INLAND NAVIGATION ECONOMICS WEBINAR SERIES

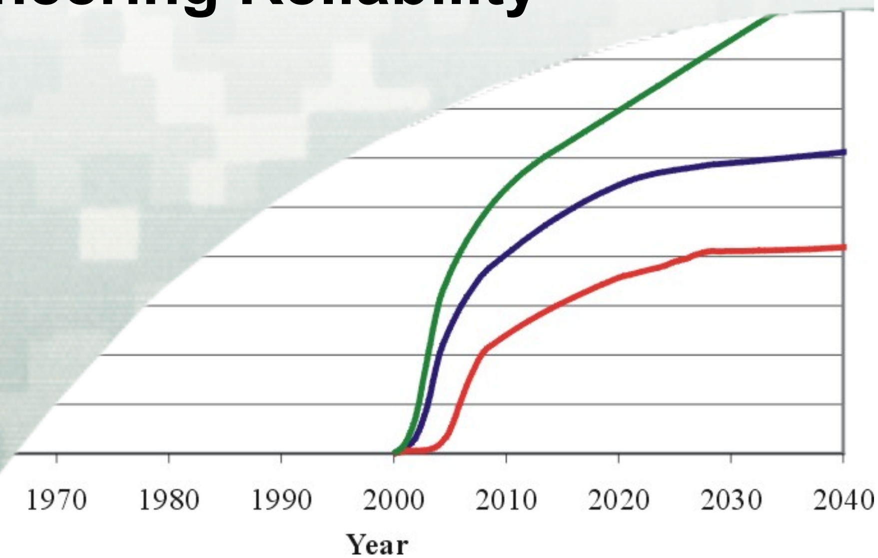
#7 – Navigation Component Engineering Reliability

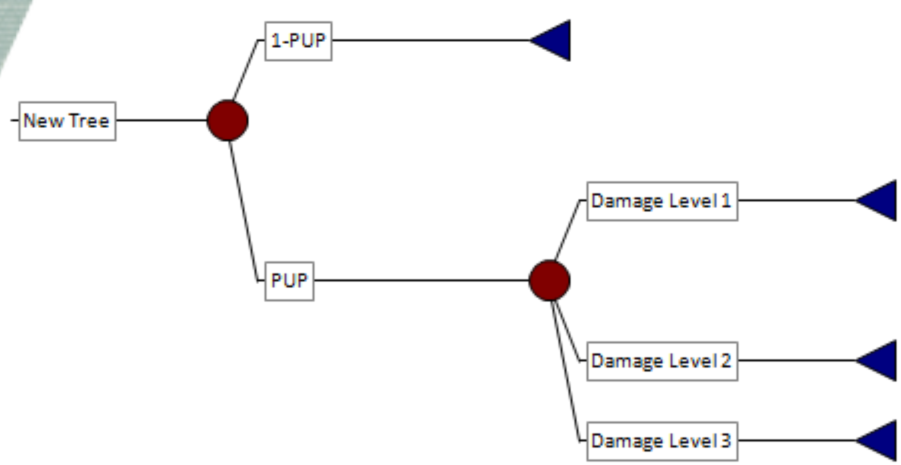
Gabriela M. Lyvers

Structural Engineer

Louisville District

3 April 2013





US Army Corps of Engineers

BUILDING STRONG®

Required Information for Consequence Analysis

- Annual Hazard Rate for time dependant components
- Single PUP for non-time dependant components
- Consequence Event Tree
  - Significant consequences
  - Various levels of repair
  - Costs to repair and other damages
- Updated hazard rates for repaired components
- Cost associated with fix as fails vs. scheduled repair prior to failure.

Overview

- Reliability Analysis
- Engineering Assessment
- Calculating Hazard Function
- Event Trees and Consequence Levels

Reliability Analysis

Reliability:

Probability that a system will perform its intended function for a specific period of time under a given set of conditions.

$$R = 1 - P_f$$

Reliability is the probability that unsatisfactory performance will not occur.

- Risk: Pf x Consequences = Risk

Methods of Reliability Analysis

- Hazard Function Analysis
  - Time Dependant Reliability Models
  - Non-time Dependant Reliability Models
- Expert Opinion Elicitation
- Historical Frequency Method

Engineering Assessment

- Systematic assessment of all components or infrastructure
- What components should be evaluated? What are the critical components?
- Numerical Screening Method
  - ► Ranking based on different categories
  - ► Categories weighted based on criticality
  - ► Relative ranking
  - ► Consistency is important

Example Screening Criteria

ASSESSMENT CATEGORIES

- Planned replacement/upgrade? Funding in place? Yes/No
- Component Redundancy 0.1
- Current Condition of component 0.1
- Likelihood of future problems 0.3
- Relative costs to replace/upgrade and quantity 0.15
- Impact to navigation/outage time 0.25
- Other impacts 0.1

Example Screening Criteria

- Each category was rated 1-5 by the assessment team.
- 1 being the worst and 5 being the best
- All ratings were multiplied by the category multiplier and summed
- Components with the smallest ratings moved to the top of the list.
- Assessment team reviewed list and came up with a cut off point and reviewed excluded components to make sure all that were thought to be critical were included.
- Components evaluated individually.

