Remaining Useful Life for Gravity Sewer Assets

Presented by NASSCO's Technical Advisory Council

NASSCO

Session Overview

Part 1:

History of PACP™ and Remaining Useful Life (RUL)

Part 2:

RUL of Gravity Pipes – Using PACP to Better Understand and Estimate RUL

Part 3:

The Big RUL Picture - Modeling Deterioration with a PACP Database to Better Understand Short and Long Term Funding Ramifications

- Approach and Case Study Reviews

History of PACP™ and Remaining Useful Life

Jerry Weimer
Owner, Jerry Weimer Consulting
PACP™ Master Trainer
Member of NASSCO's Technical Advisory Council

The History of NASSCO's PACP™ and Remaining Useful Life (RUL)

1. Early PACP™ and RUL
2. Problems with Early RUL
3. Current PACP and RUL

PACP Observation Descriptions Prior to Version 6 (2010)

GRADE	DESCRIPTION	DEFINITION
5	Immediate Attention	Defects requiring immediate attention **RUL: Pipe has failed or will likely fail within the next 5 years**
4	Poor	Severe defects that will become Grade 5 defects within the foreseeable future **RUL: Pipe will probably fail in 5 to 10 years**
3	Fair	Moderate defects that will continue to deteriorate **RUL: Pipe may fail in 10 to 20 years**
2	Good	Defects that have not begun to deteriorate **RUL: Pipe unlikely to fail for at least 20 years**
1	Excellent	Minor defects –**RUL: Failure unlikely in the foreseeable future**

A qualifier was included in the discussion that the mechanisms and rate of pipe deterioration were dependent on local conditions, and that the guidelines needed verification by research.

Grade 1 Defect

Crack Circumferential

A qualifier was included in the discussion that the mechanisms and rate of pipe deterioration were dependent on local conditions, and that the guidelines needed verification by research.

Grade 2 Defect

Fracture Circumferential

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Grade 3 Defect

Fracture Longitudinal

A qualifier was included in the discussion that the mechanisms and rate of pipe deterioration were dependent on local conditions, and that the guidelines needed verification by research.

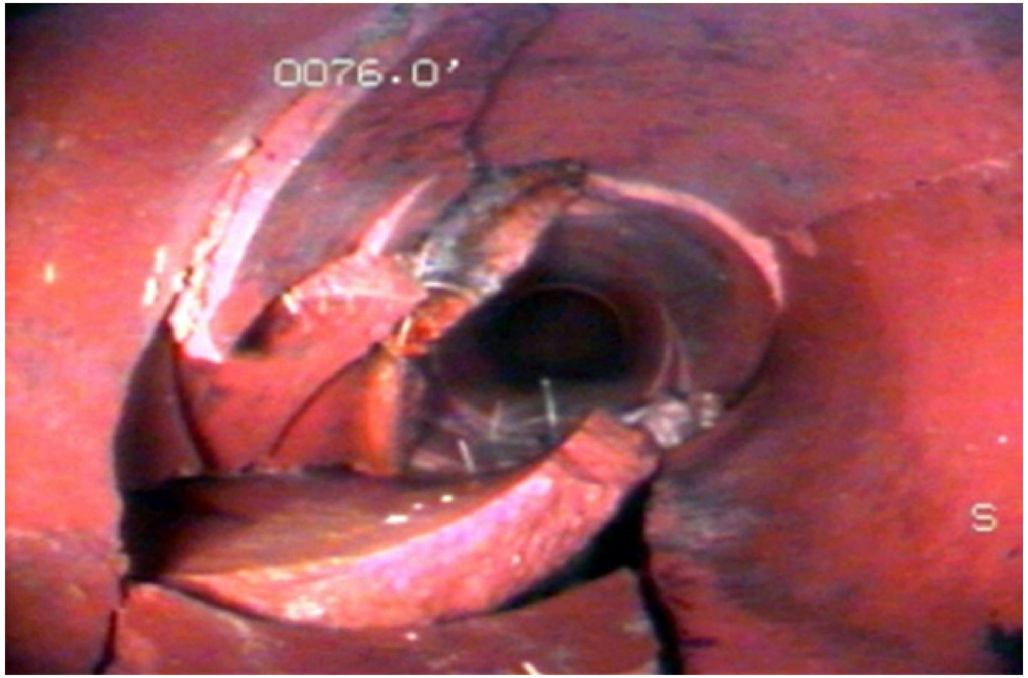
Grade 4 Defect

Broken

A qualifier was included in the discussion that the mechanisms and rate of pipe deterioration were dependent on local conditions, and that the guidelines needed verification by research.

