Risk Assessment Methodologies for US Army Corps of Engineers Civil Works Infrastructure

Presentation to the Pipeline Risk Model Work Group

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TOPICS

- Background on USACE
- Risk Assessment Methodologies
  - Major Rehabilitation Program
  - Dam Safety Program
  - Levee Safety Program
  - Asset Management Program
- Conclusions
USACE Mission Areas

Military Programs
- Military Construction
- COCOM Support, Overseas Contingency Operations (OCO)
- Installation Support, Environmental, Energy and Sustainability

Civil Works
- Navigation, Hydropower
- Flood Control, Shore Protection
- Water Supply, Regulatory
- Recreation, Disaster Response
- Environmental Restoration

Homeland Security
- Critical Infrastructure
- Anti-Terrorism Plans
- Intelligence
- Facility Security Partnership

Real Estate
- Acquire, Manage and Dispose
- DoD Recruiting Facilities
- Contingency Operations

Research & Development
- Warfighter
- Installations & Energy
- Environment
- Water Resources

Interagency Support
- Federal
- State
- Local
- International

Geospatial Support
- Support to Civil Works Programs
- Support to Military Programs
- Common Operating Picture/Environment
- Support to Emergency & Contingency Ops

USACE Has a Diverse Mission Set Driven by Diverse Customers

Source: MG Jackson – OPM
Civil Works Value to the Nation

- Every $1 spent on Flood Risk Management prevented nearly $8 in flood damages (Both adjusted for inflation)
  - 709 dams; 14,700 miles of levees; 400 miles of shoreline protection
  - 183 major ports (250K+ tons of commerce), 884 smaller harbors
    - 12,000 miles of commercial inland waterways
  - Marine transportation supports $1 trillion in commerce and 13,000,000 jobs annually
  - Environmental restoration
  - Response to 17 Presidential declared disasters (2015)
- Largest US outdoor recreation program – 370 million visits a year
  - Stewardship of 11.7 million acres of public lands
  - 75 hydropower plants produce 3% of US electric energy
    - Water supply: 6.9 billion gallons per day
    - Nearly $4.9 B in contracts to private business

“The Nation’s security depends on its economic strength, and its economic strength depends on its infrastructure”
I am a dam.
I am many things to many people.

I am a protector.
I keep floodwaters off many communities.

I am a water supply.
Many towns count on me for their water needs.

I am a recreational facility.
I provide areas where people from all over come to swim, fish and camp.

I am an employer.
I create jobs for many communities.

I am an economic boost.
The tourism dollars I generate are spread throughout the local area.

I am a power plant.
Some of us help produce electricity for your homes and businesses.

I am a sanctuary.
I provide a habitat for fish, bird and wildlife species.

I am a navigation manager.
River traffic depends on me for navigable water levels.

I am a tourist attraction.
People come from miles around to see me in action.

I am yours.
I am part of the Corps of Engineers' Civil Works Infrastructure.

MULTIPLE Corps "Business Lines," and more, provide Value and benefits and influenced by investments in a single asset!

"Knowing the assets contribution to value"
Major Rehabilitation

- Major Rehabilitation (MR) Program
  - MR process started in USACE in early 1990’s
    - Joint effort between engineering, planning and operations
  - MR still in usage today by many USACE Districts
    - Widely applied to number of USACE projects over the past 25 years
    - Future increase in number of projects performing MR in FY15.
Major Rehab Authorization

- WATER RESOURCES DEVELOPMENT ACT OF 1992
  - Section 205 - DEFINITION OF REHABILITATION FOR INLAND WATERWAY PROJECTS.
    - 106 Stat. 4827
    - 33 USC 2327
  - Title 33 - NAVIGATION AND NAVIGABLE WATERS
  - CHAPTER 36 - WATER RESOURCES DEVELOPMENT
  - SUBCHAPTER V - GENERAL PROVISIONS
  - Sec. 2327 - Definition of rehabilitation for inland waterway projects
Major Rehabilitation for USACE Projects

- Engineering Pamphlet (EP) 1130-2-500
  - Dated - 27 Dec 1996
  - CECW-O - Operations policy document
    - Rehabilitation Evaluation and Report preparation will be funded under the Operation and Maintenance, General, appropriation
    - Major Rehabilitation Construction, funded out of Construction, General appropriation
    - 3 year budget cycle submission for CG funds
Major Rehabilitation for USACE Projects

- Engineering Pamphlet (EP) 1130-2-500
  - Chapter 3 – Major Rehabilitation Program
    - Purpose, Background and Guidance
  - Appendix B – Rehabilitation Evaluation Report
  - Appendix C – Conceptual Approach for Analyzing Rehabilitation
  - Appendix D – Introduction to Assessment of Structural Reliability
  - Appendix E – Benefit Evaluation Procedures
  - Appendix F – Example of Combining Risks and Consequences
Risk and Reliability Engineering for Major Rehabilitation Studies

1. **Purpose.** This Engineer Circular (EC) presents comprehensive guidance for engineering risk and reliability for Major Rehabilitation studies. This EC includes the methods for developing engineering reliability applications. It covers applications for multiple engineering disciplines. Although there is discussion of economic consequences from unreliable performance, the focus of this EC is on predicting engineering performance, not in the economics of investment decisions. A fuller treatment of risk assessment to inform the major rehabilitation investment decisions will be developed while this EC is used as interim guidance.

2. **Applicability.** This circular is applicable to all USACE commands having responsibility for the major rehabilitation studies.

3. **Distribution Statement.** Approved for public release; distribution is unlimited.

4. **References.** References are at Appendix A.

