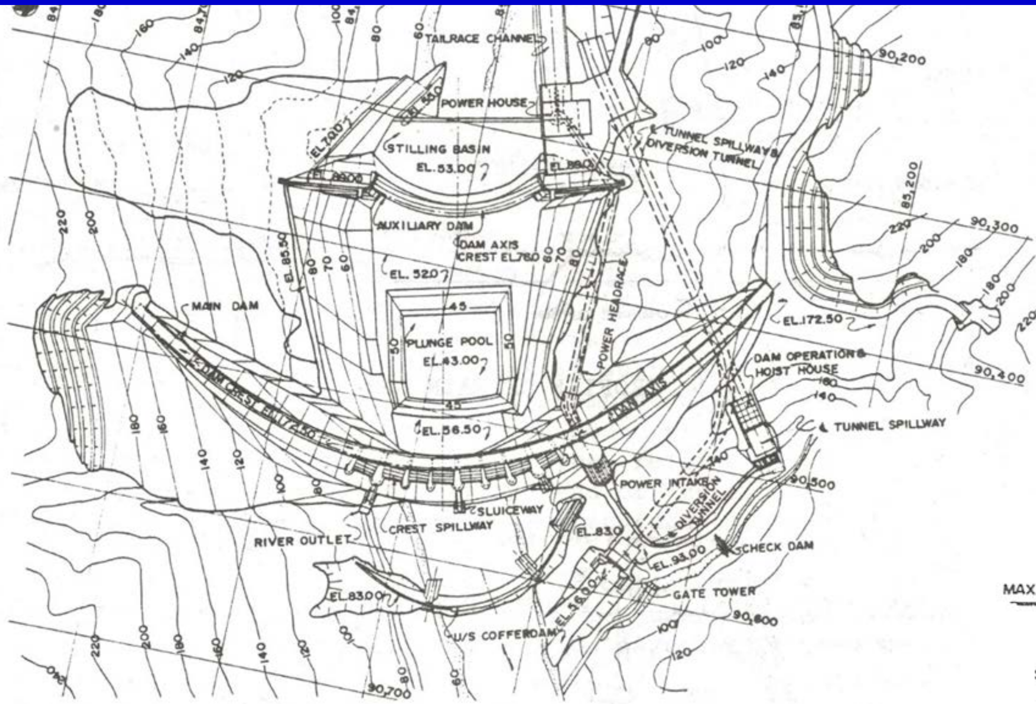



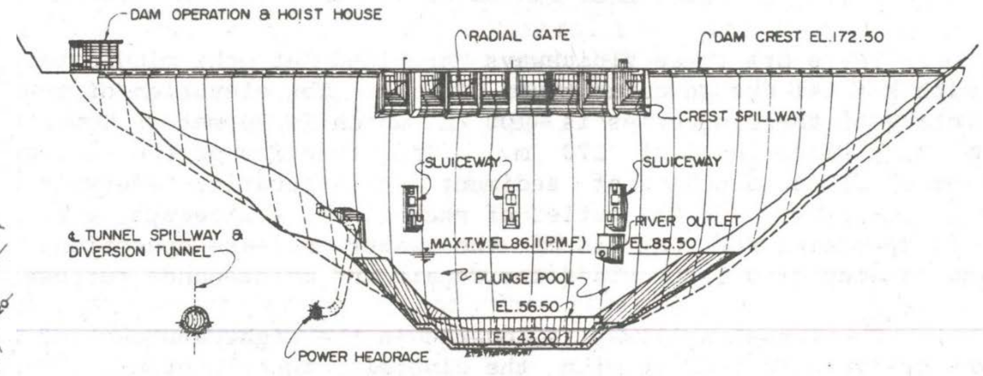

Feitsui Dam

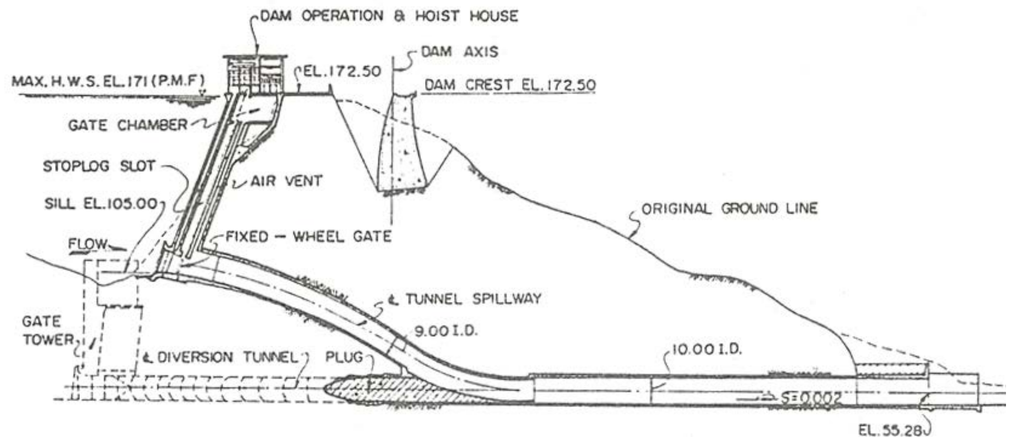
- The Feitsui Dam is a three-centered double curvature and variable thickness concrete arch dam
  - ➡ The reservoir capacity is the largest of all concrete dams in Taiwan
- It was completed in 1987 and only 30 km away from Taipei city
- The dam is 122.5 meters high and 510 meters long from the crest, with a volume of 700,000 cubic meters of concrete
- More than 4 million people living in the downstream area