C	D	E	F	G	H	I	J	K	L	M	N
GLSLS Project	DECISION TO UPGRADE ALREADY MADE	REDUNDANCY	CURRENT CONDITION OF COMPONENT	LIKELIHOOD OF FUTURE PROBLEMS	RELATIVE COST REPLACE/UPGRADE (incl con	Qty. Rating	Combined Rating	IMPACT TO NAVIGATION	OTHER IMPACTS	OVERALL RANKING	SCREENING RESULTS
Maisonneuve	N	1.0	2.0	1.0	1.0	4.0	1.0	1.0	4.0	1.40	Reliability Mc
Welland	N	1.0	2.0	1.0	1.0	5.0	1.0	3.0	1.0	1.60	Reliability Mc
USDOT	N	1.0	2.0	2.0	1.0	5.0	1.0	1.0	4.0	1.70	Expert Elicita
Soo - Poe	N	1.0	1.0	1.0	1.0	5.0	1.0	3.0	5.0	1.90	Reliability Mc
USDOT	N	2.0	2.0	1.0	3.0	4.0	3.0	1.0	5.0	1.90	Reliability Mc
Soo - Poe	N	2.0	2.0	1.0	3.0	5.0	3.0	1.0	5.0	1.90	Reliability Mc
Soo - Dam	N	1.0	1.0	1.0	2.0	5.0	2.0	4.0	1.0	1.90	Reliability Mc
Maisonneuve	N	1.0	3.0	3.0	2.0	3.0	2.0	1.0	1.0	1.95	Reliability Mc
USDOT	N	1.0	2.0	2.0	2.0	5.0	2.0	3.0	1.0	2.05	Reliability Mc
Maisonneuve	N	1.0	3.0	3.0	4.0	3.0	3.0	1.0	1.0	2.10	Expert Elicita
Welland	N	1.0	3.0	2.0	2.0	3.0	2.0	2.0	3.0	2.10	Reliability Mc
Maisonneuve	N	1.0	3.0	2.0	2.0	4.0	2.0	2.0	3.0	2.10	Reliability Mc
Welland	N	1.0	3.0	3.0	2.0	4.0	2.0	1.0	3.0	2.15	Reliability Mc
USDOT	N	1.0	2.0	3.0	2.0	5.0	2.0	1.0	4.0	2.15	Expert Elicita
Maisonneuve	N	1.0	3.0	2.0	3.0	5.0	3.0	2.0	2.0	2.15	Reliability Mc
Welland	N	1.0	2.0	1.0	2.0	3.0	2.0	3.0	5.0	2.15	Expert Elicita
USDOT	N	1.0	2.0	1.0	2.0	5.0	2.0	4.0	3.0	2.20	Expert Elicita
Welland	N	1.0	2.0	3.0	3.0	4.0	3.0	1.0	4.0	2.30	Expert Elicita
Welland	N	1.0	2.0	3.0	4.0	4.0	3.0	1.0	5.0	2.40	
Maisonneuve	N	2.0	2.0	1.0	4.0	2.0	2.0	4.0	5.0	2.50	Expert Elicita
Maisonneuve	N	1.0	3.0	3.0	4.0	4.0	3.0	1.0	5.0	2.50	
Soo - MacArthur	N	3.0	2.0	1.0	4.0	4.0	3.0	3.0	5.0	2.50	
Welland	N	1.0	3.0	3.0	4.0	4.0	3.0	2.0	3.0	2.55	Expert Elicita
Soo - Poe	N	1.0	3.0	4.0	2.0	5.0	2.0	1.0	4.0	2.55	
Welland	N	1.0	2.0	1.0	3.0	5.0	3.0	5.0	3.0	2.60	Expert Elicita
USDOT	N	2.0	3.0	3.0	3.0	4.0	3.0	1.0	5.0	2.60	
USDOT	N	1.0	2.0	2.0	3.0	4.0	3.0	3.0	5.0	2.60	
Maisonneuve	N	3.0	2.0	1.0	4.0	2.0	2.0	4.0	5.0	2.60	Expert Elicita
Soo - Poe	N	4.0	2.0	1.0	4.0	4.0	3.0	3.0	5.0	2.60	Expert Elicita
Soo - Dam	N	1.0	3.0	3.0	1.0	5.0	1.0	4.0	2.0	2.65	
Soo - MacArthur	N	1.0	3.0	3.0	1.0	5.0	1.0	3.0	5.0	2.70	Expert Elicita
Soo-Dam	N	1.0	3.0	3.0	2.0	5.0	2.0	4.0	1.0	2.70	
Welland	N	1.0	3.0	2.0	3.0	3.0	2.0	4.0	4.0	2.70	
Maisonneuve	N	1.0	3.0	4.0	3.0	4.0	3.0	1.0	4.0	2.70	
Welland	N	1.0	3.0	4.0	3.0	5.0	3.0	1.0	4.0	2.70	
Maisonneuve	N	1.0	3.0	3.0	4.0	5.0	4.0	2.0	3.0	2.70	
USDOT	N	5.0	2.0	1.0	4.0	3.0	3.0	3.0	5.0	2.70	
Welland	N	2.0	3.0	4.0	3.0	3.0	2.0	1.0	5.0	2.75	
Soo - MacArthur	N	3.0	2.0	2.0	3.0	5.0	3.0	3.0	5.0	2.80	
USDOT	N	1.0	3.0	4.0	4.0	4.0	3.0	1.0	5.0	2.80	
Maisonneuve	N	2.0	3.0	3.0	3.0	4.0	3.0	2.0	5.0	2.85	
Welland	N	1.0	2.0	2.0	3.0	5.0	3.0	4.0	5.0	2.85	
Welland	N	1.0	3.0	4.0	4.0	5.0	4.0	1.0	4.0	2.85	
Welland	N	1.0	4.0	4.0	4.0	3.0	3.0	2.0	3.0	2.95	
Maisonneuve	N	2.0	3.0	4.0	4.0	4.0	3.0	2.0	3.0	2.95	
Soo - Poe	N	1.0	3.0	4.0	4.0	5.0	4.0	1.0	5.0	2.95	

Calculating PUP

- Hazard Function Analysis
  - Time Dependant Reliability Models
  - Non-time Dependant Reliability Models
- Expert Opinion Elicitation
- Historical Frequency Method

Hazard Function Analysis

- Computes the rate of change at which the probability changes over a selected time step (usually annually).
  - Not a snapshot in time.
  - Uses Monte Carlo simulations to calculate probability of failure.
  - Time dependant or Non-time dependant

Hazard Function Analysis

Hazard function h(t) is the conditional probability of unsatisfactory performance of a structure or component at a time (t) given that it has survived up to the selected time.