5. **Discussion.** The use of probabilistic analytical methods, including the development of hazard functions, is a relatively new concept within USACE. In the last 15 years, the use of probabilistic and risk-based methods has become an acceptable and required analysis technique for USACE studies. Most of the historical use of engineering reliability analysis within USACE has included the development and utilization of hazard functions for major rehabilitation studies, systems studies, and evaluation of the need for new navigation projects when the existing structure is in a deteriorated condition.

FOR THE COMMANDER:

JAME C. DALTON, P.E., SES
Chief, Engineering and Construction Division
Directorate of Civil Works
Major Rehab Process

- Assemble PDT – PM, Engineering, Environmental, Economist, Cost, etc…
- Document Project History
  - Current and historical
    - Condition
    - Poor performance
    - Maintenance – annual and emergency
    - Cost of repairs
    - Etc…. 
Major Rehab Process

- Failure Modes Effects and Criticality Analysis (FMECA)
- Establish Base Condition
  - “Fix as Fails”
  - Used as measuring stick against all alternatives
- Perform Reliability Analysis
  - Estimate PUP or hazard rate (time-dependent) using reliability models
Reliability Methods

- Two ways to estimate reliability for Major Rehabilitation Studies:
  - Non-Probabilistic
  - Probabilistic
Non-Probabilistic Reliability Methods

- Historical Frequency of Occurrence
- Survivorship Curves (hydropower equipment)
- Expert Opinion Elicitation
**Historical Frequencies**

- Use of known historical information for records at site to estimate the failure rates of various components.

- For example, if you had 5 hydraulic pumps in standby mode and each ran for 2000 hours in standby and 3 failed during standby. The failure rate during standby mode is:

  \[
  \text{Total standby hours} = 5(2000 \text{ hours}) = 10,000 \text{ hours} \\
  \text{Failure rate in standby mode} = \frac{3}{10,000} \\
  = 0.0003 \text{ failures per hour}
  \]
Manufacturers’ survivorship/mortality curves

- Curves are available from manufacturers’ for different motors, pumps, electrical components, etc...
- Curves are developed from field data and “failed” components
  - Caution is to be exercised on mode of failure
  - Failure data may have to be censored
- However, usually this data is not readily available for equipment at Corps projects except mainly hydropower facilities
- Report available at IWR on hydropower survivorship curve as well as many textbooks on the subject
Expert Opinion Elicitation (EOE)

- Solicitation of “experts” to assist in determining probabilities of unsatisfactory performance or rates of occurrence.
- Need proper guidance and assistance to solicit and train the experts properly to remove all bias and dominance.
- Should be documented well for ATR/IEPR
- Used frequently when limit states are not easily defined and data is poor
- Used commonly in Dam and Levee Safety Risk Assessments
Probabilistic Reliability Methods

- Reliability Index ($\beta$) Methods
  - First Order Second Moment (Taylor Series)
  - Advanced Second Moment (Hasofer-Lind)
  - Point Estimate Method

- Monte Carlo Simulation
- Time-Dependent (Hazard Functions)
- Response Surface Modeling
Hazard Functions

Degradation of Structures

- Relationship of strength (R) (capacity) vs. load (S) (demand)
- **Hazard Function (conditional failure rate)**

  - Developed for the ORMSSS economists/planners to assist in performing their economic simulation analysis for ORMSSS investment decisions

  - \( h(t) = P[\text{fail in } (t, t+dt)| \text{ survived } (0, t)] \)

  - \( h(t) = \frac{f(t)}{L(t)} \)
    - \( = \) No. of failures in \( t \)
    - No. of survivors up to \( t \)
Event Trees

- Used in many engineering applications for risk assessments
  - Risk
    - Probability of Failure
    - Consequences
  - Probability of events
  - Developed by engineers with input from economists
## Dashields Guard Wall Event Tree

### Anchor Wall Prior to Failure
$2,000,000 / 3$ Days of Closure

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Applied</th>
<th>Model Results</th>
<th>Repair Level</th>
<th>Repair Level Consequences</th>
<th>Cost/Closure</th>
<th>Future Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Minor Damage 60%</td>
<td>5 Days</td>
<td>$350,000</td>
<td>No Change</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Repair Damaged Areas</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Unsat. Perform. 14.34%</td>
<td>Significant Damage 35%</td>
<td>15 Days</td>
<td>$700,000</td>
<td>R = 1.0 for remainder of life cycle</td>
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<td></td>
</tr>
<tr>
<td>Impact 10%</td>
<td></td>
<td></td>
<td>Make Repairs and Anchor Wall</td>
<td>5 Days</td>
<td>2,500,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Wall Section Completely Fails 5ft</td>
<td>60 Days</td>
<td>$10,000,000</td>
<td>R = 1.0 for remainder of life cycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Replace Wall Section and Anchor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No Unsat. Perform. 85.66%</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Dashields</td>
<td>No Barge Load 70%</td>
<td></td>
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</tr>
<tr>
<td>Guide Wall Event Tree</td>
<td></td>
<td></td>
<td>No Unsat. Perform. 100%</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Unsat. Perform. 0%</td>
<td></td>
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<tr>
<td>Hawser Pull 20%</td>
<td></td>
<td></td>
<td>No Unsat. Perform. 100%</td>
<td></td>
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</tr>
</tbody>
</table>
Major Rehab Process

- Economic simulations
  - Determine BCR and NED
    - Base Condition
      - Uses PUP from Engineering
    - With Rehabilitation
      - Alternatives
      - Advanced maintenance or scheduled repair or maintenance strategies.
GO TO HUMAN RESOURCES FOR A PSYCHOLOGICAL EVALUATION.

WHY??? HAVE I SAID ANYTHING THAT IS ABNORMAL?