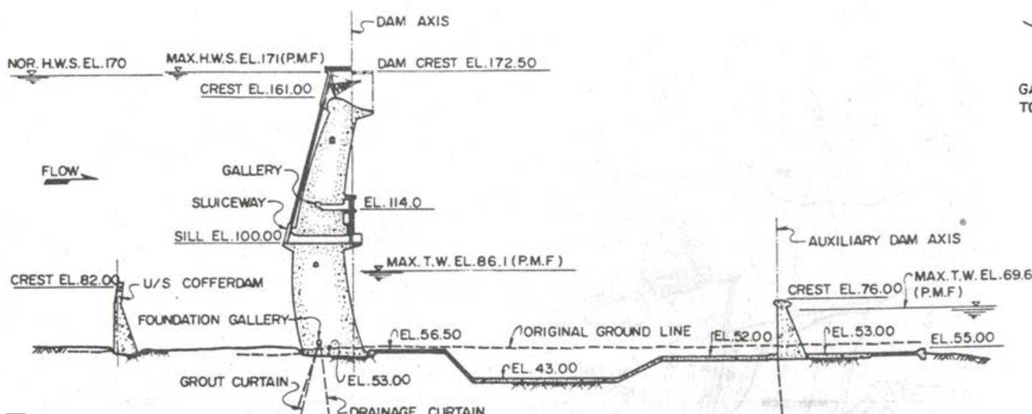
SINOTECH

Feitsui Dam



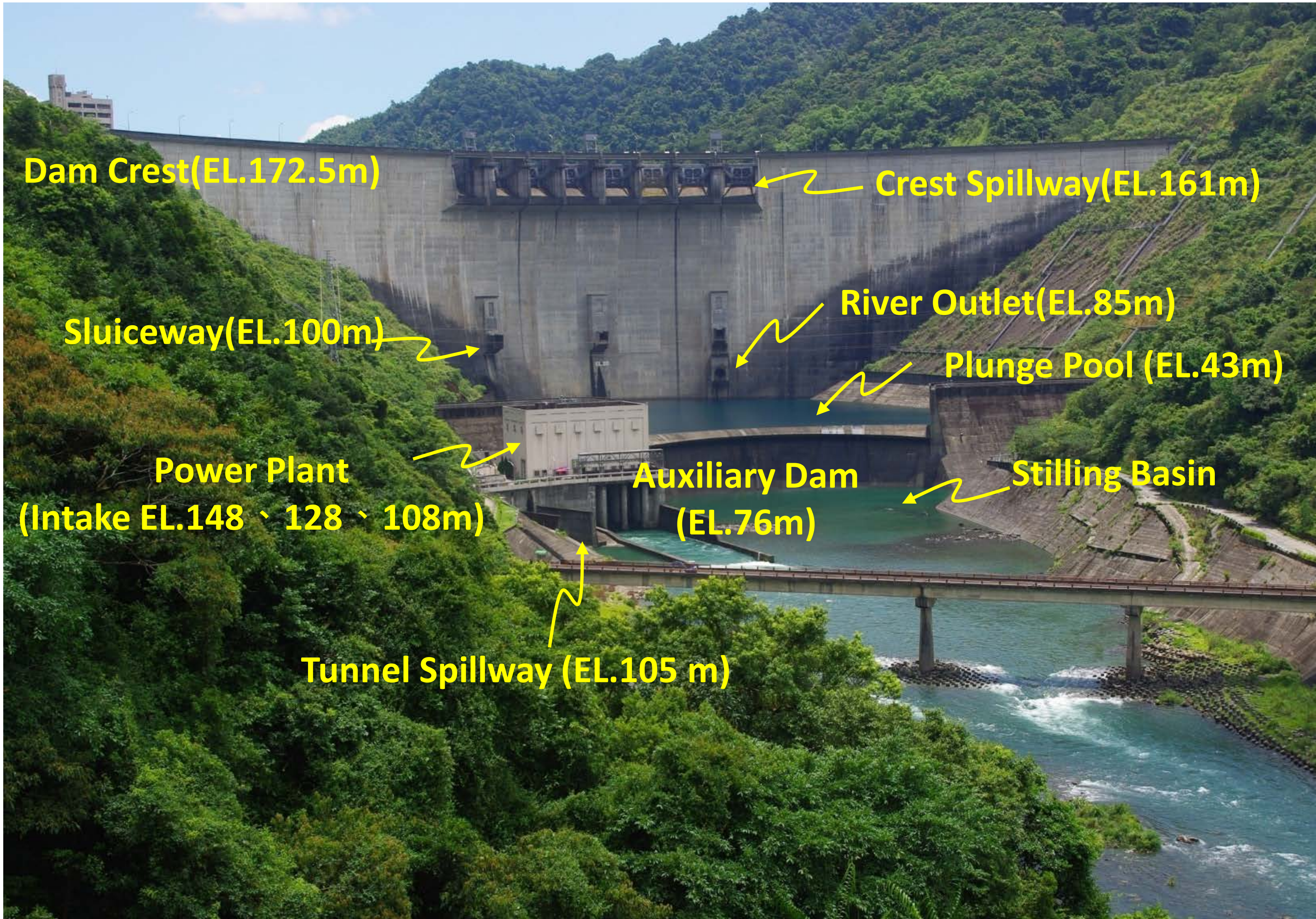






SINOTECH

Feitsui Dam

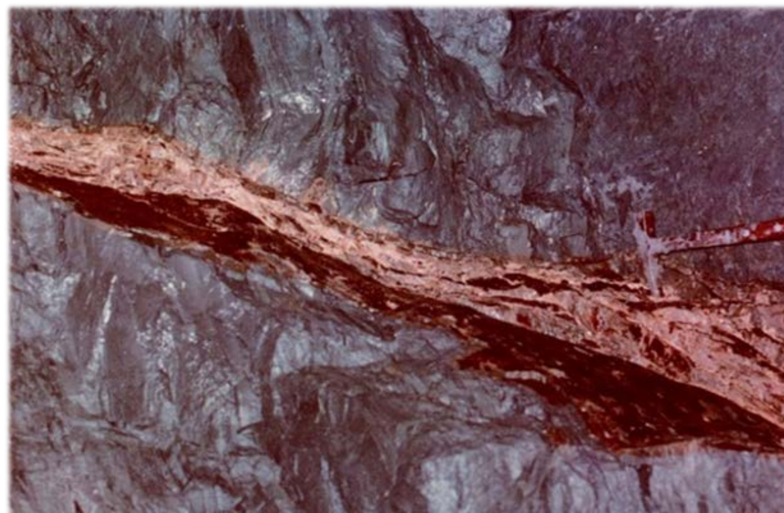

Dam Crest(EL.172.5m)
Crest Spillway(EL.161m)
River Outlet(EL.85m)
Sluiceway(EL.100m)
Plunge Pool (EL.43m)
Power Plant
(Intake EL.148、128、108m)
Auxiliary Dam
(EL.76m)
Stilling Basin
Tunnel Spillway (EL.105 m)

Geology of Dam site

Feitsui Valley

Rock Layers at Feitsui Valley

Dam site Geology Investigation



Clay Bedding Seams

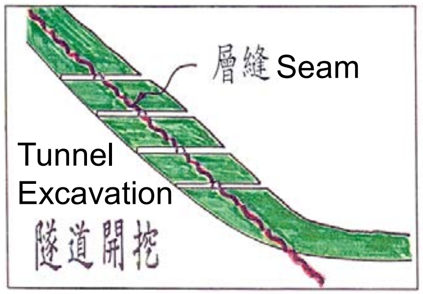
SINOTECH

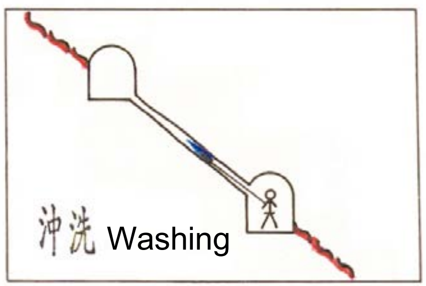
Geology condition of Feitsui Dam

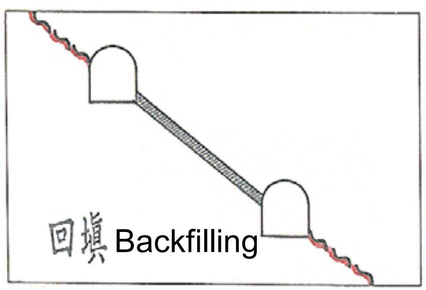
- **Special seam treatments were conducted during the construction of the dam to improve the shear strength and the deformability of the left abutments**