Grade 5 Defect

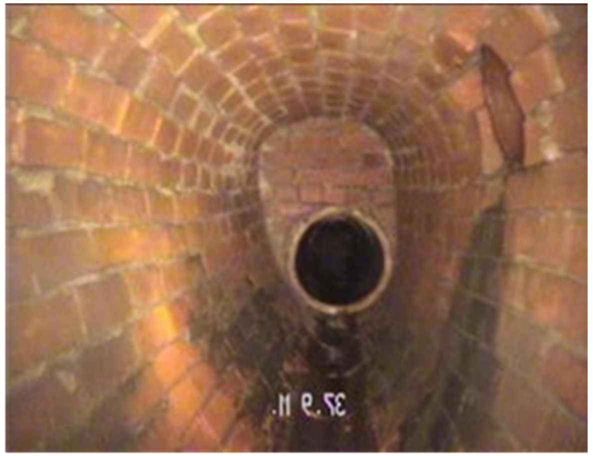
Collapsed

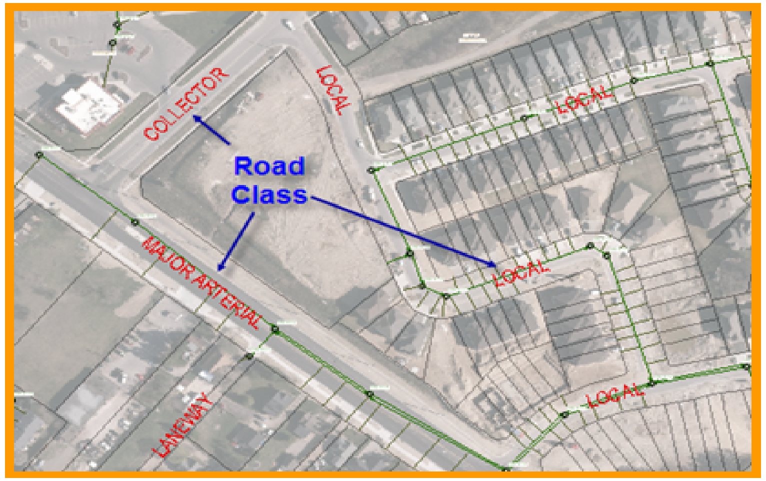


A qualifier was included in the discussion that the mechanisms and rate of pipe deterioration were dependent on local conditions, and that the guidelines needed verification by research.

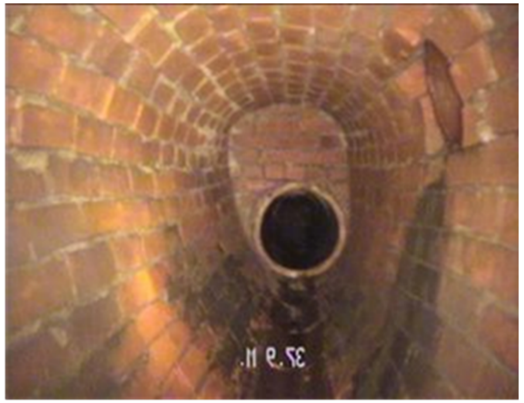
- No Consequence of Failure
- Local Conditions not included
- Scores of 4 and 5 used without context

- Soil
- Pipe Material
- Depth
- Surface Conditions





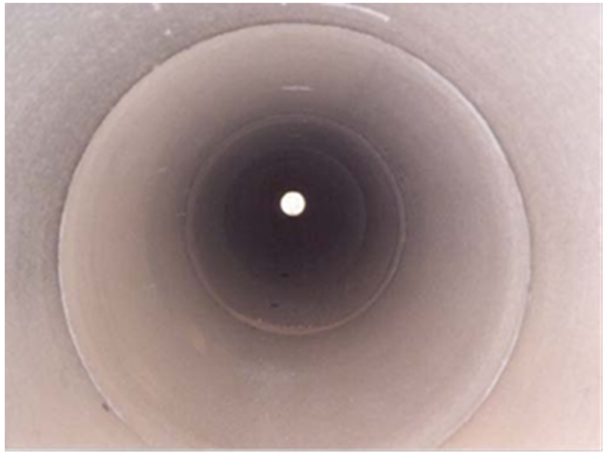
- **Soil**
  - **Sand**
  - **Clay**
  - **Stone**
- Pipe Material
- Depth
- Surface Conditions