YOU'RE AN ENGINEER. EVERYTHING YOU SAY IS ABNORMAL.
Dam Safety Program

- **ER 1110-2-1156 – Safety of Dams (2014)**

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<table>
<thead>
<tr>
<th>TABLE OF CONTENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary of Changes</td>
</tr>
<tr>
<td>Chapter 1. Dam Safety Program - Introduction, Overview, and Guiding Principles</td>
</tr>
<tr>
<td>Purpose</td>
</tr>
<tr>
<td>Applicability</td>
</tr>
<tr>
<td>Distribution Statement</td>
</tr>
<tr>
<td>References</td>
</tr>
<tr>
<td>Glossary</td>
</tr>
</tbody>
</table>
Dam Safety Program

- Dam Safety Assurance Program (~1996)
  - Follow on to Major Rehab Program
  - Probabilistic Risk Assessments
    - Loading – Flood or seismic
    - Fragility - utilize similar reliability methods from Major Rehab program
    - Consequences – damage to property or life loss
  - Flood Risk Management projects put into Major Rehab cue for funding
Dam Safety Program

- Screening Portfolio Risk Assessment (2003-2007)
  - Examined USACE portfolio of ~620 flood control and navigation dams
  - Relative risk method
    - Loading ranges established for flood and seismic loads
    - Used base rate adjustment for critical failure modes
      - Base rates adjusted by four descriptors (A, PA, PI, I)
    - Consequences for load events
# Engineering Rating Summary

<table>
<thead>
<tr>
<th>Feature Navigation High Head Dam</th>
<th>Normal Water Level</th>
<th>50% Exceedence Duration Water Level with OBE</th>
<th>50% Exceedence Duration Water Level with MDE</th>
<th>Unusual (100yr)</th>
<th>Extreme (PMF)</th>
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<tbody>
<tr>
<td>Concrete Structures – Rock Foundation</td>
<td></td>
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<tr>
<td>External Stability</td>
<td>A</td>
<td>PA</td>
<td>PA</td>
<td>I</td>
<td>I</td>
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<tr>
<td>Internal Stability</td>
<td>A</td>
<td>PA</td>
<td>PA</td>
<td>I</td>
<td>I</td>
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<td>Foundation Stability – under dam</td>
<td>PA</td>
<td>A</td>
<td>A</td>
<td>PA</td>
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<td>Scour Protection</td>
<td>PA</td>
<td>A</td>
<td>A</td>
<td>PA</td>
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<tr>
<td>Foundation -Seepage &amp; Piping</td>
<td>PA</td>
<td>A</td>
<td>A</td>
<td>PA</td>
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<tr>
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<td>A</td>
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<td>Concrete Structures – Pile Foundation</td>
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<td>Foundation Seepage &amp; Piping (incl. upstream cut)</td>
<td>NA</td>
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<td>Foundation Liquilaction</td>
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<td>Internal Stability</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Scour Protection</td>
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<td>NA</td>
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</tr>
<tr>
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<tr>
<td>Gates &amp; Gate Structure</td>
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<td>Spillway gate(s) failure 2</td>
<td>A</td>
<td>PA</td>
<td>PA</td>
<td>I</td>
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<td>Spillway gate piers – structural capacity</td>
<td>PA</td>
<td>A</td>
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<td>Gates – Electrical/Mechanical</td>
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<td>Lock gates (struct/elect/mech)</td>
<td>A</td>
<td>A</td>
<td>PA</td>
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<td>Embankment &amp; Closure Dikes</td>
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<tr>
<td>Embankment Seepage &amp; Piping</td>
<td>PA</td>
<td>A</td>
<td>A</td>
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<td>Embankment Stability and/or Liquifaction</td>
<td>A</td>
<td>A</td>
<td>A</td>
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<td>A</td>
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<tr>
<td>Erosion: Toe, Surface &amp; Crest</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
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<td>Abutments Seepage &amp; Piping</td>
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<td>Foundation Stability and/or Liquifaction</td>
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<td>Emergency Closure Systems</td>
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<td>Service bridge</td>
<td>A</td>
<td>A</td>
<td>PA</td>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>Crane &amp; Power</td>
<td>A</td>
<td>A</td>
<td>PA</td>
<td>A</td>
<td>A</td>
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<tr>
<td>Bulkheads</td>
<td>PI</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
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<tr>
<td>Other Features</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feature 1</td>
<td>A</td>
<td>A</td>
<td>PA</td>
<td>A</td>
<td>PA</td>
</tr>
<tr>
<td>Feature 2</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Feature 3</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Feature 4</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Definition of Engineering Ratings**

- **A** Adequate = 1
  - Confidence backed up by data, studies, or obvious project characteristics and judged to meet current engineering standards and criteria.

- **PA** Probably Adequate = 10
  - May not specifically meet criteria. Requires additional investigation or studies to confirm adequacy.

- **PI** Probably Inadequate = 100
  - Confidence and requires additional studies and investigations to confirm. Judged to not meet current criteria.

- **I** Inadequate = 1000
  - Confidence. Physical signs of distress are present. Analysis indicates factor of safety near limit state.

- **NA** Not Applicable = 0
  - Feature does not exist
Dam Safety Program

- ER 1156 Risk Assessment Methodology
  - Potential Failure Mode Analysis (PFMA)
    - Evaluate and Describe Potential Failure Modes
  - Construct Event Trees to Analytically Describe the Potential Path to Failure
  - Use Expert Elicitation with an Experienced Facilitator to Evaluate Relative Likelihoods of Each Event Tree Branch
  - Use the Analysis to Develop a Rational Case to Support a Decision
  - Examine tolerable risk curves (Farmer’s Curves)
Risk Assessment Framework

- Likelihood of a Loading Event
- Flood Loading or Seismic Loading

P(Load)

- Given the Event Occurs, What is the Likelihood of Adverse Structural Response of the System?
- Event Tree Construction

P(Failure | Load)

- For Each Specific Adverse Response, What are the Life Safety and Economic Consequences?