$$h(t) = f(t)/R(t)$$

$f(t)$ = pdf at time $t + \Delta t$

$R(t)$ = cmumulative reliability up to time t

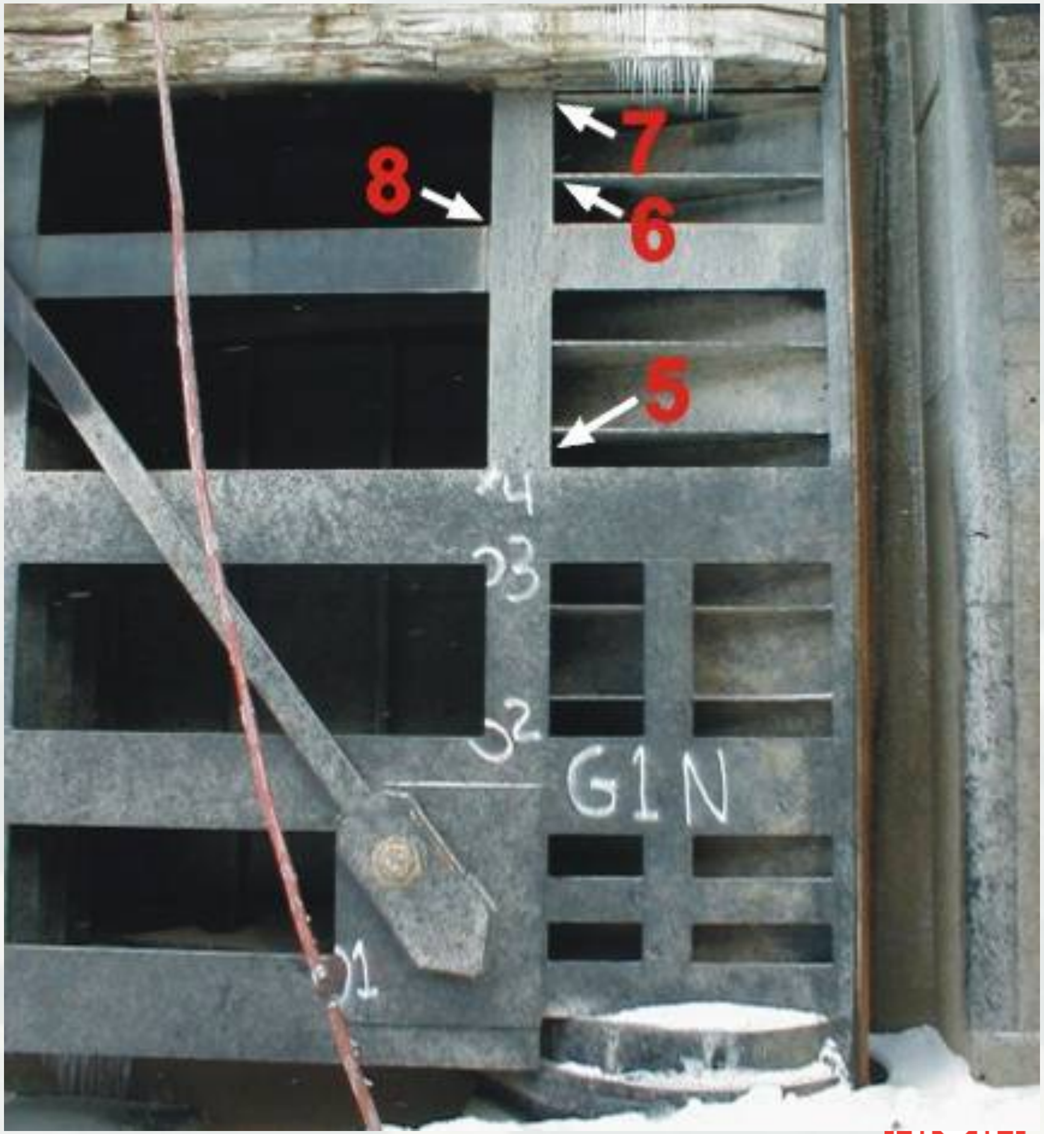
When using Monte Carlo simulations h(t) can be simplified to:

$$h(t) = \#\ \text{failures}\ (t_i) / \#\ \text{of survivors}\ (t_{i-1})$$

Time Dependant Reliability Models

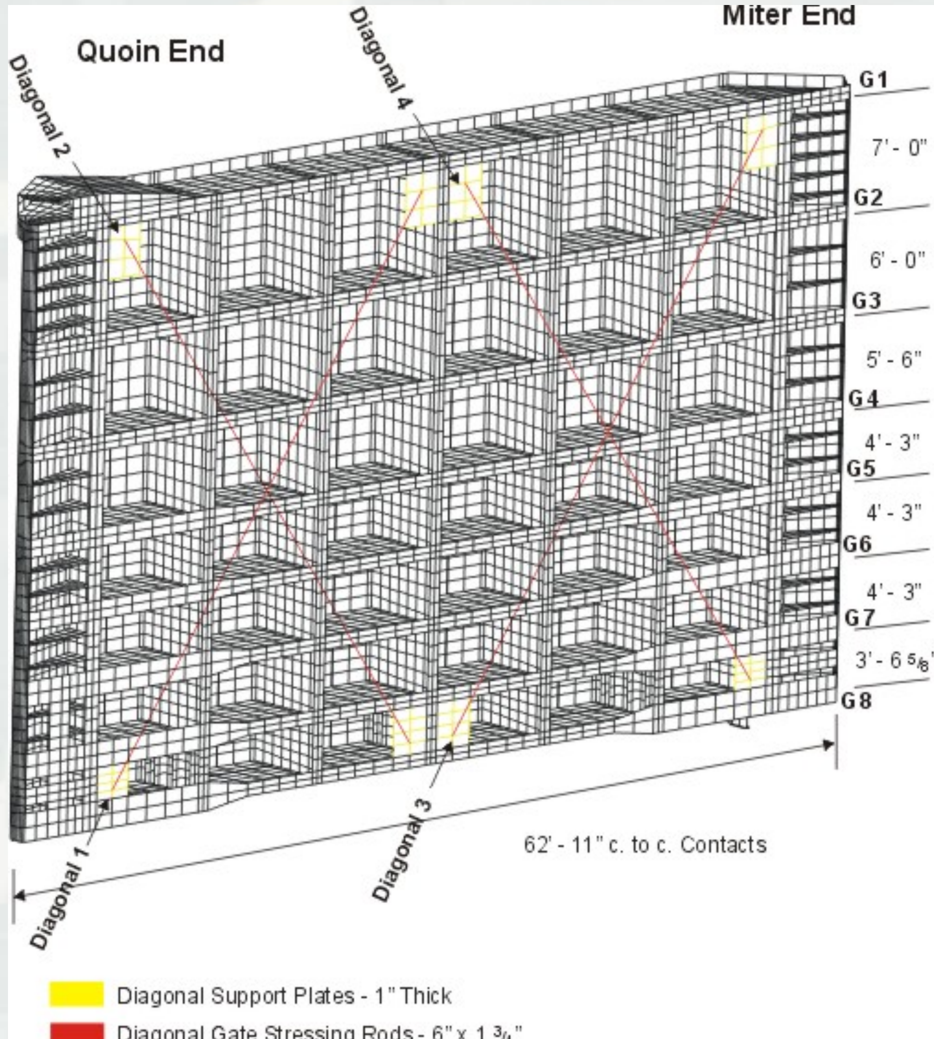
- Probabilities of Unsatisfactory Performance that degrade over time
  - Hydraulic Steel Structures (crack propagation)
  - Monolith instability due to scour
  - Deteriorating concrete
  - Mechanical/electrical equipment

