Modeling Sewer Pipe Deterioration for Risk Based Planning using a Markov Chain Model

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August 27, 2014

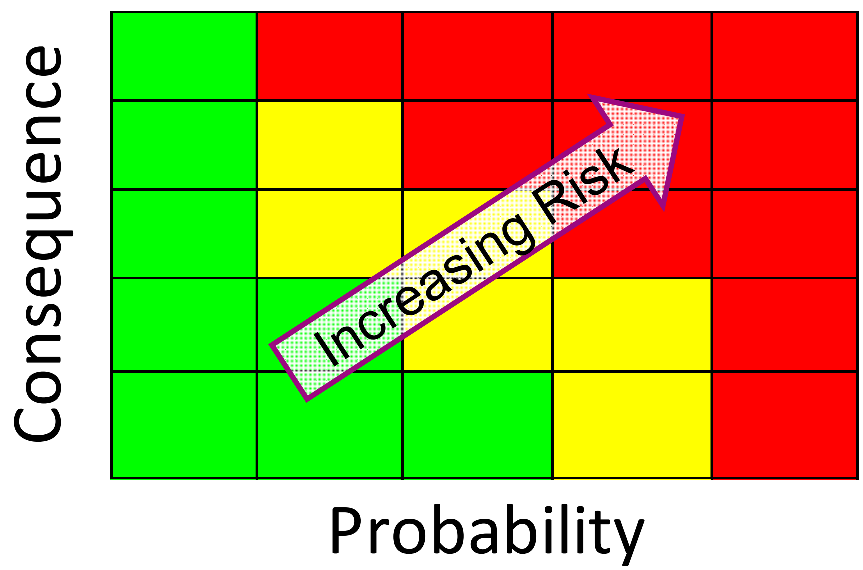
Asset Management Using Risk Based Planning

- Limited Funds
- “Unlimited” Needs
- Risk Based Decision Support to Do More With Less

One Water AECOM

Risk Framework

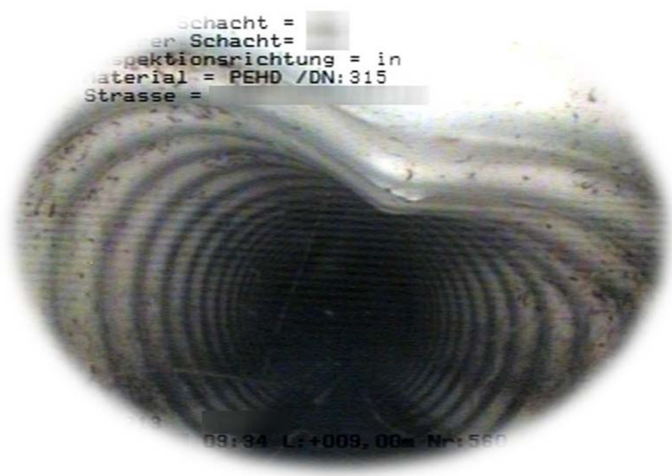
- RISK = Consequence of Failure X Probability of Failure



Consequence of Failure

Probability of Failure

- Failure
  - Hydraulic
    - Level of Service
  - Structural
    - Condition
    - Failure Event



Failure Models[1]

- Deterministic: Based on fixed relationships, ignore uncertainty
  - Empirical or Physical
- Statistical: Take into account uncertainty in relationships
  - Probit Regression
  - Markov Chain
  - Bayesian belief networks
- Physical Probabilistic
  - Consider failure modes and uncertainty
- Soft Computing
  - Neural Network
  - Fuzzy Logic

[1]Marlow, David, et al. "Remaining Asset Life: A State of the Art Review." *Water Environment Research Foundation. Alexandria* (2009)