Consequences

RISK = RISK

BUILDING STRONG®
### Event Information

<table>
<thead>
<tr>
<th>Loading Condition:</th>
<th>Hydrologic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure Mode:</td>
<td>Overtopping Erosion of the Levee</td>
</tr>
<tr>
<td>Location:</td>
<td>Low Areas based on Survey Results</td>
</tr>
<tr>
<td>Event and Initiator:</td>
<td>Very Large Flood with Possible Debris Blockage at Bridges</td>
</tr>
</tbody>
</table>

### Influence Factors

<table>
<thead>
<tr>
<th>More Likely (Adverse)</th>
<th>Less Likely (Favorable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expect there to be more debris at large flood flows than has been seen in the past</td>
<td>Needs close to SPF to trigger (overtop) without debris blockage</td>
</tr>
<tr>
<td>Trestle bridge has closely spaced supports which are more likely to catch debris</td>
<td>Except for trestle bridge, bridge piers are typically widely spaced</td>
</tr>
<tr>
<td>Bridge decks may catch debris at high flow since they are typically close to the levee crest</td>
<td>Backwater at bridges due to debris would be of limited extent upstream</td>
</tr>
<tr>
<td>Some areas of the levee would overtop at SPF without debris blockage by up to 1 to 2 feet</td>
<td>Small area near DART line most susceptible (lowest crest), could be sand bagged (1,000 to 2,000 feet)</td>
</tr>
<tr>
<td>Largest peak storm is a flashy local thunderstorm occurring between the upstream reservoirs and the levee – may not have much time to react</td>
<td>Could attempt to deal with debris at bridges using backhoes or other equipment</td>
</tr>
<tr>
<td>Local inundation of the exit roadways may hinder evacuation</td>
<td>Fairly confident in hydraulic model and predicted water surface profile, so should have relatively good idea when overtopping will occur (with no debris)</td>
</tr>
<tr>
<td>Vulnerable population (hospitals, nursing homes, etc.) may need assistance to evacuate</td>
<td>Short distance to safety – the inundated areas will be relatively close to the river, evacuation to upper floors of buildings possible</td>
</tr>
<tr>
<td></td>
<td>EAP would likely be initiated for event like this which would lead to early evacuations</td>
</tr>
<tr>
<td></td>
<td>Short duration of overtopping may not breach levee – hydrographs indicate peak flows may not be long duration</td>
</tr>
</tbody>
</table>

**Likelihood Category:** Low to Moderate  
**Confidence:** Moderate  

**Rationale:** Although it is likely the levee embankments would overtop during a flood equal to the Standard Project Flood (SPF) or greater, the compacted clay soils of the embankments will likely survive some level of overtopping without breach. The main uncertainty had to do with the possible duration of overtopping at large floods similar to the SPF that would overtop the dam.
Event Trees

Overtopping West Levee

- Flood 0.048659874
  - 321,000 cfs 0.0182%
    - Yes 60.0% 0
    - No 40.0% 0

- Intervention Fails 189.06
  - Yes 60.0% 0
    - Breach 6.56E-05 525.1666667
  - No 40.0% 0
    - Breach 0.0044% 0

- 282,000 cfs 0.0497%
  - Yes 30.0% 0
    - Breach 4.48E-05 317.1833333
  - No 70.0% 0
    - Breach 0.0104% 0

Threshold 99.932%
  - Yes 99.932% 0
  - No 0
Dam Safety Program

- Semi-Quantitative Risk Assessment (SQRA)
  - Screening level approach but more rigor than SPRA
  - Risk matrix approach to examining probability of failures and consequences
  - Uses PFMA to estimate probability of failure
  - Uses rough estimates for consequences (loss of life and direct economic loss)
**SQRA**

![SQRA Diagrams](image)

### Unit/Reach | PFM | Failure Likelihood | Confidence | Incremental Loss of Life | Confidence | Economic Loss | Confidence |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 2 A-2/I</td>
<td>PFM 11 – Backwards erosion piping in foundation</td>
<td>High</td>
<td>Low</td>
<td>Very High to Extremely High</td>
<td>Moderate</td>
<td>High to Very High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Unit 2 1</td>
<td>PFM 1 – Overtopping with breach</td>
<td>Low</td>
<td>Low</td>
<td>Very High to Extremely High</td>
<td>Moderate</td>
<td>High to Very High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Unit 2 1</td>
<td>PFM 10 – Concentrated leak erosion along pipe penetrations</td>
<td>Remote</td>
<td>Moderate</td>
<td>Very High to Extremely High</td>
<td>Moderate</td>
<td>High to Very High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Dam Safety Program

- Event driven process – flood or seismic
- PFMA does not look at consequences or criticality directly
- Relies on Expert Opinion Elicitation for ET nodes
  - Kent Tables for descriptors and probabilities
  - No probabilistic methods
- Does not include time dependency
- Does not include uncertainty
- Does not include operational risks
We'll need a risk analysis on this project before I can approve it.

Risk 1: Indecisiveness
Risk 2: Overanalysis
Risk 3: Cluelessness
Risk 4: Micromanagement...

I don't understand these risks.

That's number thirty-six.
Levee Safety Program

- ER 1120-2-XXXX Safety of Levees (guidance still under development)
- Reliability of levees were first developed under the Major Rehabilitation Program in 1990’s
  - Developed reliability models for levees and floodwalls (Taylor Series Finite Difference)
  - Examined consequences (property damage but not life loss) of levee failures
Hurricane Katrina – Aug 2005

Overtopping along Gulf Intracoastal Waterways
Hurricane Katrina – Aug 2005

17th Street Canal Breach
Hurricane Katrina – Aug 2005

London Avenue Canal North Near the Robert E. Lee Bridge
Interagency Performance Evaluation Task (IPET) Force

...“to provide credible and objective scientific and engineering answers....”