Foundation Treatment

- **Cleaning the clay seams with high pressure water jets and then backfilled with non-shrinking cement mortar**



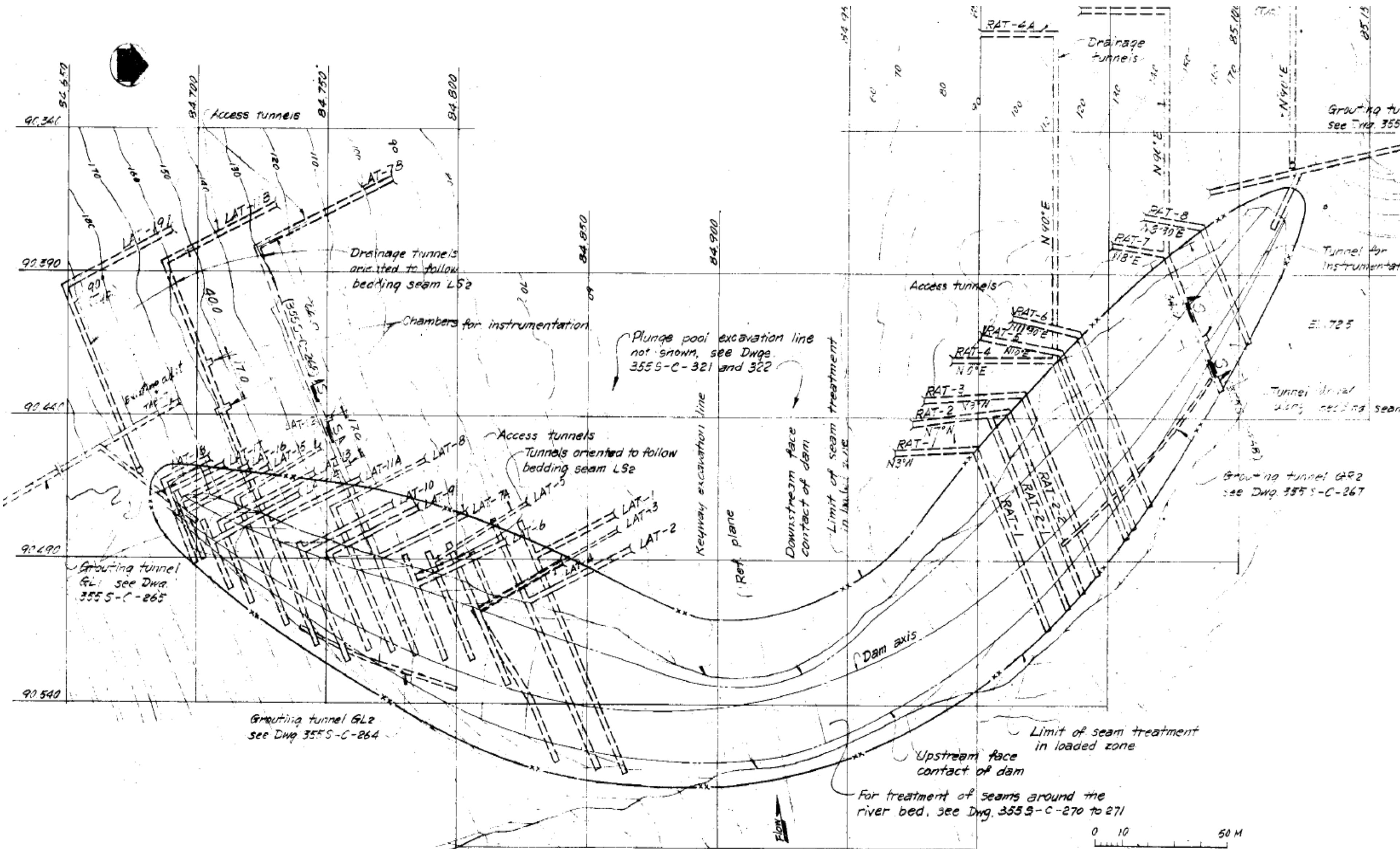