Failure of Miter Gate Member due to Fatigue Cracking

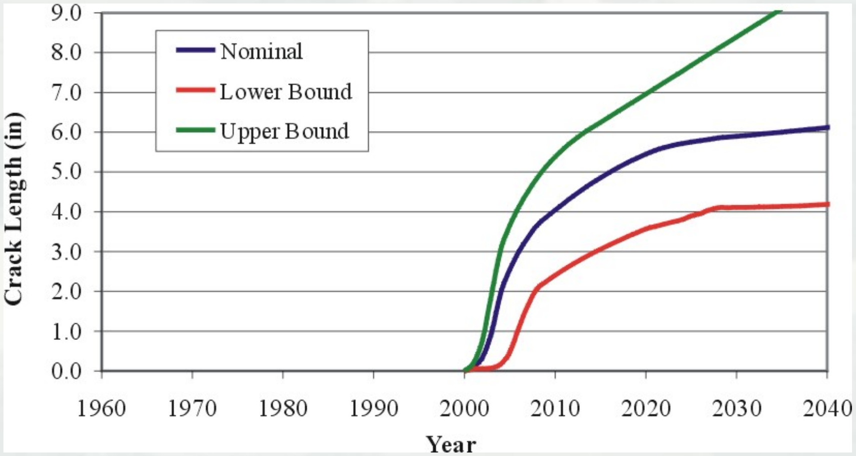


Miter Gate Fatigue Cracking

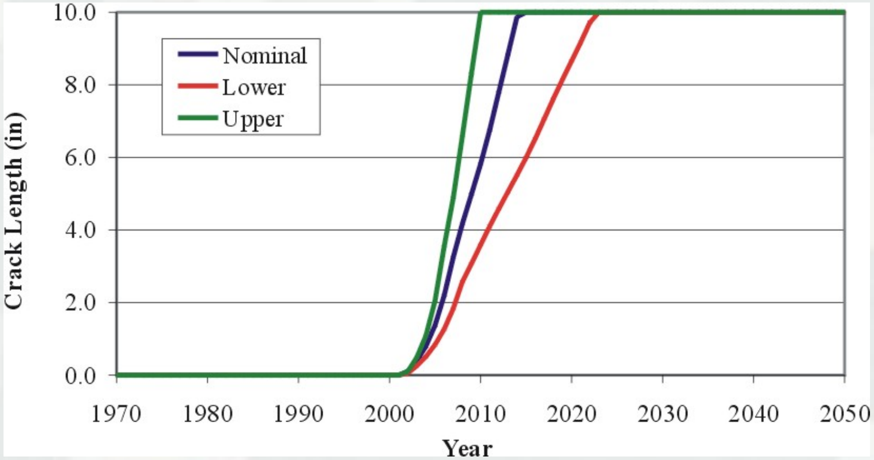
- Failure limit state was set to 10 inches.
- Finite element model used to calculate stresses.
- Failure due to stress reversals (tension/compression)
- Monte Carlo simulation varying stress concentrations, corrosion rates, gate component wear, material properties, and initial crack size.