Chief of Engineers

<table>
<thead>
<tr>
<th>System</th>
<th>Storm</th>
<th>Performance</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Repair/Rebuild**
  - Report - Draft JUN06
  - Report - Final MAR07

- **Higher Protection**
  - Maps JUN/JUL 07
  - Maps AUG 07
  - Maps MAR 08
  - Report – Draft NOV 07
  - Report – Final MAY 08

https://ipet.wes.army.mil
NOLArisk.usace.army.mil
IPET Risk Assessment

- IPET Background
- Risk Assessment Model
- Hazard
- System Identification
- Reliability Modeling
- Risk Analysis
- Uncertainty
- Validation
- Lesson Learned
Risk Assessment

1. Finalize Project Objectives
2. Identify Hurricane Protection System Components
3. Failure Modes & Effects Analysis
4. Vulnerability Analysis
5. Inundation Mapping
6. Consequence Analysis
7. System Analysis
8. Risk Quantification & Uncertainty Analysis

Graphical representations of probability vs. load and load vs. probability are shown.
Storm Modeling
- ADCIRC
- Historic storms in parameter set
  - 100+ Low Res Runs
  - 1800+ Med Res Runs
  - 60+ High Res Runs
- Frequency Analysis
- Calibrate (HWM & Storm Team Results)
  - Add Waves
System Performance

Orleans Main Basin
100 Year Elevations
NAVD88 (EPOCH 2004.65) Feet

“Fragility”

Erodibility Index Factor

Erosion

Global Stability

Elevations consider expected sea level rise, subsidence and settlement

Legend
- Reach End Points
- # 100 Year Elevations
- OMxx Reach Name
- Sub-basin Number

Probability of Failure

Elevation (NAVD88 (2004.65))
## Event Tree

**Hazard analysis** (hurricane rates and effects)

**Polder system probabilities & water volumes** (conditional values per event)

**Polder consequences** (water volume, elevation & loss per event)

**HPS Risks**

| Hurricane 

\( (h, \lambda_i) \) | Hurricane spatial effects | Closure & operations 

\( (C) \) | Overtopping 

\( (O) \) | Breach* 

\( (B) \) | Drainage, pump & power 

\( (P) \) | Net water-levels 

\( (W) \) | Evacuation effectiveness | Life loss | Economic loss (\$) | Life risk | Economic risk (\$) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial peak surge &amp; effective wave height ( (SW_i) ) and durations</td>
<td>All closed ( C )</td>
<td>O</td>
<td>B</td>
<td>P</td>
<td>Water volume</td>
<td>Low effectiveness ( E_1 )</td>
<td>Inundation elevations</td>
<td>Point estimates with epistemic uncertainty estimates</td>
<td>Loss exceedance rates &amp; probabilities: 1. per polder 2. per Parish 3. for region 4. for storm categories</td>
</tr>
<tr>
<td>( \vdots )</td>
<td>Not all closed ( C )</td>
<td>O</td>
<td>B</td>
<td>P</td>
<td>Water volume</td>
<td>Medium effectiveness ( E_2 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \vdots )</td>
<td>Precipitation inflow ( (Q) )</td>
<td>Rainfall volume</td>
<td>Water volume</td>
<td>High effectiveness ( E_3 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \vdots ) ( (h_n, \lambda_n) )</td>
<td>*includes all failure modes of all reaches and their features</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Note:**

- \( h \) and \( \lambda \) represent the rate and characteristics of hurricane events, respectively.
- \( C \) indicates closure and operations.
- \( O \) represents overtopping.
- \( B \) signifies breach events.
- \( P \) denotes drainage, pump, and power functions.
- \( W \) is related to net water levels.
- \( E \) indicates evacuation effectiveness.
- \( T \) represents time periods.

---

**Building Strong®**

[Brand logo]
Before Katrina, you had a 1% chance every year of flooding this deep from Hurricanes

Notes:
- The water surface elevations are mean values
- The scale sensitivity of the legend is +/- 2 feet
- The info does not depict interior drainage modeling results
- The storm surge is characterized as the result of a probabilistic analysis of 5 to 6 storm parameters of a suite of 152 storms and not a particular event

Assumes 0% Pumping Capacity
Stage-loss relationships for Pre-Katrina population and property
Loss of Life Risk Maps
(Pre-K Population and Property)
Economic 1% Risk Maps
(Pre-K Population and Property)

PAST

Pre-Katrina, 100-year, 0% Pump

Pre-Katrina, 100-year, 50% Pump

PAST

PRESENT

2007, 100-year, 0% Pump

2007, 100-Year, 50% Pump

PRESENT

FUTURE

2011, 100-Year, 0% Pump

2011, 100-Year, 50% Pump

BUILDING STRONG®
Levee Screening Tool (2009)