Failure: Structural Condition

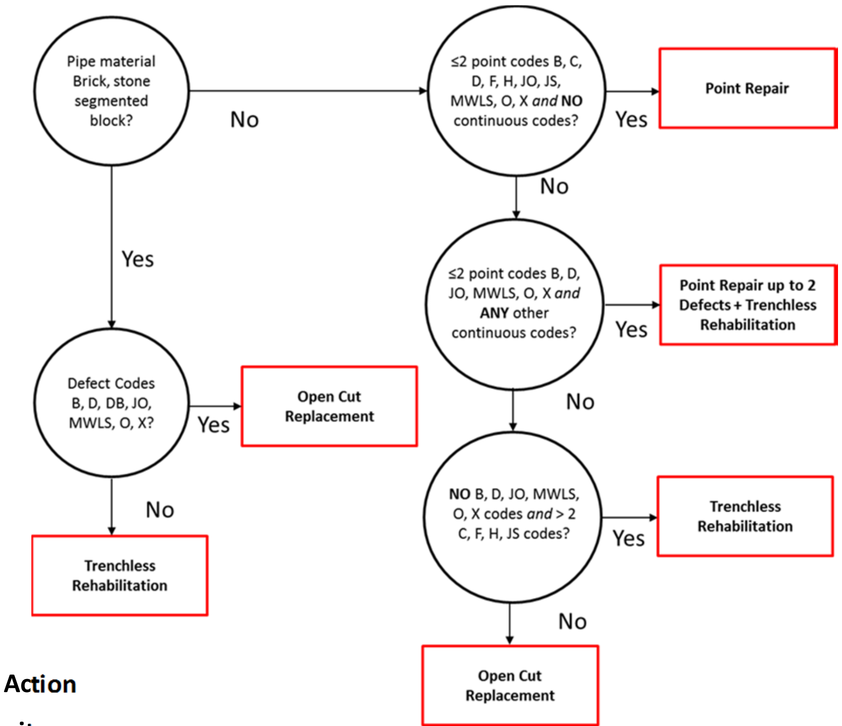
- Condition grades or states defined
  - NASSCO PACP

Condition Grade	Rating	Failure[2]
1	Excellent	Unlikely
2	Good	Unlikely for 20 years
3	Fair	May fail in 10-20 years
4	Poor	Probably fail in 5-10 years
5	Attention Required	Likely fail within 5 years

[2]CS Feeney et al. White Paper on Condition Assessment of Wastewater Collection Systems. USEPA publication EPA/600/R-09/049

Risk Matrix—Structural Condition

- Risk guides response based on asset
  - Consequence of failure
  - Probability of failure



Consequence					
	5	10	15	20	25
	4	8	12	16	20
	3	6	9	12	15
	2	4	6	8	10
	1	2	3	4	5
	Probability of Failure				

Blue	No Action
Green	Monitor every 20-yrs
Yellow	Monitor every 10-yrs
Orange	Monitor every 5-yrs
Red	Action Required

Markov Models

- Transitions between states are governed by probabilities
  - Markov property: Next state depends on current state only
- Transition probabilities can be homogeneous or non-homogeneous in time
- Semi-Markov models allow time spent in a state to be probabilistic
  - Allows for a greater flexibility when matching data

Simple Markov Chain Model

From \ To	1	2	3	4	5
1	1-P12	P12	0	0	0
2	0	1-P23	P23	0	0
3	0	0	1-P34	P34	0
4	0	0	0	1-P45	P45
5	0	0	0	0	1

- Segments can remain in current state or move to a worse state (unless there is an intervention)
- Segments cannot jump more than one state at a time
  - Time step must be appropriately short
- Transitions in time given by simple matrix multiplication

One Water AECOM

Data Limitations

- Longitudinal surveys (repeated condition data) of individual pipes are rare
  - Use data over entire population
- Historical data often lacking, or hidden—introduces bias
  - Keep data on pipes replaced in past!
  - Early repairs often not recorded
- When did condition change? (left censored data)
- Pipes replaced before fully aging (right censored data)