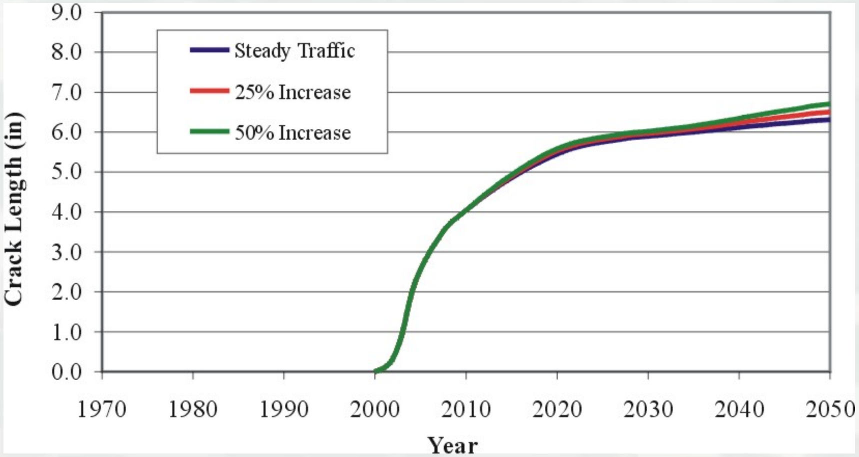


Crack Growth for Stiffener Plate



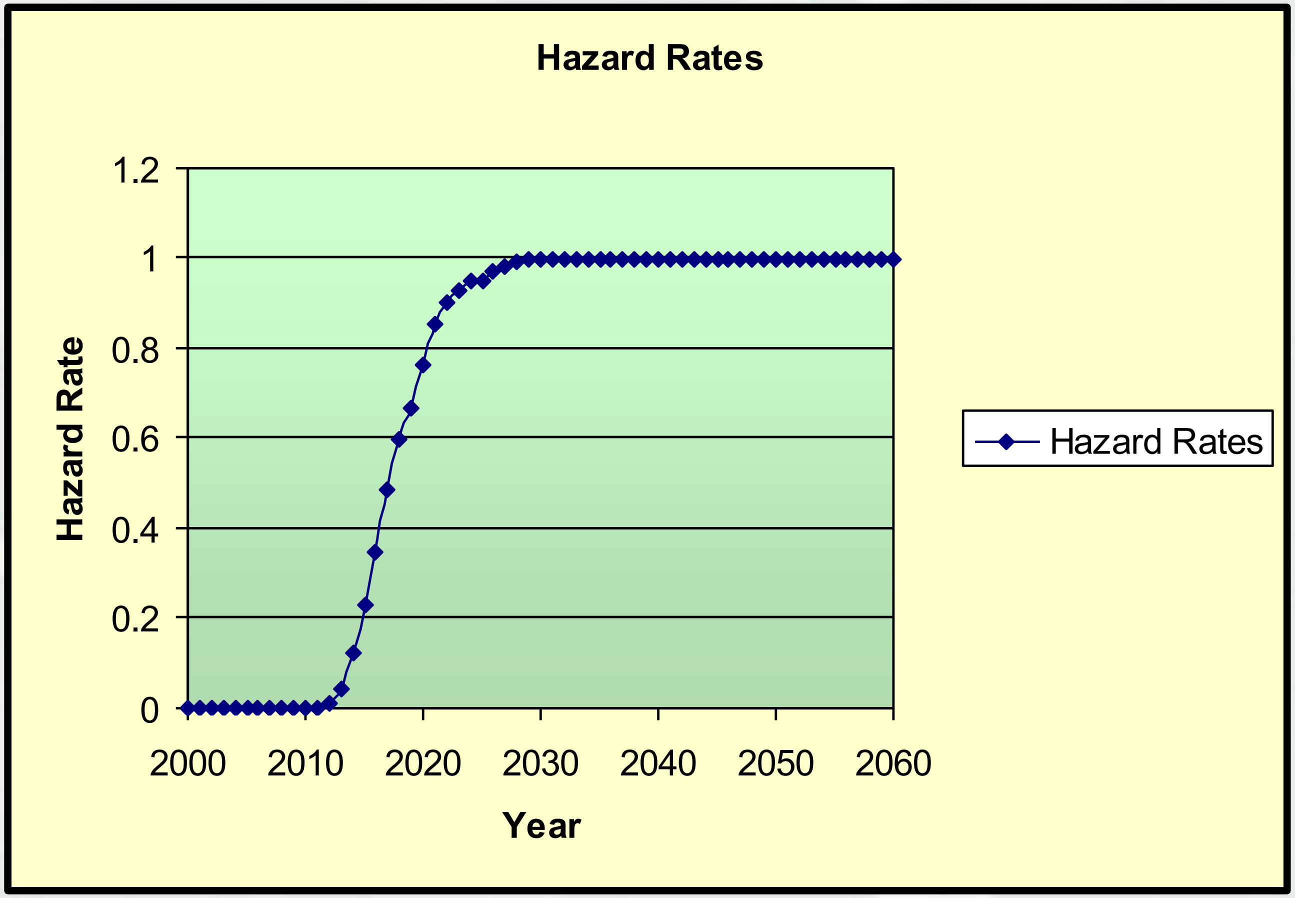
Cracking of DS Girder Flanges





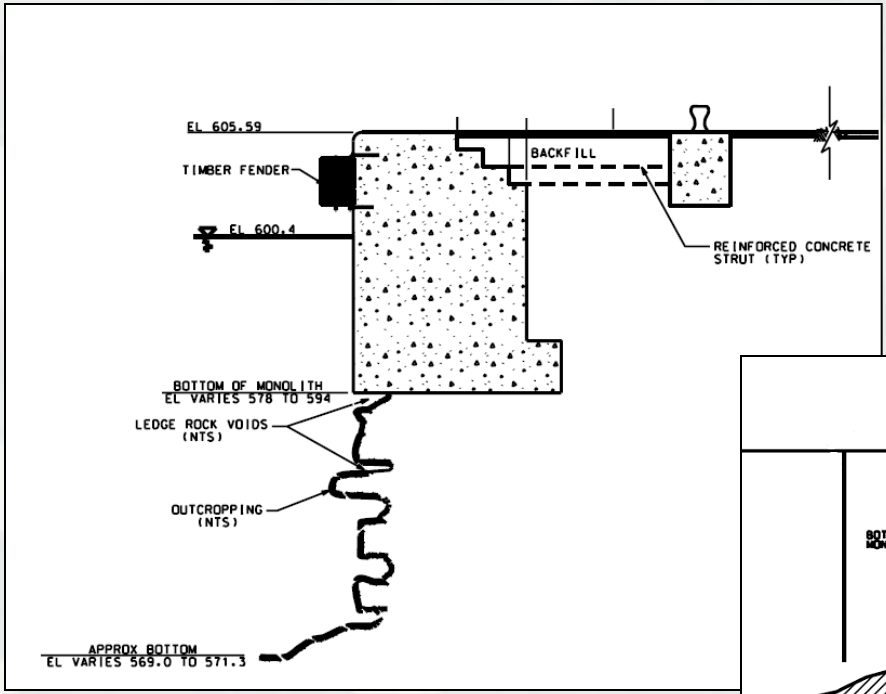
Effect of Traffic Increase on Stiffener Plate Cracking

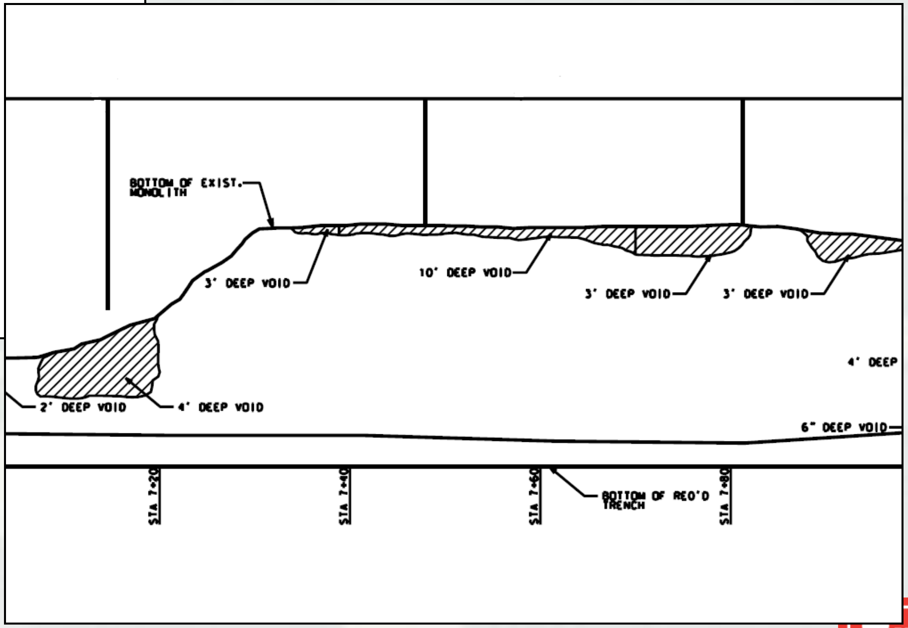
Miter Gate Hazard Function



Monolith Instability due to Scour

Monolith Instability due to Scour





BUILDING STRONG®

Monolith Instability due to Scour

- Probabilistic Analysis using Excel and @Risk
- Variables
  - Erosion Rate
  - Shear strength at the concrete rock interface
  - Bearing capacity of rock
  - Ship pull force
  - Pool elevation