- Used to rank levees in terms of Levee Safety Action Classification (LSAC) ratings and prioritization for future risk assessments
- Base failure rate for critical performance modes for levees and floodwalls
- Base rate adjustment made using Bayesian techniques and three likelihood modifiers (A, M, U)
<table>
<thead>
<tr>
<th>Performance Mode</th>
<th>Inspection Item Category</th>
<th>Inspection Item Number</th>
<th>Inspection Item Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levees</td>
<td>1</td>
<td>Unwanted Vegetation Growth</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>3</td>
<td>Encroachments</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>7</td>
<td>Settlement</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>9</td>
<td>Cracking</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>10</td>
<td>Animal Control</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>11</td>
<td>Culverts / Discharge Pipes</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>14</td>
<td>Under Seepage Relief Wells / Toe Drainage Systems</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>15</td>
<td>Seepage</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>2</td>
<td>Sod Cover</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>6</td>
<td>Erosion / Bank Caving</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>12</td>
<td>Riprap Revetements and Bank Protection</td>
<td></td>
</tr>
<tr>
<td>Levees</td>
<td>13</td>
<td>Revetments other than Riprap</td>
<td></td>
</tr>
<tr>
<td>Closure Systems</td>
<td>4 / 3</td>
<td>Closure Systems</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>1</td>
<td>Unwanted Vegetation Growth</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>2</td>
<td>Encroachments</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>4</td>
<td>Concrete Surfaces</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>5</td>
<td>Tilting, Sliding, or Settlement of Concrete Structures</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>6</td>
<td>Foundation of Concrete Structures</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>8</td>
<td>Under Seepage Relief Wells / Toe Drainage Systems</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>1</td>
<td>Unwanted Vegetation Growth</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>2</td>
<td>Encroachments</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>8</td>
<td>Under Seepage Relief Wells / Toe Drainage Systems</td>
<td></td>
</tr>
<tr>
<td>Floodwalls</td>
<td>9</td>
<td>Seepage</td>
<td></td>
</tr>
<tr>
<td>Culverts / Discharge Pipes</td>
<td>n / a</td>
<td>Closure Systems</td>
<td></td>
</tr>
</tbody>
</table>
Levee Screening Tool
Levee Safety Program

- Current Risk Assessment Methodology
  - Potential Failure Mode Analysis (PFMA)
    - Evaluate and Describe Potential Failure Modes
  - Construct Event Trees to Analytically Describe the Potential Path to Failure
  - Use Expert Elicitation with an Experienced Facilitator to Evaluate Relative Likelihoods of Each Event Tree Branch
  - Use the Analysis to Develop a Rational Case to Support a Decision
  - Use tolerable risk guidelines (Farmer’s curves)
Levee Safety Program

- Semi-Quantitative Risk Assessment (SQRA)
  - Screening level approach but more rigor than SPRA
  - Risk matrix approach to examining probability of failures and consequences
  - Uses PFMA to estimate probability of failure
  - Uses rough estimates for consequences (loss of life and direct economic loss)
Levee Safety Program

- Event driven process – flood or seismic
- PFMA does not look at consequences or criticality directly
- Relies on Expert Opinion Elicitation for ET nodes
  - Kent Tables of descriptors and probabilities
  - No probabilistic methods
- Does not include time dependency
- Does not include uncertainty
AS YOU CAN CLEARLY SEE IN SLIDE 397...

GAAAAH!

"POWERPOINT POISONING."
Asset Management

- USACE AM program started in 2006
- Program is developed to support risk-informed decision making and prioritization of USACE Operations and Maintenance budget work packages (~14,000 work packages a year, ~$2B)
- AM looks at and across all USACE business lines
- AM focuses on value and utility of each work package
USACE Asset Management

What, where and when do I invest? Providing “Line of Sight” to enable the assets greatest Value to the Nation!
Lifecycle Portfolio Management Process

### Assets
- **MMIP**
- **FEM Asset Visibility**
  - Age
  - Failures
  - Repairs
  - Cycles
  - Etc.
- **PMMP**
  - Full Maintenance Requirements
  - Work Management & Communications
    - Local
    - Regional
    - National

### Condition
- OCA
  - OCA Models & Condition (Nat’l QA/QC)
- Condition

### Mission
- ORA
  - Workbooks/Utility Model
- P(f)

### Risk
- Budget Development
- Risk Buy-down and Investment

### Value
- Budget Prioritization
- Portfolio Analytics & Total Risk Exposure

6 information elements required for effective Lifecycle Portfolio Management:
- Inventory
- Condition
- Consequences
- Requirements
- Prioritization
- Execution
Lifecycle Portfolio Management Process

6 information elements required for effective Lifecycle Portfolio Management:

- Inventory
- Condition
- Consequences
- Requirements
- Prioritization
- Execution

Condition

OCA Models & Condition (Nat’l QA/QC)

Mission

ORA Workbooks/Utility Model

Condition

Risk

Risk Buy-down and Investment

Budget

Budget Prioritization

Value

Portfolio Analytics & Total Risk Exposure

Assets

MMIP

FEM Asset Visibility

- Age
- Failures
- Repairs
- Cycles
- Etc.

PMMP

- Full Maintenance Requirements
- Work Management & Communications
  - Local
  - Regional
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Lifecycle Portfolio Management Process

Assets
- MMIP
- FEM Asset Visibility

Condition
- OCA
  - OCA Models & Condition (Nat’l QA/QC)
- Condition

Mission
- ORA
  - Workbooks/Utility Model
- P(f)

Risk
- Budget Development
  - Risk Buy-down and Investment

Value
- Budget Prioritization
  - Portfolio Analytics & Total Risk Exposure
  - Budget Execution

6 information elements required for effective Lifecycle Portfolio Management:
- Inventory
- Condition
- Consequences
- Requirements
- Prioritization
- Execution
Operational Risk Assessment

Risk = Probability of Failure X Consequences

- 5x5 Relative Risk Matrices
  - Currently available in Budget EC
  - Known limitations – based on one consequence

- Prototype ORA Workbook tool for Nav Locks & Dams
  - OCA data, probability of failure for components, economic impacts
  - Started with FY13 budget development

- Hydropower Modernization Initiative (HMI)
  - Used to help plan non-BPA capital investments

- Other BL’s – No Risk Assessment tool
# 5x5 Risk Matrix

**TABLE D-5 Relative Risk Value Matrix (1-25 Matrix)**

<table>
<thead>
<tr>
<th>Consequence Category</th>
<th>Consequence</th>
<th>FRM Project Condition Tool (Illustration D.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>F (1)</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Failed</td>
</tr>
<tr>
<td>1</td>
<td>High</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Medium High</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Medium</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>Minimal</td>
<td>11</td>
</tr>
</tbody>
</table>