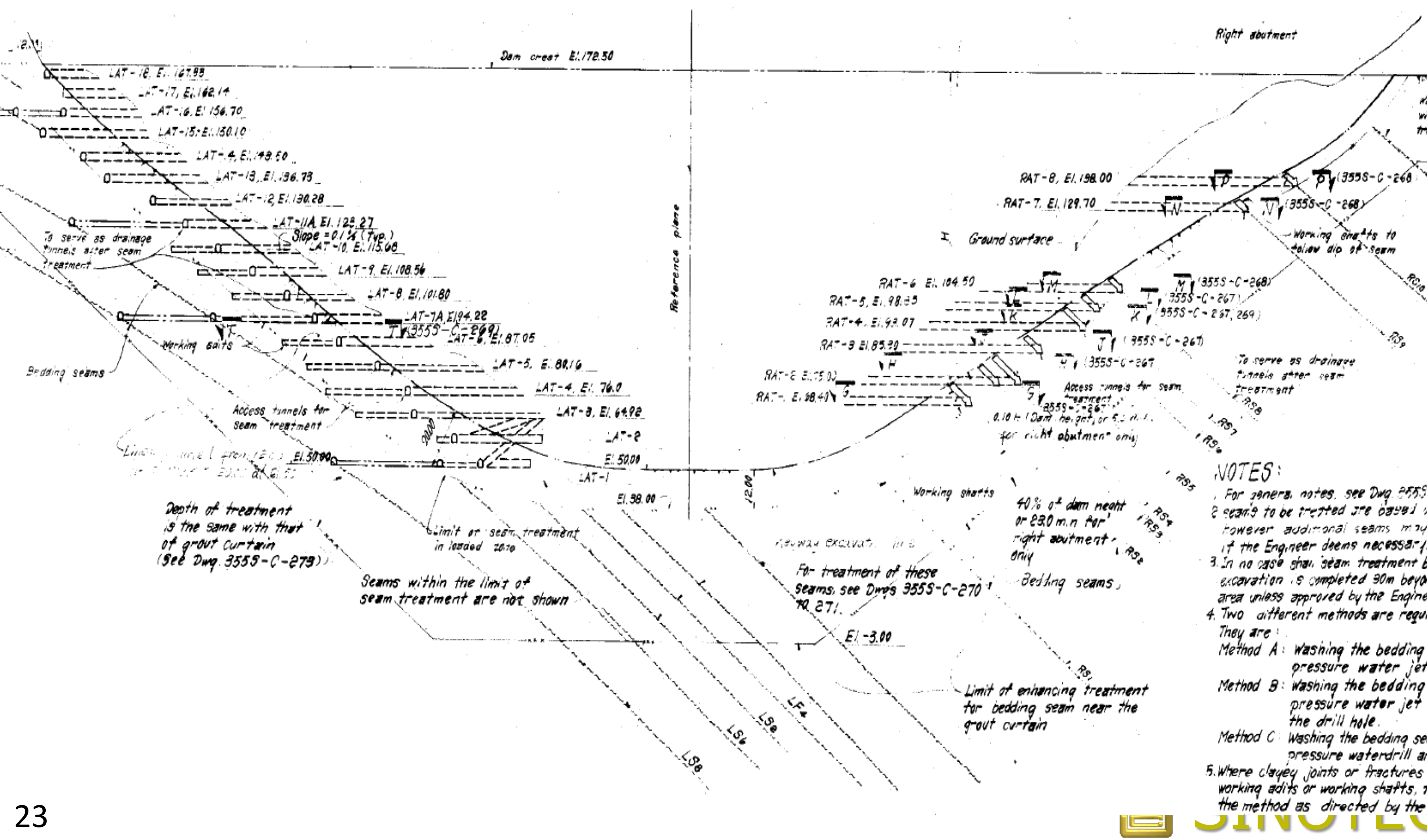
Water pressure up to 2400kg/cm^2

SINOTECH

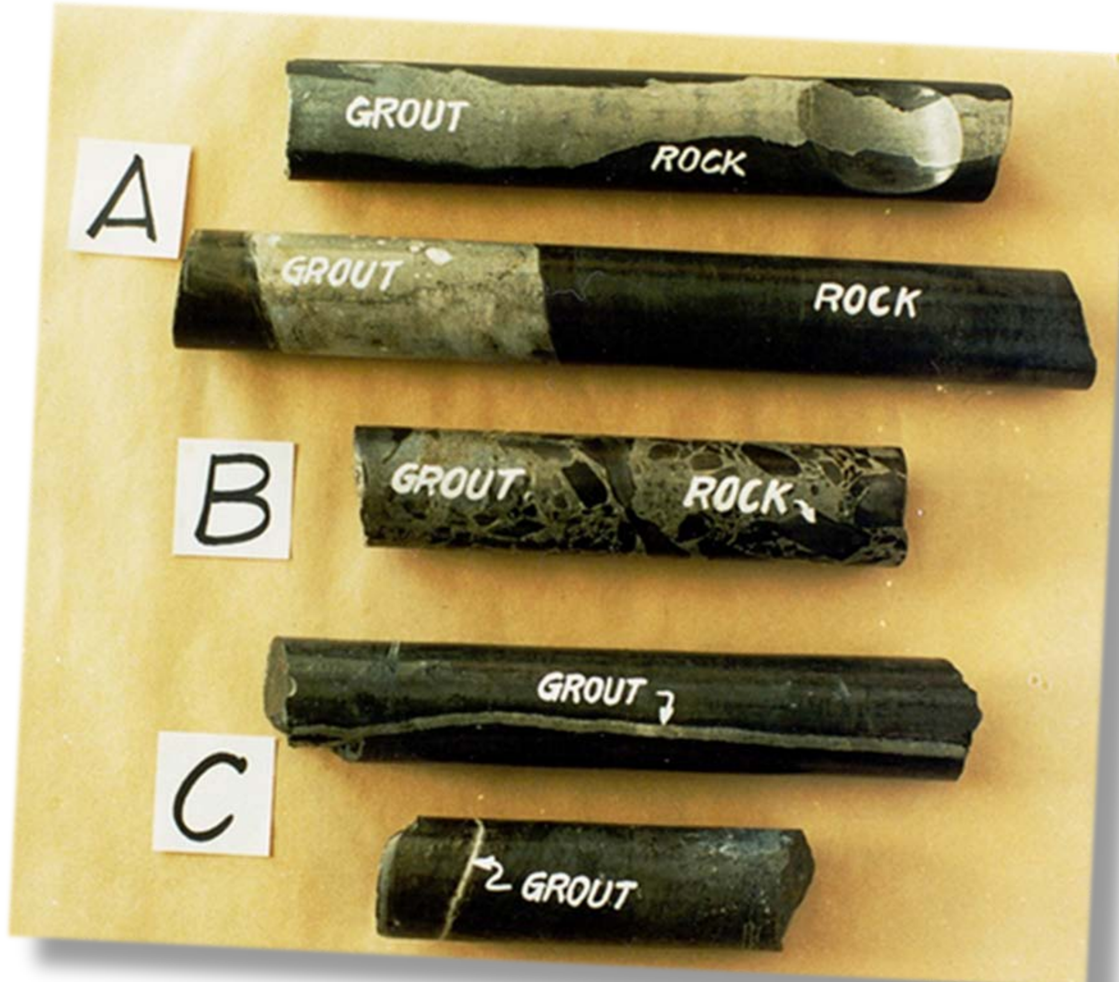
Layout of Foundation Treatment(1/2)