Data Preparation

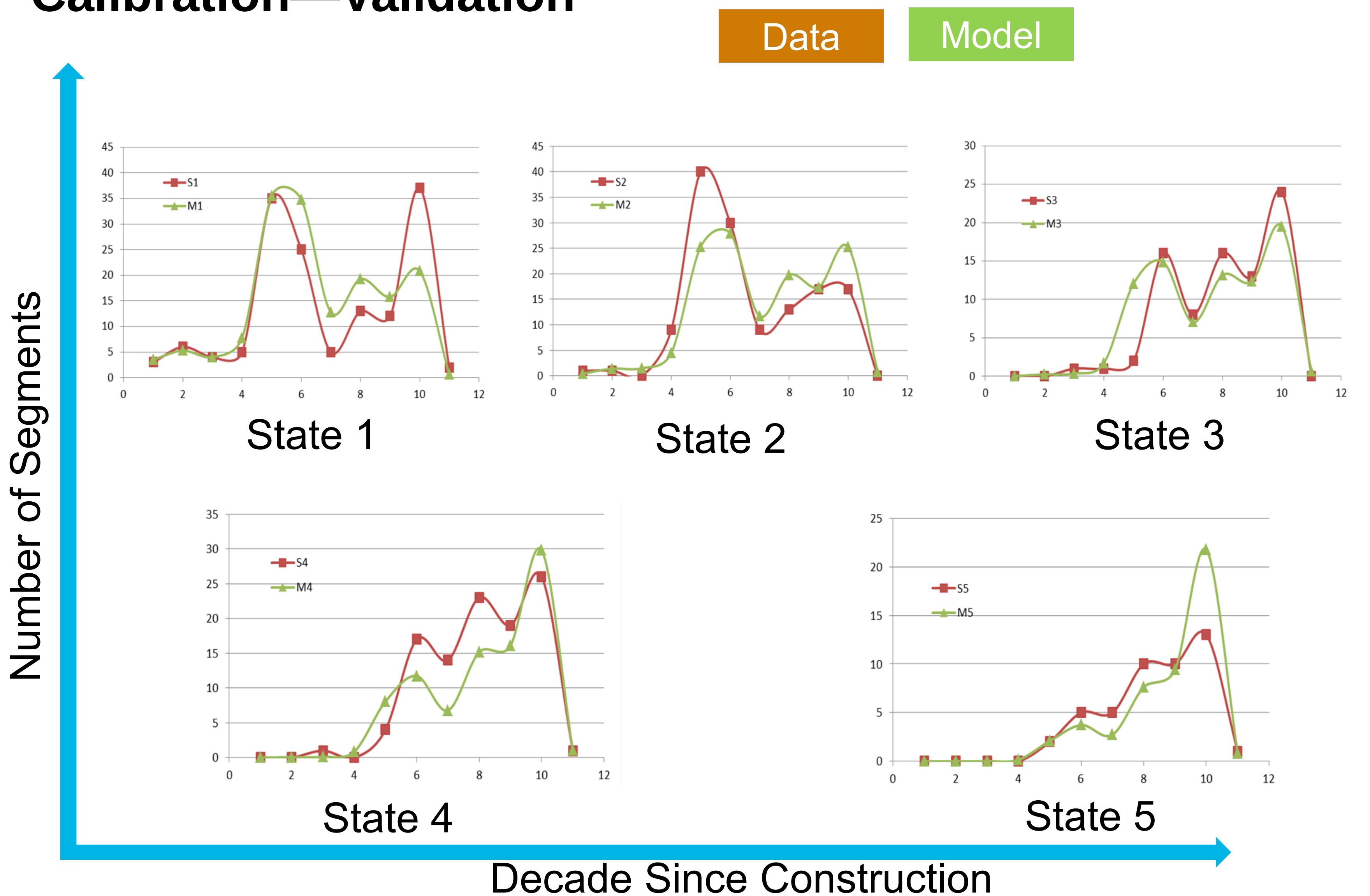
- Group pipes into similar cohorts
  - Size, Material, Soils, etc.
  - Partitioning limited by size of data set
- Take into account repairs/rehabilitation!
  - Want “natural” deterioration rate
  - Find most recent condition rating prior to any intervention

Calibration

- Condition and age data for 1569 pipes out of 2055
- Calibration set of 1053
- Validation set of 516 (1/3 of total)