RESULTS

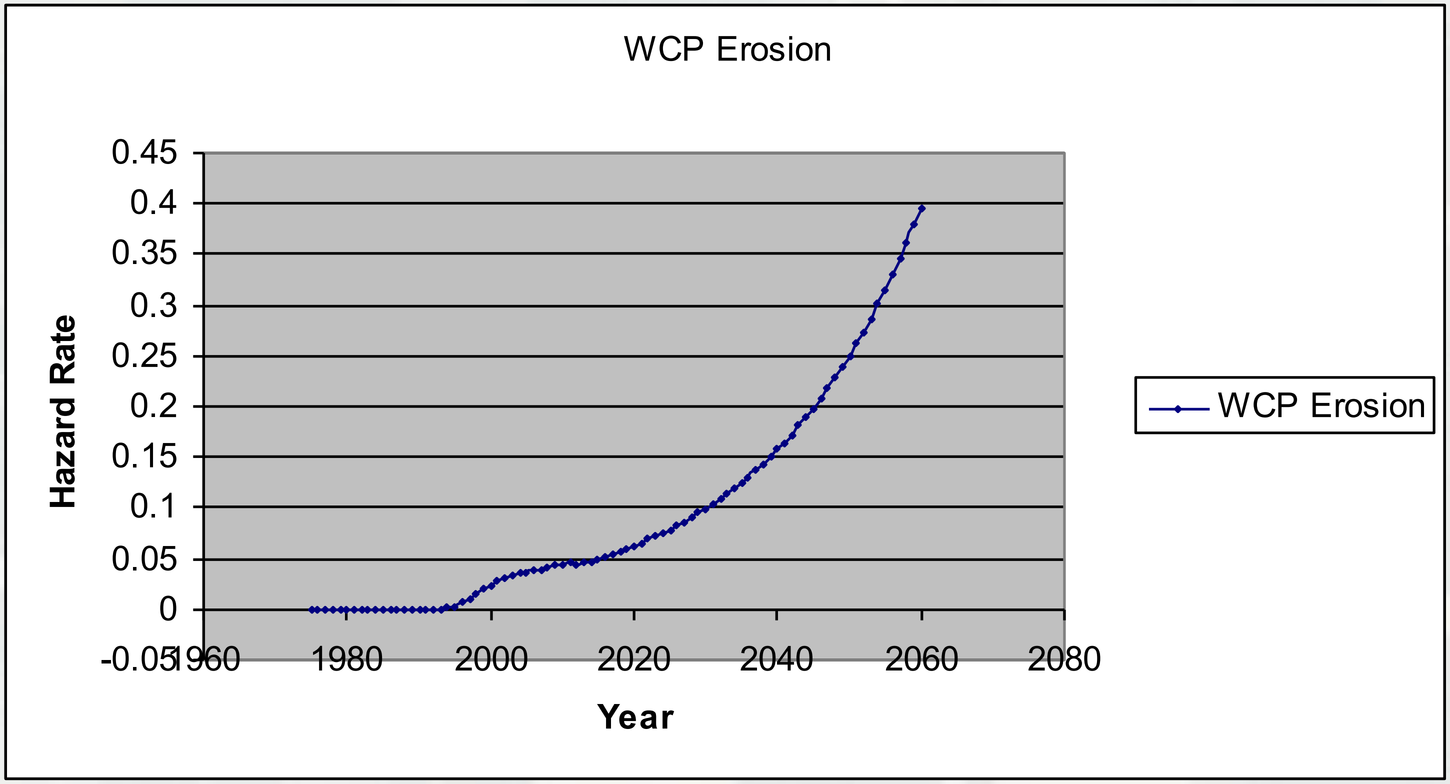
Resultant Location from Toe (ft)	Percent Base in Compression	Max. Foundation Pressure (ksf)	Sliding F.S	Overturning F.S.*	Bearing F.S.	Failure	
8.40	30.04%	4.76	2.70	1.1	16.36	0	1975
8.39	29.60%	4.86	2.68	1.1	16.03	0	1976
8.38	29.16%	4.96	2.67	1.1	15.70	0	1977
8.38	28.71%	5.07	2.66	1.1	15.37	0	1978
8.22	4.13%	46.08	2.19	1.1	1.69	0	2016
8.22	3.20%	59.87	2.18	1.1	1.30	0	2017
8.22	2.26%	85.61	2.16	1.1	0.91	1	2018
8.22	1.30%	150.65	2.15	1.1	0.52	1	2019
8.22	0.31%	635.36	2.14	1.1	0.12	1	2020
8.22	0.00%	Base not in Comp	2.13	1.0	0	1	2021
8.22	0.00%	Base not in Comp	2.13	1.0	0	1	2022
8.21	0.00%	Base not in Comp	2.13	1.0	0	1	2023
8.21	0.00%	Base not in Comp	2.12	1.0	0	1	2024
8.21	0.00%	Base not in Comp	2.12	1.0	0	1	2025
8.21	0.00%	Base not in Comp	2.12	1.0	0	1	2026
8.21	0.00%	Base not in Comp	2.12	1.0	0	1	2027
8.21	0.00%	Base not in Comp	2.11	1.0	0	1	2028
8.21	0.00%	Base not in Comp	2.11	1.0	0	1	2029
8.29	0.00%	Base not in Comp	2.03	1.0	0	1	
2060							

Year	Annual Failures	Cumulative Failures	# of Survivors	Hazard Rate
1987	0	0	50,000	0.000
1988	1	1	49,999	0.000
1989	0	1	49,999	0.000
1990	1	2	49,998	0.000
1991	7	9	49,991	0.000
1992	3	12	49,988	0.000
1993	14	26	49,974	0.000
1994	53	79	49,921	0.001
1995	110	189	49,811	0.002
1996	301	490	49,510	0.006
1997	502	992	49,008	0.010
1998	750	1,742	48,258	0.015
1999	1030	2,772	47,228	0.021
2000	1127	3,899	46,101	0.024
2001	1262	5,161	44,839	0.027
2002	1425	6,586	43,414	0.032
2003	1437	8,023	41,977	0.033
2004	1502	9,525	40,475	0.036
2005	1458	10,983	39,017	0.036
2006	1546	12,529	37,471	0.040
2007	1479	14,008	35,992	0.039
2008	1482	15,490	34,510	0.041
2009	1502	16,992	33,008	0.044
2010	1449	18,441	31,559	0.044
2011	1426	19,867	30,133	0.045
2012	1355	21,222	28,778	0.045
2013	1343	22,565	27,435	0.047
2014	1299	23,864	26,136	0.047
2015	1296	25,160	24,840	0.050
2016	1213	26,373	23,627	0.049
2017	1145	27,518	22,482	0.048
2018	1023	28,541	21,459	0.046
2019	1028	29,569	20,431	0.048
2020	947	30,516	19,484	0.046
2021	868	31,384	18,616	0.045
2022	800	32,184	17,816	0.043

$$h(t) = \frac{\text{\# of Failures in year t}}{\text{\# of survivors up to year t}}$$

$$h(2020) = \frac{947}{20{,}431} = 0.046$$

West Center Pier Hazard Function



BUILDING STRONG®

Calculating PUP

- Hazard Function Analysis
  - Time Dependant Reliability Models
  - Non-time Dependant Reliability Models
- Expert Opinion Elicitation
- Historical Frequency Method

Non-time Dependant Reliability Models

Probabilities of Unsatisfactory Performance that do not vary with time:

- Stability Analysis w/o scour or another time dependant parameter
- Seismic Analysis

Non-time Dependant Reliability Models

- Probability of the loading occurring on a given year
  - Seismic event
  - Pool loading
- Probabilistic analysis varying foundation parameters and uplift conditions
- PUP is constant for the entire study period.

Calculating PUP

- Hazard Function Analysis
  - Time Dependant Reliability Models
  - Non-time Dependant Reliability Models
- Expert Opinion Elicitation
- Historical Frequency Method

EOE

- Expert Opinion Elicitation is used when analysis cannot be performed or to supplement analysis findings.
- Formal process with a facilitator, panel of experts, observers and a recorder.
- Failure rates elicited for pre determined periods (1, 10 and 25 year)
- Produces an annualized reliability that changes through the study period