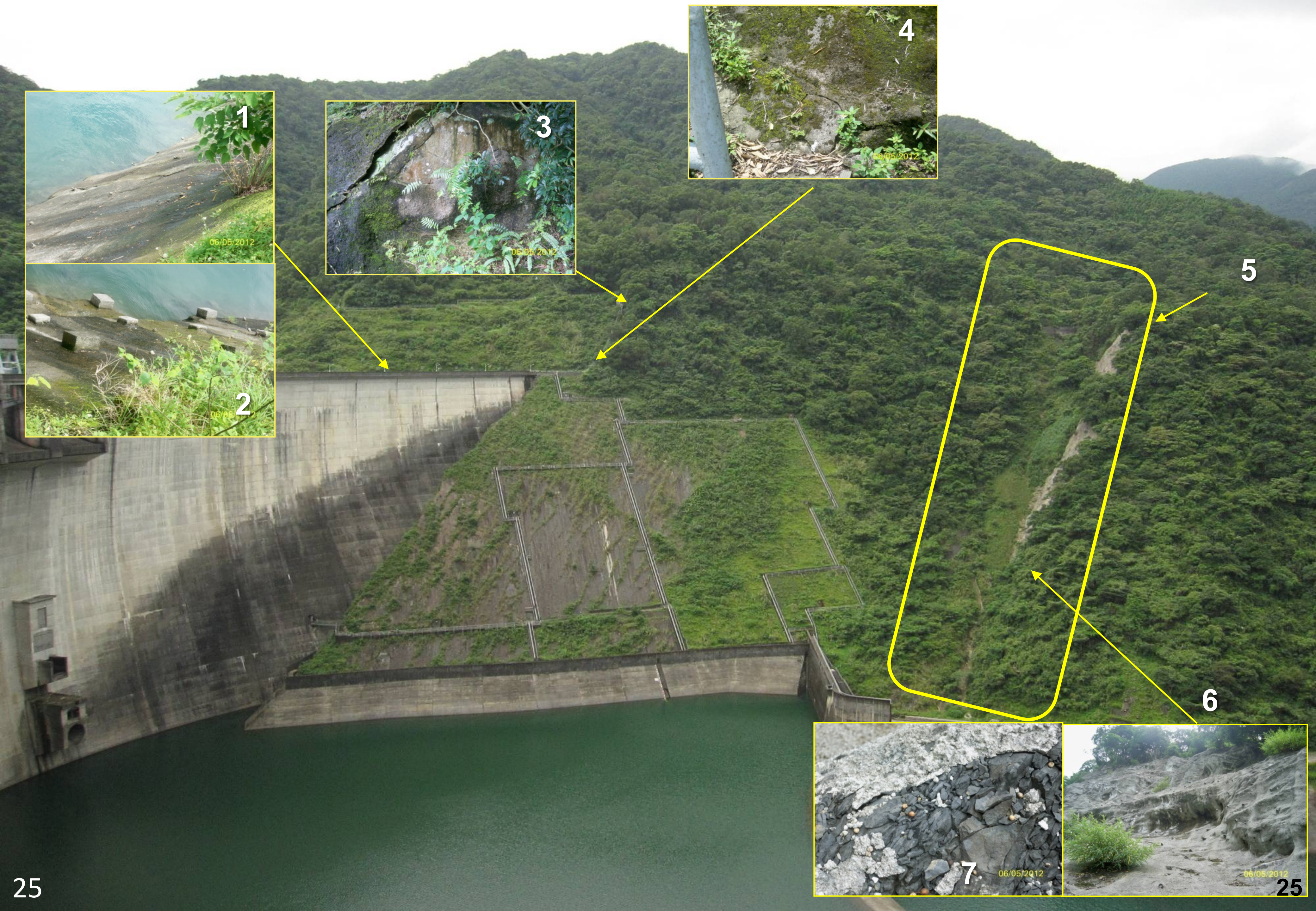


Layout of Foundation Treatment(2/2)



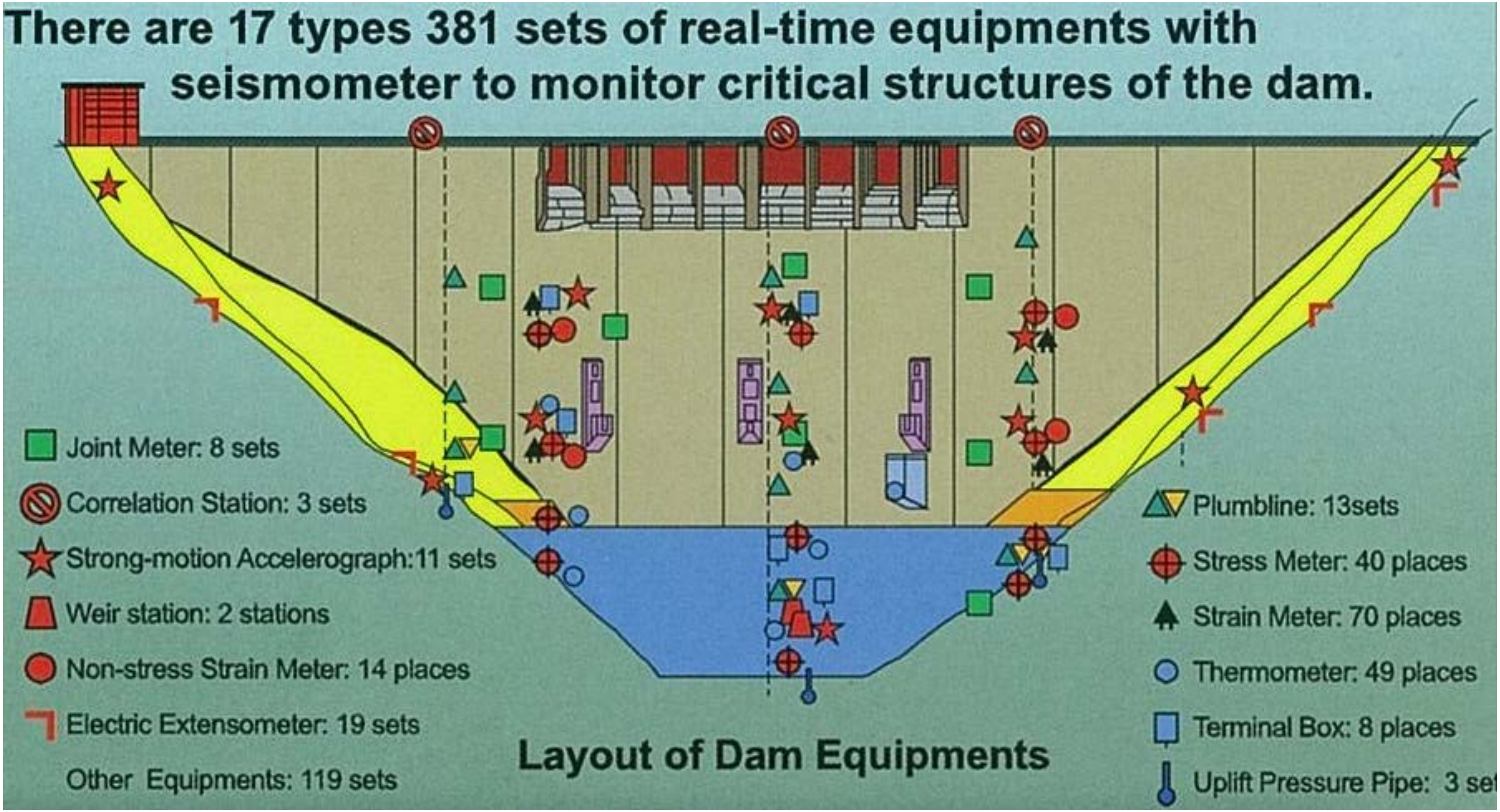
Treatment Efficiency Checking




1
2
3
4
5
6
7
06/05/2012
25


06/05/2012
06/05/2012

Instrumentation

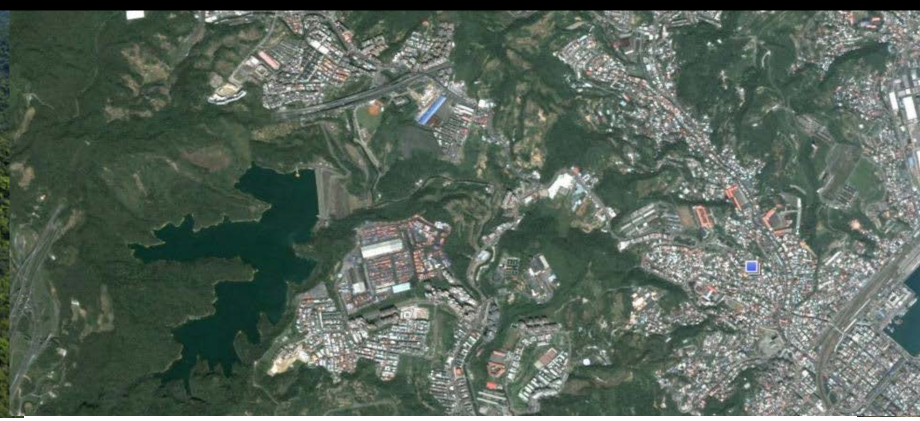


SINOTECH

Dam Safety Surveillance Program

	Items	Frequency
1	Automatic Monitoring System	Once every day in general, Once every hour during typhoon, flood period Once every 3 minutes during earthquake
2	Site Inspection	3 times a week in ordinary, Extra inspections during typhoon period, Overall checkup when earthquake intensity is greater than 3
3	Artificial survey	Once every 2 weeks
4	Comprehensive Dam Safety Evaluation	Once every 5 years