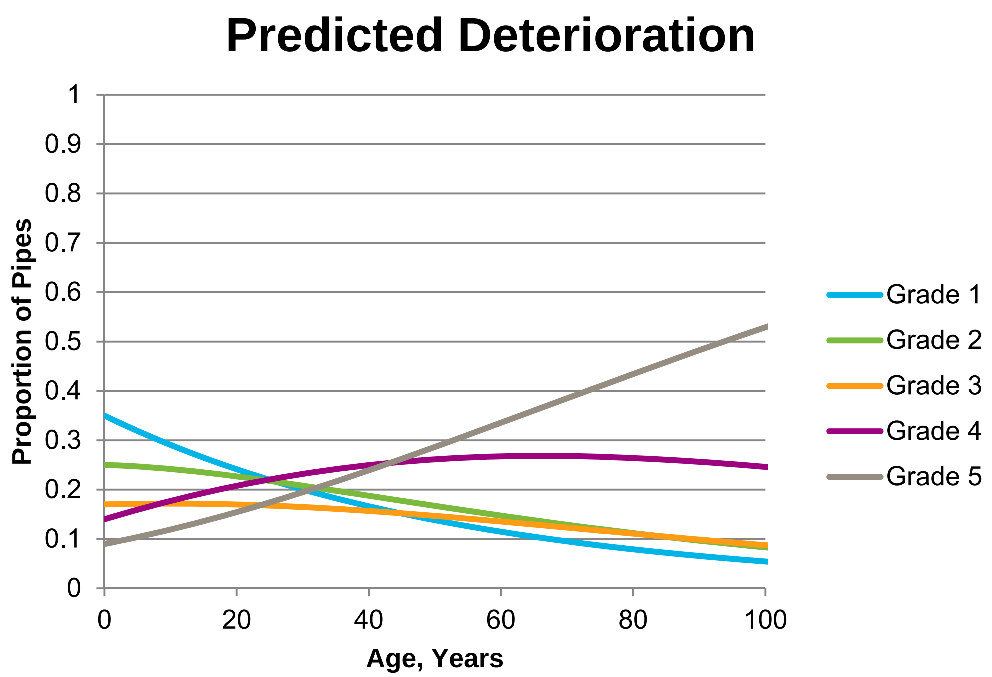
From \ To	1	2	3	4	5
1	0.981572	0.018428	0	0	0
2	0	0.972661	0.027339	0	0
3	0	0	0.961408	0.038592	0
4	0	0	0	0.981525	0.018475
5	0	0	0	0	1

Calibration—Validation



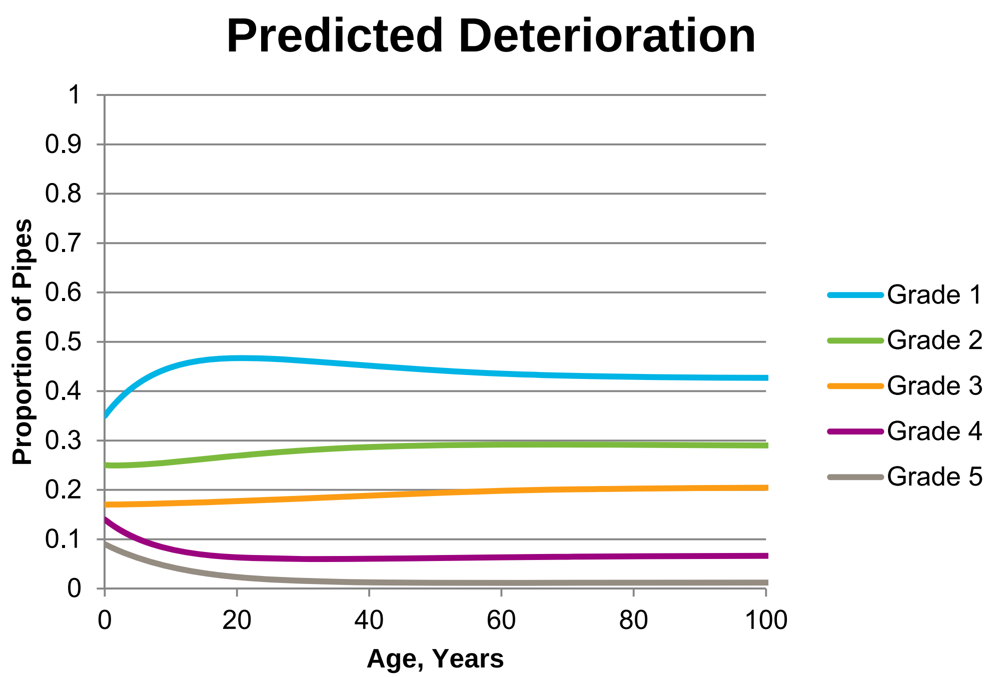
Applications—Project Condition Grade into Future