Legend:
- High Relative Risk
- Med-High Relative Risk
- Medium Relative Risk
- Low Relative Risk
- Minimal Relative Risk
### 5x5 Risk Matrix - OCA & Consequences

**Or** logic – can only use 1 consequence

<table>
<thead>
<tr>
<th>Consequence Category 1 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAR: 100,000</td>
<td>1</td>
</tr>
<tr>
<td>10,000 - PAR &lt; 100,000</td>
<td>2</td>
</tr>
<tr>
<td>1,000 - PAR &lt; 10,000</td>
<td>3</td>
</tr>
<tr>
<td>PAR &lt; 1,000</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Category 2 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic Impact:</td>
<td></td>
</tr>
<tr>
<td>Damages to residential and nonresidential structures, their contents, and vehicles ranging from $100M to $1B</td>
<td>1</td>
</tr>
<tr>
<td>Damages to residential and nonresidential structures, their contents, and vehicles ranging from $1M to $10M</td>
<td>2</td>
</tr>
<tr>
<td>Damages to residential and nonresidential structures, their contents, and vehicles ranging from $100K to $1M</td>
<td>3</td>
</tr>
<tr>
<td>Damages to residential and nonresidential structures, their contents, and vehicles less than $100K</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Category 3 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental:</td>
<td></td>
</tr>
<tr>
<td>Permanent affects to Federal listed threatened or endangered species and their designated critical habitat</td>
<td>1</td>
</tr>
<tr>
<td>Permanent loss of irreplaceable socio-economic or ecological assets</td>
<td>2</td>
</tr>
<tr>
<td>Temporary adverse impacts to all designated special status species and habitats</td>
<td>3</td>
</tr>
<tr>
<td>Significant loss of scenic value; no effect on special status species</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Category 4 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Infrastructure:</td>
<td></td>
</tr>
<tr>
<td>5% &lt; Ratio of Essential Structures Damaged &lt; 25%</td>
<td>1</td>
</tr>
<tr>
<td>0% - 5% Ratio of Essential Structures Damaged &lt; 25%</td>
<td>2</td>
</tr>
<tr>
<td>0% - 5% Ratio of Essential Structures Damaged &lt; 25%</td>
<td>3</td>
</tr>
<tr>
<td>0% &lt; Ratio of Essential Structures Damaged &lt; 10%</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Category 5 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legal Mandate:</td>
<td></td>
</tr>
<tr>
<td>Federal law dictates closure or suspension of the project operations</td>
<td>1</td>
</tr>
<tr>
<td>Financial penalties or criminal liabilities imposed but do not impact the operations of the project</td>
<td>2</td>
</tr>
<tr>
<td>Federal Mandates are based solely on State or Local statutes</td>
<td>3</td>
</tr>
<tr>
<td>No Legal Mandate exists</td>
<td>4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Category 6 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Social Vulnerability:</td>
<td></td>
</tr>
<tr>
<td>Population over 65 &gt; 100%</td>
<td>1</td>
</tr>
<tr>
<td>Population over 65 &gt; 5% - 10%</td>
<td>2</td>
</tr>
<tr>
<td>Population over 65 &gt; 5% - 25%</td>
<td>3</td>
</tr>
<tr>
<td>Population over 65 &gt; 25% - 50%</td>
<td>4</td>
</tr>
<tr>
<td>Population over 65 &gt; 50%</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Consequence Category 7 Rating Criteria</th>
<th>Category Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastal Projects:</td>
<td></td>
</tr>
<tr>
<td>High economic impact $100M - $1B</td>
<td>1</td>
</tr>
<tr>
<td>Moderate economic impact $10M - $100M</td>
<td>2</td>
</tr>
<tr>
<td>Low economic impact $1M - $10M</td>
<td>3</td>
</tr>
<tr>
<td>Moderate to high economic impact &lt; $1M</td>
<td>4</td>
</tr>
</tbody>
</table>
The Pieces of the Puzzle

Assigning Condition Ratings

- Operational Condition Assessments (OCA) developed by IMTS BPR group, approved by IMTS BoD and implemented by MSC Teams

Economic Conseq to Shippers and Carriers

- Economic Consequences on Shippers and Carriers (varying durations, 1-365 days) from Planning Center of Expertise for Inland Navigation (PCXIN)

Recovery Durations

- Baseline “Recovery Durations” to restore Mission after an Unscheduled Outage due to a Critical Component Failure

Probability of Operational Failure (Unsatisfactory Performance) X Consequence of Failure

1. Correlate the cost of operational failure with consequences: OCA x P(f)

All of this for 166,000 asset components across the IMTS!!
OCA and ORA

- AM needed methodology to estimate the probability of failure for Operational Risk Assessment (ORA) processes.
- AM required the development of a relationship between both Operational Condition Assessment (OCA) data and the estimate of the probability of failure.
  - Utilize state-of-practice and state-of-the-art models and methods to map OCA to Pf.
Development of Baseline Weibull Curves

- Initial estimate of OCA to probability of failure translation for predefined set of components by major categories

- Estimated probabilities of failure using Expert-Opinion Elicitation
  - Navigation SME/RTS from USACE Districts nationwide
  - Real-time processing data to Weibull curves for experts input and review
Development of Baseline Weibull Curves

- Estimate OCA and Pf transitions based on statistical estimation of the Maximum Likelihood Estimator (MLE) properties of Weibull Distributions
  - Translations can be adjusted as age and condition are defined by OCA resulting in updated Pf
- As additional OCA and failure data are collected Bayesian updating process can be utilized to modify and adjust baseline Weibull parameters
  - Permits more accurate estimation of Pf as additional data is collected and processed
Expert-Opinion Elicitation

Weibull Distribution

MTTF

Cumulative Density

A to B

B to C

C to D

D to E

Year

0 50 100 150 200 250
Calculating Operational Risk (ORA)

**Probability of Operational Failure**  \( \times \)  **Consequence of Failure**

(Unsatisfactory Performance)

What is the **Condition** of Components in your site specific Inventory? and based on the condition of THAT Component what is its **Probability of Failure**?