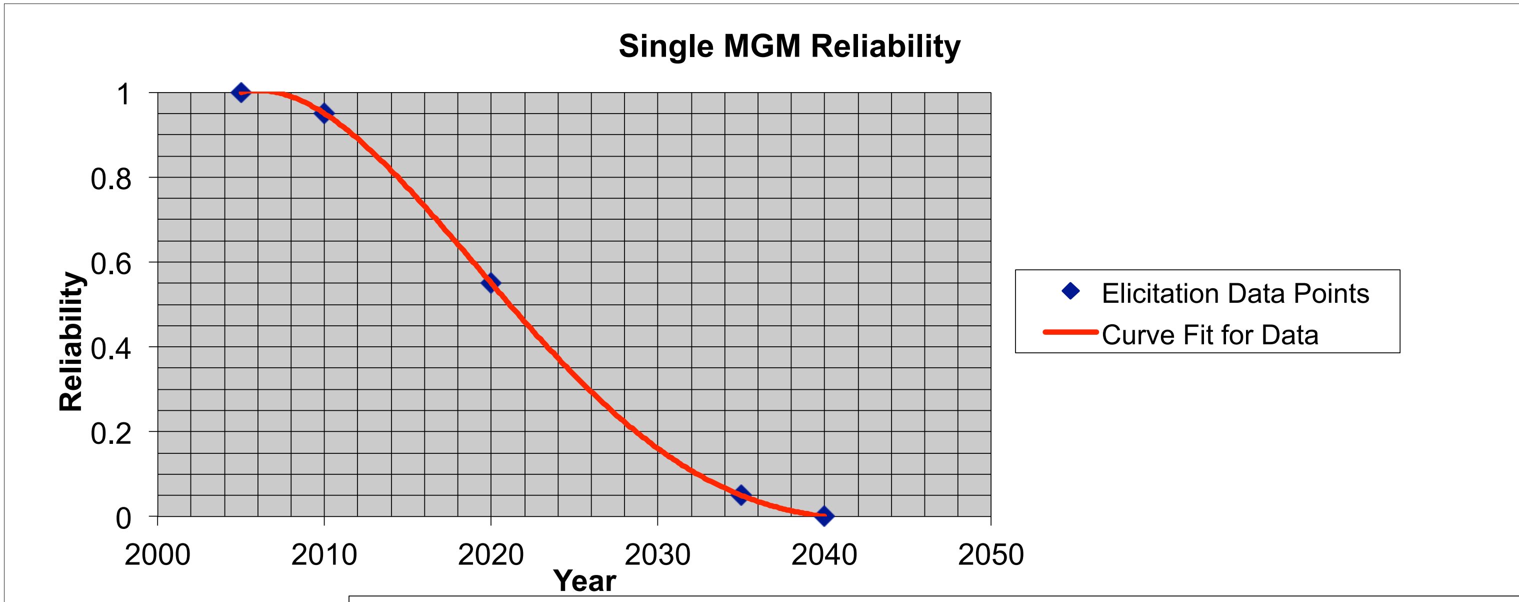
Example EOE Response Table

Event Name	Full Description of Issue	Expert-opinion elicitation					
		First Response			Second Response		
The miter gate machinery performs unsatisfactorily and fails to open/ close the miter gates.	What are the probabilities of unsatisfactory performance for the miter gate machinery in Year 1, Year 10 and Year 25?	Year 1	Year 10	Year 25	Year 1	Year 10	Year 25
	Expert #1	5.0%	40.0%	80.0%	3.0%	45.0%	100.0%
	Expert #2	1.0%	35.0%	75.0%	1.0%	45.0%	85.0%
	Expert #3	2.0%	30.0%	80.0%	2.0%	45.0%	95.0%
	Expert #4	5.0%	70.0%	100.0%	2.0%	70.0%	98.0%
	Expert #5	1.0%	50.0%	100.0%	2.0%	50.0%	95.0%
Summary Table	**Minimum** =	1.00%	30.00%	75.00%	1.00%	45.00%	85.00%
	25 Percentile =	1.00%	35.00%	80.00%	2.00%	45.00%	95.00%
	Median =	2.00%	40.00%	80.00%	2.00%	45.00%	95.00%
	75 Percentile =	5.00%	50.00%	100.00%	2.00%	50.00%	98.00%
	Maximum =	5.00%	70.00%	100.00%	3.00%	70.00%	100.00%

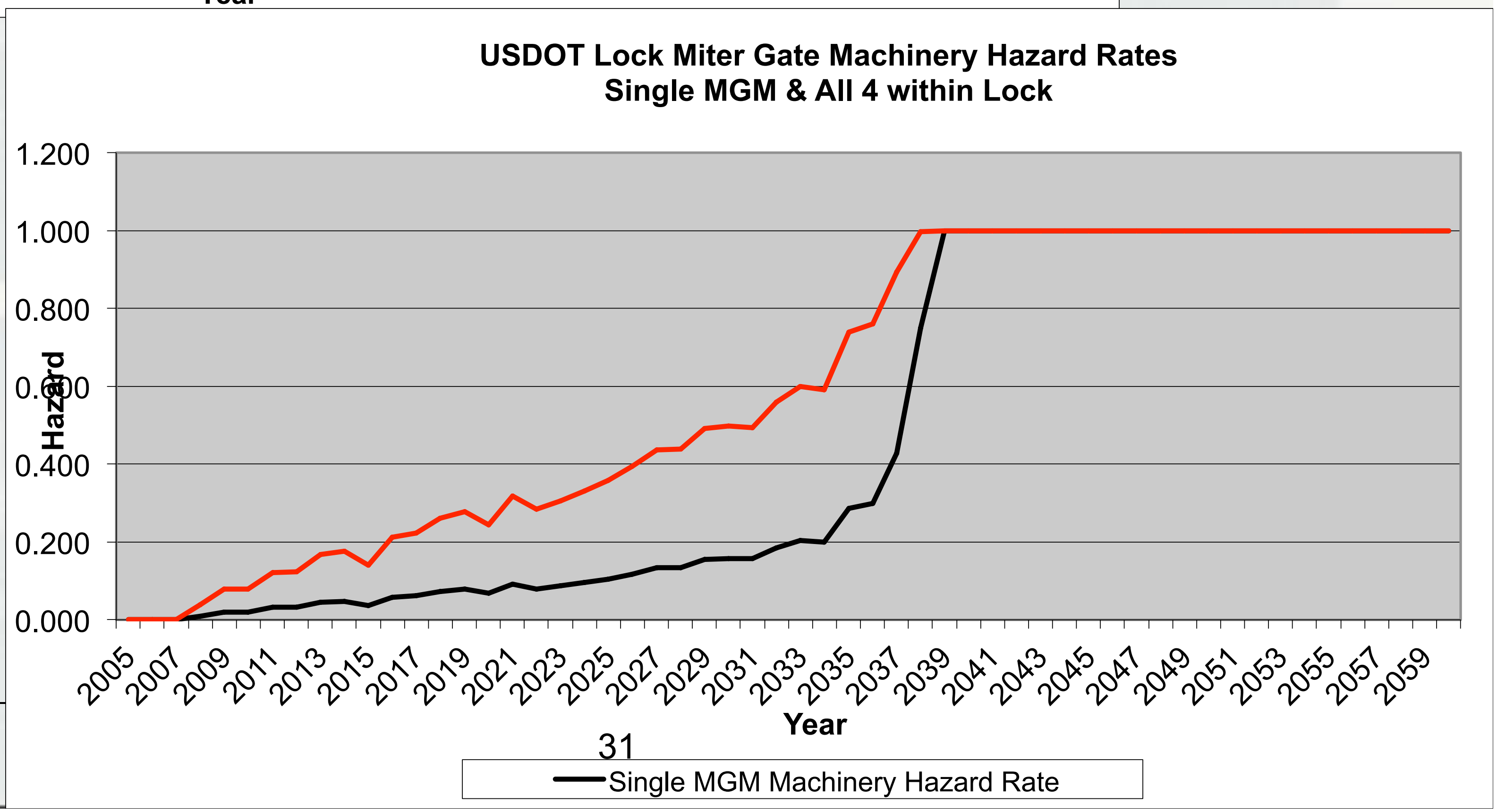
Expert Elicitation Hazard Rate Calculation				
	Single Leaf MG		Series of 4 MG Leafs	
Year	Reliability	Hazard Rate	Reliability	Hazard Rate
2005	1.000	0.000	1.000	0.000
2006	1.000	0.000	1.000	0.000
2007	1.000	0.000	1.000	0.000
2008	0.990	0.010	0.961	0.039
2009	0.970	0.020	0.885	0.078
2010	0.950	0.021	0.815	0.080
2011	0.920	0.032	0.716	0.120
2012	0.890	0.033	0.627	0.124
2013	0.850	0.045	0.522	0.168
2014	0.810	0.047	0.430	0.175
2015	0.780	0.037	0.370	0.140
2016	0.735	0.058	0.292	0.212
2017	0.690	0.061	0.227	0.223
2018	0.640	0.072	0.168	0.260
2019	0.590	0.078	0.121	0.278
2020	0.550	0.068	0.092	0.245
2021	0.500	0.091	0.063	0.317
2022	0.460	0.080	0.045	0.284
2023	0.420	0.087	0.031	0.305
2024	0.380	0.095	0.021	0.330
2025	0.340	0.105	0.013	0.359
2026	0.300	0.118	0.008	0.394
2027	0.260	0.133	0.005	0.436
2028	0.225	0.135	0.003	0.439
2029	0.190	0.156	0.001	0.492
2030	0.160	0.158	0.001	0.497
2031	0.135	0.156	0.000	0.493
2032	0.110	0.185	0.000	0.559
2033	0.088	0.205	0.000	0.600
2034	0.070	0.200	0.000	0.590
2035	0.050	0.286	0.000	0.740