- Current System Conditions:
  - 35% Condition Grade 1
  - 25% Condition Grade 2
  - 17% Condition Grade 3
  - 14% Condition Grade 4
  - 9% Condition Grade 5
- In 100 Years
  - 5% Condition Grade 1
  - 8% Condition Grade 2
  - 9% Condition Grade 3
  - 25% Condition Grade 4
  - 53% Condition Grade 5



Applications—Project Intervention Strategy into Future

- Rehabilitate 10% of Grade 4, 5 pipes per year
  - Steady State Conditions:
    - 43% Condition Grade 1
    - 29% Condition Grade 2
    - 20% Condition Grade 3
    - 7% Condition Grade 4
    - 1% Condition Grade 5



Applications—Risk Costing

- Monetize Risk
- Pipe failure carries a cost premium
  - For rehabilitation itself
  - Attendant impacts of failure

Consequence	Cost Premium
1-3	10%
4	30%
5	50%

Applications—Risk Costing

Year	Present Value Factor	Annualized Inspection Cost	Probability of Failure	Premium Replacement Cost	Risk Cost
1	1	$1,000	1%	$100,000	$2,000
2	0.986	$1,000	1%	$100,000	$1,972
⋮	⋮	⋮	⋮	⋮	⋮
20	0.761	$1,000	1%	$100,000	$1,522

Annual Risk Cost = Present Value Factor*(Annualized Inspection Cost + Probability of Failure*Premium Replacement Cost)

Total Risk Cost = Sum of annual risk costs

$$NPV = RC_{Baseline} - RC_{Alternative} - C_{Alternative}$$

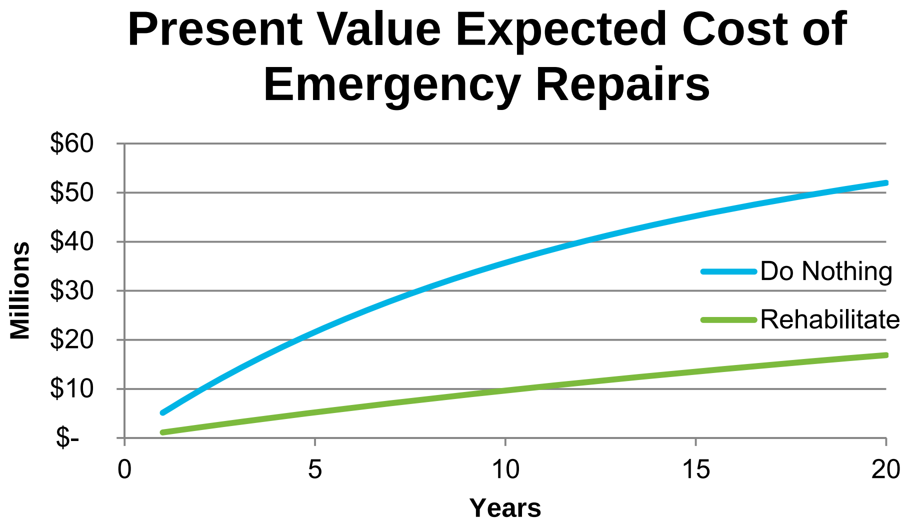
Applications—Risk Costing

- Add a "Failure" state (Emergency Repair Necessary)
  - Pipes in condition grade 4 have 5% chance of failing in a given year, 50% chance in 12-13 years
  - Pipes in condition grade 5 have 10% chance of failing in a given year, 50% in 6-7 years

From \ To	1	2	3	4	5	Fail
1	0.981572	0.018428	0	0	0	0
2	0	0.972661	0.027339	0	0	0
3	0	0	0.961408	0.038592	0	0
4	0	0	0	0.931525	0.018475	0.05
5	0	0	0	0	0.9	0.1
Fail	0	0	0	0	0	1