Brick

Flexible

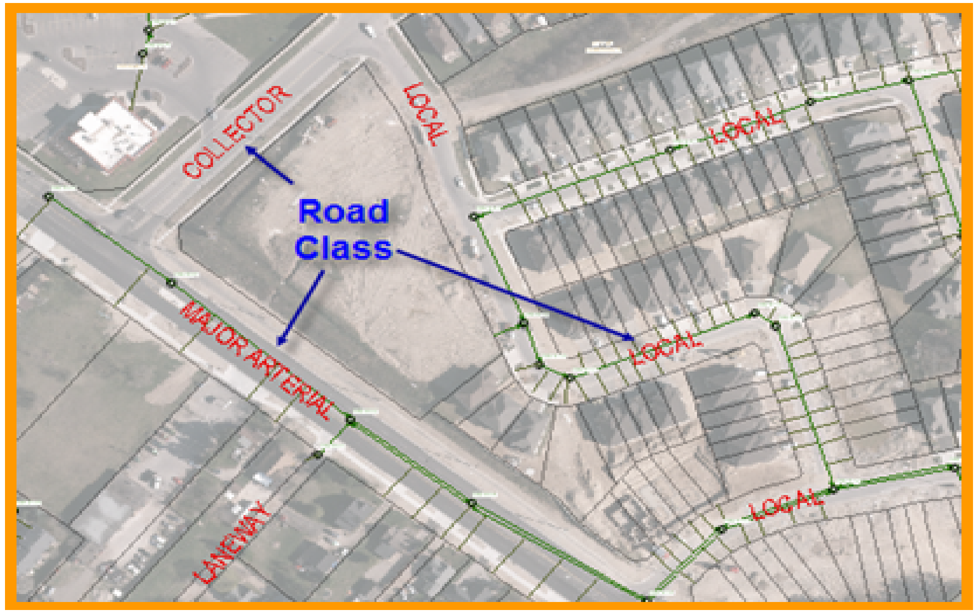
- Soil
- **Pipe Material**
  - **Rigid**
  - **Flexible**
  - **Brick**
- Depth
- Surface Conditions



Rigid

- Soil
- Pipe Material
- **Depth**
- Surface Conditions

- Soil
- Pipe Material
- Depth
- **Surface Conditions**



Current PACP Observation Descriptions

GRADE	DESCRIPTION	
5	Most Significant Defect Grade	Remaining Useful Life Not Defined for Any PACP Grade
4	Significant Defect Grade	
3	Moderate Defect Grade	
2	Minor to Moderate Defect Grade	
1	Minor Defect Grade	

Summary:

1. Early PACP and RUL had some issues on what was not included in the documentation and calculation

2. There were various issues
   - Consequence of Failure
   - Local Conditions
   - Scores of 4 and 5 no context in early RUL

3. The Current PACP is used in RUL, but is not the sole determination of RUL

Using PACP™ to Better Estimate RUL: The Big Picture

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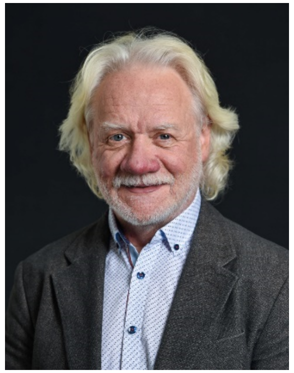
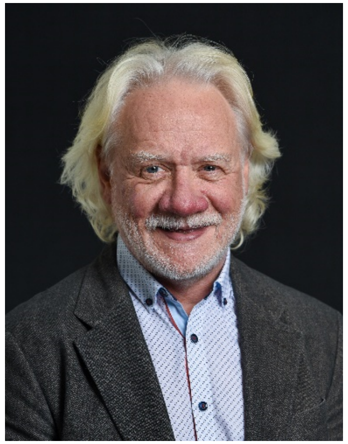


Chris Macey, P. Eng.
America's Technical Practice Leader, Condition Assessment and Rehabilitation, AECOM
Member of NASSCO's Technical Advisory Council

Part 2 – RUL of Gravity Pipes – Using PACP™ to Better Understand and Estimate RUL

Part 3 – The Big RUL Picture - Modeling Deterioration with a PACP Database to Better Understand Short and Long Term Funding Ramifications



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Part 2 - RUL of Gravity Pipes – Using PACP™ to Better Understand and Estimate RUL

- Why do most gravity pipes fail?
  - Understanding the problem goes back a lot further than you think
- Condition Assessment for RUL
  - Using PACP to start the condition assessment process
  - Using supplementary information to get a better handle on RUL
- Extending RUL and Managing Risk
  - Building capital programs and reinspection frequency

Why do gravity pipes fail?
Understanding the ground around the pipe

- The majority of the gravity pipes that we assess are rigid pipes
  - Rigid pipe ~ will not accept significant deformation without experiencing structural distress (cracking)
  - Rigid pipes only mobilize active soil pressures (not passive like a flexible pipe)
  - They don't rely on the soil a lot
    - ***Until they fail!***
- It may seem a little strange but to fully understand the longevity of broken rigid pipes….
  - we need to understand the ground around the pipe

Condition Assessment Starts with PACP

- It doesn't end there
- Condition Assessment relies on defect observations collected
  - Two step process:
    - Internal Condition Grade (ICG)
      - Calculated using defect scores
      - Filters out sewers with high probability of requiring repair
    - Structural Performance Grade (SPG)
      - Apply supplementary information
      - Rationalize probability of collapse