Dam Risk Management



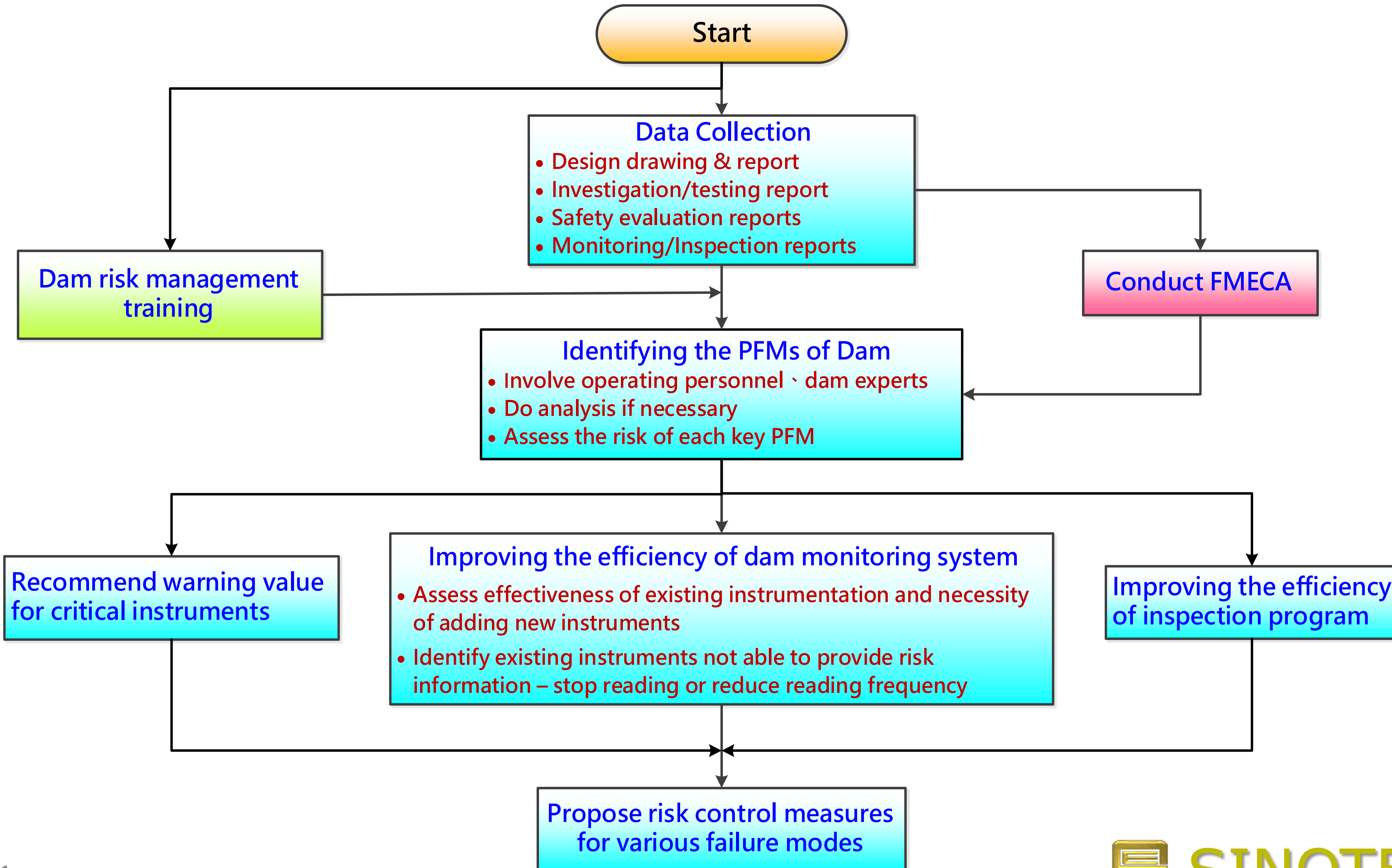
Why Introduced Dam Risk Management

- Realize the system and risks will change over the lifespan of a dam
  - Risks are dynamic
  - Hazards change (climate change, earthquake….)
  - Infrastructure performance degrades
  - Dam fail Consequences Increase

- State of the practice has evolved
- Evolution of dam safety management in the world
  - Move from Standard-Based approach to Risk-Informed approach
- International dam society encourage the use of risk analysis in dam safety decision-making

SINOTECH

Flow Chart of the Project



SINOTECH

Potential Failure Modes Analysis

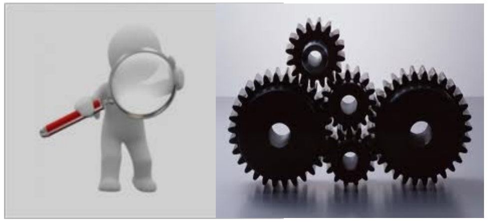
- PFMA – essential in dam risk management
- Find out if any critical issues related to dam safety have been omitted from traditional standards-based assessment
- Improve the efficiency of dam safety surveillance program
- Key Concepts of PFMA

  - Collect all relevant background material
  - Take a fresh look
  - Review background material diligently
  - By more than one qualified engineer
  - Perform site examination with eye toward potential vulnerabilities
  - Involve operating personnel in the potential failure modes discussions
  - Think beyond traditional analyses
  - Human factors/operational factors
  - Deterioration/malfunction of equipment

SINOTECH

Why FMECA (Failure Modes, Effects and Criticality Analysis)

- So far the Feitsui Dam is the last arch dam in Taiwan and it was completed **34** years ago. It is noted that
  - **The current safety assessment is carried out by engineers who have no experience in the design or construction of arch dam**
  - **The operating personnel change frequently and experience is difficult to pass on**
- For better understanding the function of each component of the dam and what happens if the component fails
  - **Analyze criticality of failures of individual dam components to whole dam system**
  - **Provide failure mode pathways information for PFM assessment**