What is the average “Impact Recovery Duration” (in DAYS) to restore Mission capability for that component from a failure that caused an Unscheduled Outage?

What **Economic impact** on Shippers-Carriers is there based on the Duration of that Unscheduled Outage?

**Notional Example:**

Component “X” in Condition “D”
Has P(f) = 0.488996058

Component “X” has an IRD = 20 days

At L&D Site Y” the Econ Impact on Shippers-Carriers for an Unscheduled Outage of 20 days = $2,663K

\[
P(f) \times \text{Consequence} = \text{Risk}
\]

\[
0.488996058 \times 2,663,000 = 1,302,197
\]

BUILDING STRONG®
For EACH IMTS Site (to Component level):

Inventory | Condition | P(f) | x

Econ Impact on Shippers and Carriers = Risk (@ Component level)

\[ \sum = \text{TRE} \]

Total Risk Exposure is composed of:

“Residual Risk” – Components in “A” & “B” condition that currently do NOT show impacts on mission performance (including components that have been Repaired/Replaced)

“Operational Risk” – Components in “C” thru “F” condition that currently show impacts on mission performance

Each IMTS Site will have varying degrees of Operational and Residual Risk which can inform Investment Strategies
Operational Risk Exposure – Feature | System
(Condition/Risk of Critical Components across entire IMTS)

Maintain and Repair the Most Critical Components that have the Potential to Cause Highest Mission Impacts
Risk Exposure assists in informing Life Cycle Investment Decisions.
Budget Prioritization

➢ AMPA tool - FRM, NAV, and HYD
  ▪ AMPA Technical Documentation (2015) - Details regarding specific business line data, value model design and process
  ▪ Very important to enter accurate data in CWIFD and complete all the fields
  ▪ Available on the AMPA SharePoint site, folder called AMPA Budget Tools-AMPA-FY18 Budget Development folder:

  https://cops.usace.army.mil/sites/AM/PA/AMPA%20Budget%20Tools/Forms/AllItems.aspx

  ▪ Or at the AM Tools site under the “AMPA Workbook Tools and Download (NAV, FRM, HYD)” link at:

  https://assetmanagement.usace.army.mil/tools/

➢ AMPA tool - Demonstration
### Value Model Attribute

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<tr>
<th>Attribute</th>
<th>Units</th>
<th>CWIFD Column</th>
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<tbody>
<tr>
<td>Avoid Forced Facility Closure ($x_1$)</td>
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<tr>
<td>GHG Equivalent ($x_2$)</td>
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<td>Generation Benefit ($x_3$)</td>
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<td>Avd Legal Mndt, Try, or ESA Violation ($x_4$)</td>
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<td>Avoid Public/Workplace Safety Item ($x_6$)</td>
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<tr>
<td>Annual Replacement Energy Cost ($x_8$)</td>
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### Prior Consequence Category from 5x5

- Weight = 0.095
- Weight = 0.048
- Weight = 0.143
- Weight = 0.190
- Weight = 0.286
- Weight = 0.238

### Decision Model Variable

- $V(F, F)$
- $V(\sim F, F)$
- $Pr(F, F)$
- $Pr(\sim F, F)$

### CWIFD Column 34

(Prior Consequence Category from 5x5)

### CWIFD Column 37

(With BY Request – Condition [A-F])

\[
x_1, \ldots, x_6 = \sum_{i} w_i v_i(x_i),
\]

### Consequence Rating Criteria

- **High:**
  - Public or Life Safety impact and/or
  - Violations of Legal Requirement(s) and/or
  - Forced Closure resulting in Highest Economic Loss and/or
  - Great Decrease in Performance (e.g., reliability, capacity, efficiency) and/or
  - Greatest Increase in Critical Maintenance Backlog and/or

- **Medium-High:**
  - Forced Closure/Closure resulting in High Economic Loss and/or
  - Greater Decrease in Performance (e.g., efficiency, capacity, reliability) and/or
  - Greater Increase in Life Cycle Costs and/or
  - Greater Increase in Critical Maintenance Backlog and/or

- **Medium:**
  - Forced Closure/Closure resulting in Moderate Economic Loss and/or
  - Moderate Decrease in Performance (e.g., efficiency, capacity, reliability) and/or
  - Moderate Increase in Life Cycle Costs and/or
  - Moderate Increase in Critical Maintenance Backlog and/or

- **Low:**
  - Forced Closure/Closure resulting in Minor Economic Loss and/or
  - Minor Decrease in Performance (e.g., efficiency, capacity, reliability) and/or
  - Minor Increase in Life Cycle Costs and/or
  - Minor Increase in Critical Maintenance Backlog and/or

- **Minimal:**
  - Forced Closure/Closure resulting in Minimal Economic Loss and/or
  - Minimal Decrease in Performance (e.g., efficiency, capacity, reliability) and/or
  - Minimal Increase in Life Cycle Costs and/or
  - Minimal Increase in Critical Maintenance Backlog and/or

### Probability Mapping to Condition

### Probability of SUCCESS mapping to Condition
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<th>Value Difference</th>
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<th>Work Package Title</th>
<th>District Rank</th>
<th>MSC Rank</th>
<th>AMPA Rank</th>
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Conclusions

- Over the past 25 years, USACE has invoked many different risk assessment methodologies for use in their risk-informed decision making processes.
- Each risk assessment methodology has their particular benefits and drawbacks.
- Risk assessment methodologies are not static but dynamic and change with the next generations.
and THIS, ladies and gentlemen, is how a Twinkie is made. Any questions?