$$h(t) = f(t)/R(t)$$

$$h(t) = (0.59-0.55)/0.59 = 0.068$$



Single MGM Reliability
Reliability
1
0.8
0.6
0.4
0.2
0
2000
2010
2020
2030
2040
2050
Year
Elicitation Data Points
Curve Fit for Data



USDOT Lock Miter Gate Machinery Hazard Rates
Single MGM & All 4 within Lock
Hazard
1.200
1.000
0.800
0.600
0.400
0.200
0.000
2005
2007
2009
2011
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
2051
2053
2055
2057
2059
Year
Single MGM Machinery Hazard Rate

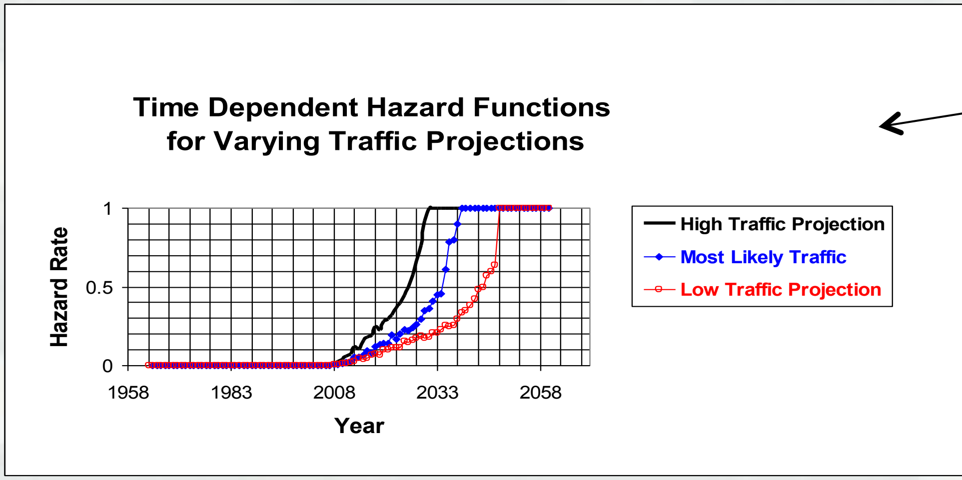
Calculating PUP

- Hazard Function Analysis
    - Time Dependant Reliability Models
    - Non-time Dependant Reliability Models
- Expert Opinion Elicitation
- Historical Frequency Method

Historical Frequency Method

- Use of known historical information from project records to estimate failure rates of components.
- USACE projects do not have enough historical failure performance to develop future probabilities.
- This method is being implemented together with Expert Elicitation for levee failures.

Requirements for Consequence Analysis



Time dependant failure Probabilities of components

Component		Annual Hazard Rate	Level of Repair	Closure Time	Repair Cost	Effect on Overall Component Reliability
		Annual Reliability Value (1 - Annual Hazard Rate)				
Horizontally-framed Miter Gate			New Gate 5%	365 days in year 1	$13,150,000	Assume R = 1.0 for All Future Years
				90 days in year 2	$3,150,000	
		Annual Hazard Rate	Major Repair 35%	45 days in year 1	$1,575,000	Move Back 5 Years
				45 days in year 2	$1,575,000	
			Temporary Repair 60%	45 days in year 1	$3,575,000	Assume R = 1.0 for All Future Years
			Replace 1st Set of Gates	45 days in year 2	$3,575,000	
			Replace 2nd Set of Gates	30 days in year 3	$5,050,000	

SCHEDULED REPLACEMENT BEFORE FAILURE INFORMATION
Year 1 -- 30 Days of Closure @ $5,050,00 Year 2 -- 30 Days of Closure @ $5,050,000
Future Reliability Will Equal 1.0 Throughout Remainder of Study Period

Consequence Event Tree given that the limit state is exceeded in reliability analysis

Consequence Event Tree

- Interface between engineering and consequences.
- Provides the level of consequence and repair associated with unsatisfactory performance.
- Consistent with the reliability analysis limit state modeling
- Developed for individual maintenance strategies.

Consequence Levels and Event Trees

Component		Annual Hazard Rate	Level of Repair	Closure Time	Repair Cost	Effect on Overall Component Reliability
		Annual Reliability Value (1 - Annual Hazard Rate)				
Horizontally-framed Miter Gate			New Gate 5%	365 days in year 1	$13,150,000	Assume R = 1.0 for All Future Years
				90 days in year 2	$3,150,000	
		Annual Hazard Rate	Major Repair 35%	45 days in year 1	$1,575,000	Move Back 5 Years
				45 days in year 2	$1,575,000	
			Temporary Repair 60%	45 days in year 1	$3,575,000	Assume R = 1.0 for All Future Years
			Replace 1st Set of Gates	45 days in year 2	$3,575,000	
			Replace 2nd Set of Gates	30 days in year 3	$5,050,000	

SCHEDULED REPLACEMENT BEFORE FAILURE INFORMATION

Year 1 -- 30 Days of Closure @ $5,050,00   Year 2 -- 30 Days of Closure @ $5,050,000

Future Reliability Will Equal 1.0 Throughout Remainder of Study Period

Questions?