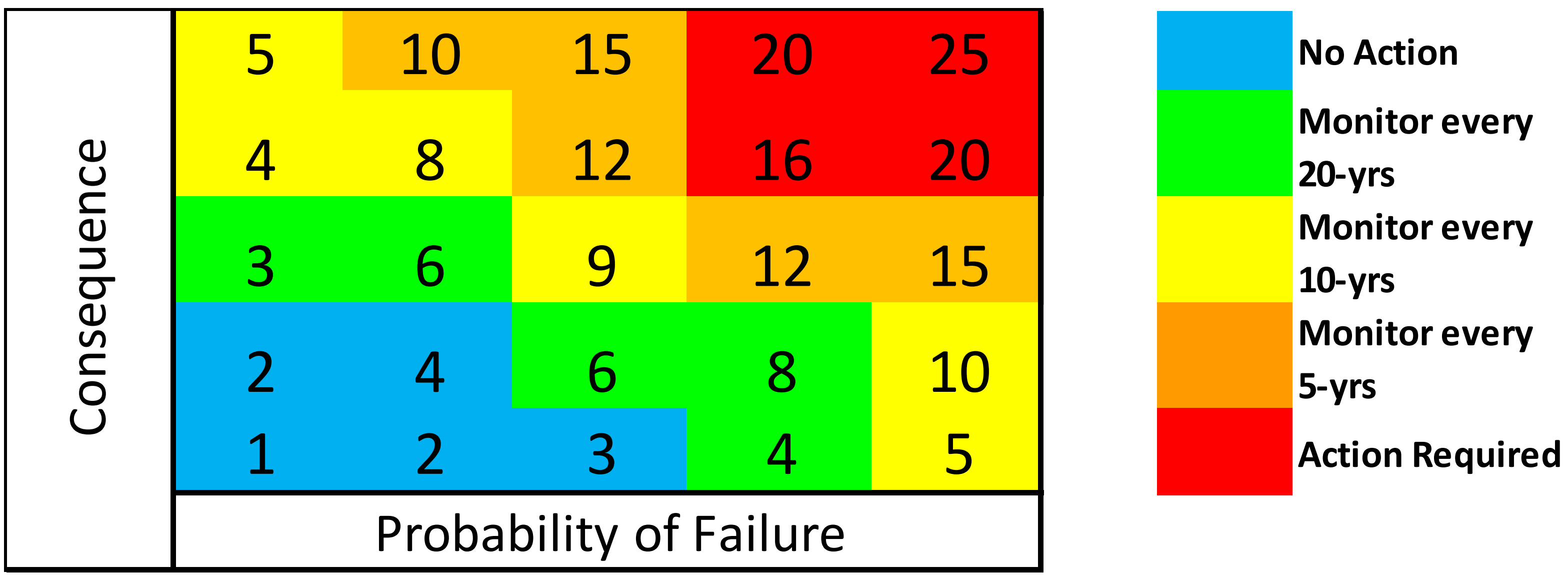
Applications—Risk Costing

- Pipe failure carries a cost premium
- Project expected cost of failure over 20 years
  - Average cost under given probabilities
- Rehabilitate for $15 million
- Avoid $35 million in expected risk
  - Net Present Value of $20 million



Applications—Risk Matrix

- Is risk matrix consistent with risk cost approach?
- If inspection cost is high enough, rehab action can be worth it
  - For each cell, vary inspection cost as % of rehab cost and determine how high % must be to make rehab cost effective



Applications—Risk Matrix

- Is risk matrix consistent with risk cost approach?
- If inspection cost is high enough, rehab action can be worth it
  - For each cell, vary inspection cost as % of rehab cost and determine how high % must be to make rehab cost effective

Consequence					
	5	>66.0%	>49.3%	>6.5%	Rehab
	4	8	>44.5%	>12.7%	Rehab
	3	6	9	>13.0%	>5.0%
	2	4	6	8	>24.1%
	1	2	3	4	5
	Probability of Failure				

Blue	No Action
Green	Monitor every 20-yrs
Yellow	Monitor every 10-yrs
Orange	Monitor every 5-yrs
Red	Action Required

Summary

- A risk based approach to asset management requires information on probability of failure
- Although many approaches to modeling structural failure exist, the Markov chain is simple, intuitive and easily applied
- Good data is key
  - Be aware of data biases
    - Keep historical data
    - Take into account previous repairs
  - Group data into cohorts if possible
- Failure model especially effective in a risk cost framework
  - Allows investigation of future rehabilitation strategies and costs

Thank You

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Acknowledgements:

Metropolitan Sewer District of Greater Cincinnati

August 27, 2014