Refer to BC Hydro's experience

SINOTECH

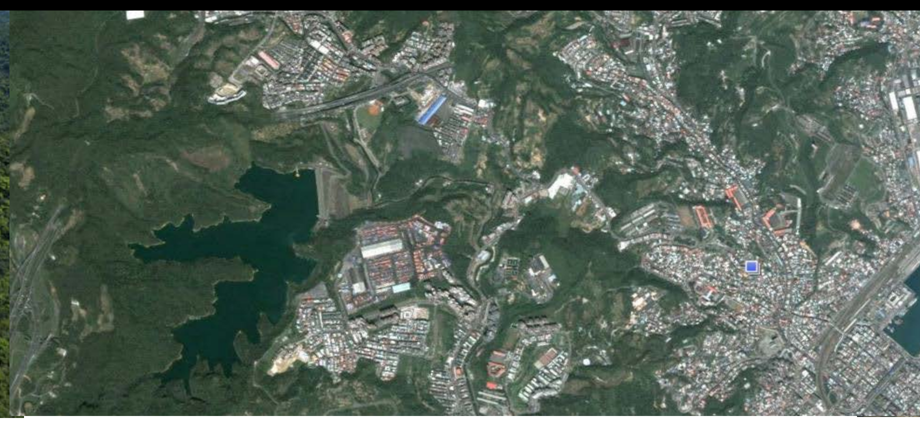
Results of FMECA

Component number	Subsystem 1	Subsystem 2	Component	Function	Failure Mode	Likelihood factor	Consequence	Conse-quence factor	Detection /Intervention	D/I factor	Criticality Index
01	Dam										
0101		Dam Body									
010101			Block1~11	Stop water and transfer stress							
01010101					Crack under strong earthquake	1	Leak, make adjacent block unstable	4	D/I impossible	5	20
01010102					Deterioration	1	Leak, make adjacent block unstable	4	Lowering Water level	4	16
010102			Block12~ 18	Stop water and transfer stress							
01010201					Cracks due to high concentration stress under strong earthquake	2	Leak, make adjacent block unstable	4	D/I impossible	5	40
01010202					Deterioration	1	Leak, make adjacent block unstable	4	Lowering Water level	4	16
01010203					Construction joint opened under strong earthquake	1	Leak make adjacent block unstable	4	D/I impossible	5	20
010103			Block19~ 29	Stop water and transfer stress							
01010301					Construction joint opened under strong earthquake	1	Leak, make adjacent block unstable	4	D/I impossible	5	20
01010302					Deterioration	1	Leak, make adjacent block unstable	4	Lowering Water level	4	16
010104			Expansion Joint	Expansion of Concrete							
01010401					opened under strong earthquake	2	Leak	2	D/I impossible	5	20
01010402					Water seal damaged	3	Leak	2	Visual inspection	3	18

Components with High CI

Component number	Component	Function	Failure Mode	Likelihood factor	Consequence	Conse-quence factor	Detection / Intervention	D/I factor	Criticality Index
01010201	Block12~18	Retaining water and transferring stress	Cracks due to high concentration stress under strong earthquake	2	Leak, make adjacent block unstable	4	Detection / intervention impossible	5	40
01030101	Rock mass of left abutment	Supporting the dam	Slides along the bedding plane during strong earthquake	2	Cause the dam to be unstable, which may induce the dam to break	4	Detection / intervention impossible	5	40
01030102		Supporting the dam	Slides along bedding plane due to high water pressure on the plane	2	Cause the dam to be unstable, which may induce the dam to break	4	Possible detection/ intervention impossible	4	32
01030501	Bedding seam treatment of left abutment	Increase shearing resistance of bedding plane	Deterioration of backfilling material	2	Reduce the shearing resistance of the treated zone and make the abutment unstable	4	Possible detection/ intervention impossible	4	32

Potential Failure Modes Identified



NO.	Description of Potential Failure Mode	Risk(FERC) Category
PFM1	The rock wedge on the right abutment slipped during strong earthquake, causing the concrete blocks 20 to 29 to lose their stability. Uncontrolled water was released from the rupture area and eventually caused the dam to collapse.	III
PFM2	The weakness plane of right abutment crack due to long term creep, reservoir water seeps into the openings reducing shear resistance of the plane and caused the rock wedge slides . The abutment began to move slowly along the weakened surface, causing the concrete blocks(No.1 to 10) to lose stability and eventually leading to the dam failure.	III
PFM3	Due to the deterioration of backfill material of treated bedding plane, the rock wedge in the left abutment slipped during strong earthquake, causing the concrete blocks (No. 1 to No. 10) to lose their stability and eventually caused the dam to break..	II
PFM4	The backfill material of the left abutment treatment layer deteriorated, and cracked due to creep. Reservoir water seeps into the open surface, reducing shear resistance and creating high water pressure. The abutment began to move slowly along the weakened surface, causing the concrete blocks (No. 1 to No. 10) to lose their stability, which eventually caused the dam to break.	II
PFM5	A rock wedge in the riverbed formed by the SZ1 shear zone and the C joint slipped during a strong earthquake, resulting in an increase in foundation leakage. The foundation was subsequently eroded, causing blocks 13 to 15 to lose stability and eventually leading to the collapse of the dam.	III

Potential Failure Modes of Feitsui dam

- A total of **11** potential failure modes are identified
  - **Including failures induced by earthquake, flood, abutment failure, landslide, mechanical failure etc.**
  - **According to the risk identification of all failure modes, most of the failure modes are classified as low risks, with the exception of those failure modes that may be triggered by the deterioration of seam treatment of the left abutment**
  - **Based on the mechanism of potential failure modes, an evaluation procedure was established to identify the key instruments and the warning values of these instruments**
- A supplementary investigation was carried out to check the conditions of the seam treatment of the left abutment

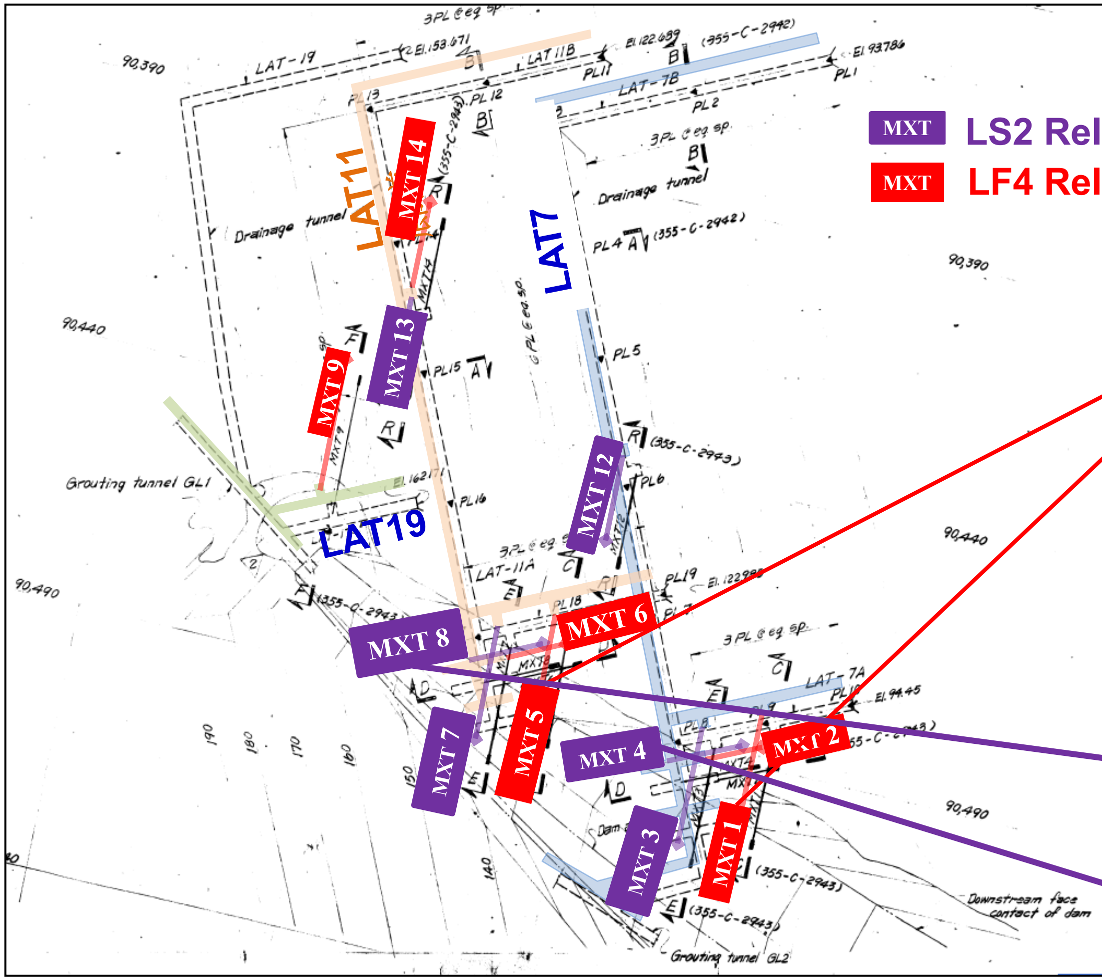
SINOTECH

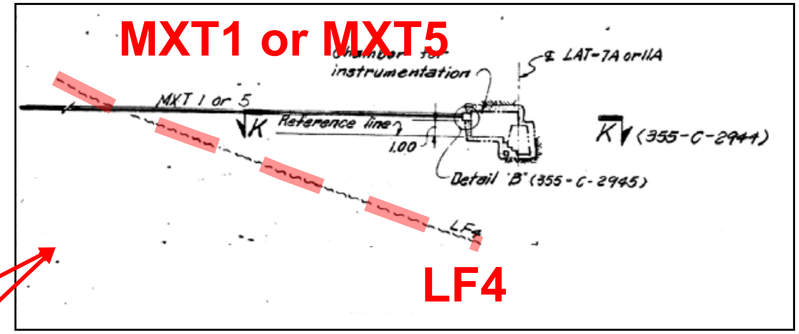
Risk-informed Instrumentation

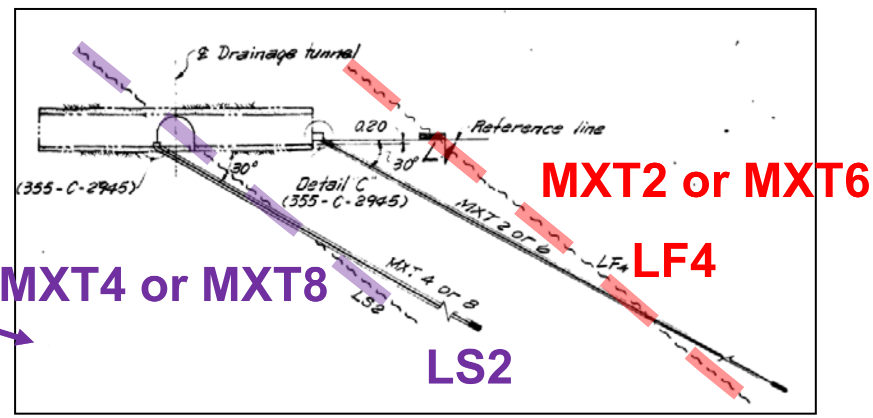
PFM 4：The degraded treatment material cracked and weakened due to creep under long-term stressed. Water seepage causing the abutment to move slowly and finally leading to the dam failure

Stage	1	2	3	4	5	6	7
Development of failure mode	The backfill material of the left abutment treatment layer deteriorated, and cracked due to creep.	Reservoir water seeps into the open surface, reducing shear resistance and creating high water pressure. Creep accelerated.	The abutment began to move slowly along the weakened surface	Concrete blocks (No. 1 to No. 10) lose their stability	Concrete blocks fall out	A large amount of water flows from the rupture area	Dam fails. Uncontrolled release of reservoir water
Potential Detection Capability	Extensometer, Inclinometers	Extensometer, Uplift Piezometer, Surface Deformation, Seepage Weir,	Joint Meter, Plumb line, Uplift Piezometer, Seepage Weir				
Intervention Opportunities			Depends on actual failure mode development, intervention could be started as early as Stage 3.				
Mitigation Measures			Lowering reservoir level				
Instruments can be used	PL1~19, TL1~5, Line1~2, EXT1~5, MXT1~9,MXT12~14, L1~10	PL1~19, TL1~5, Line1~2, EXT1~5, MXT1~9, MXT12~14, L1~10, GW1~7, PW1-1~PW3-2, J15, J17, J19, WS1~2	J15, J17, J19, IPL1、NPL1-1~3, WS1, WS2, UP1-1~4	Out of measuring range of the instruments			

Key Instruments at Left Abutment







SINOTECH

Key Instruments for failure modes

Items	Related Instruments	Key Instruments
Failure Mode 1	Extensometer, Joint Meter, Dam Seepage Weir, Drainage Gallery Seepage Weir	EXT6~9, MXT10~11
Failure Mode 2	Extensometer, Joint Meter, Plumb line, Uplift Piezometer, Surface Deformation, Underground Water Level, Dam Seepage Weir, Drainage Gallery Seepage Weir	EXT6~9, MXT10~11
Failure Mode 3	Extensometer, Joint Meter, Dam Seepage Weir, Drainage Gallery Seepage Weir	EXT1~5, MXT1~9, MXT12~14
Failure Mode 4	Extensometer, Joint Meter, Plumb line, Uplift Piezometer, Surface Deformation, Underground Water Level, Dam Seepage Weir, Drainage Gallery Seepage Weir	EXT1~5, MXT1~9, MXT12~14
Failure Mode 5	Extensometer, Joint Meter, Uplift Piezometer, Dam Seepage Weir	UP2-1~3, EXT12, WS1, WS2

Conclusion

- **This is a pilot study to introduce risk-informed concept into the dam safety management practice of Feitsui Dam**
- **A comprehensive study on the potential failure modes of the dam were conducted based on FMECA (Failure Modes, Effects and Criticality Analysis) methods suggested by the B.C Hydro**
  - ➡ **The primary objectives are to obtain a comprehensive and structured understanding of a system, the function or functions of the system components, the potential failure modes of the components, and the effects of the component failure modes on the performance of the system**
- **It shows that FMECA can help PFMA's core team members, including engineers and operators, communicate with each other and make their work more efficient**

SINOTECH

Thanks for Your Attention