Current PACP Observation Descriptions

GRADE	DESCRIPTION	
5	Most Significant Defect Grade	Remaining Useful Life Not Defined for Any PACP Grade
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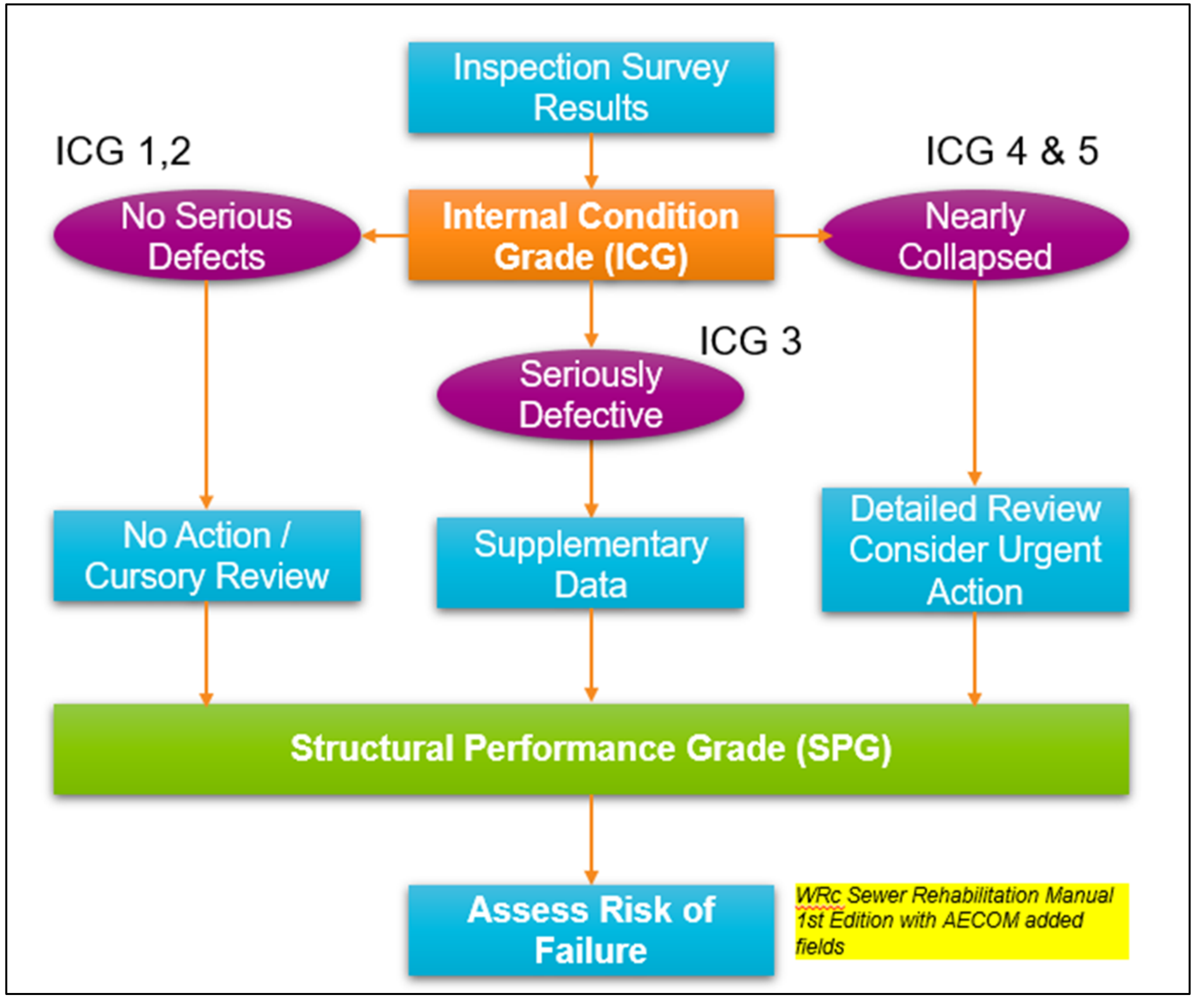
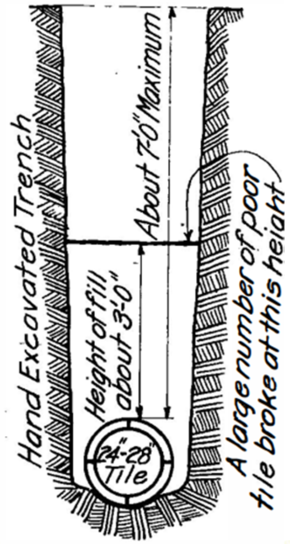
Condition Assessment Process to better understand RUL



Rigid pipes are complex beasts

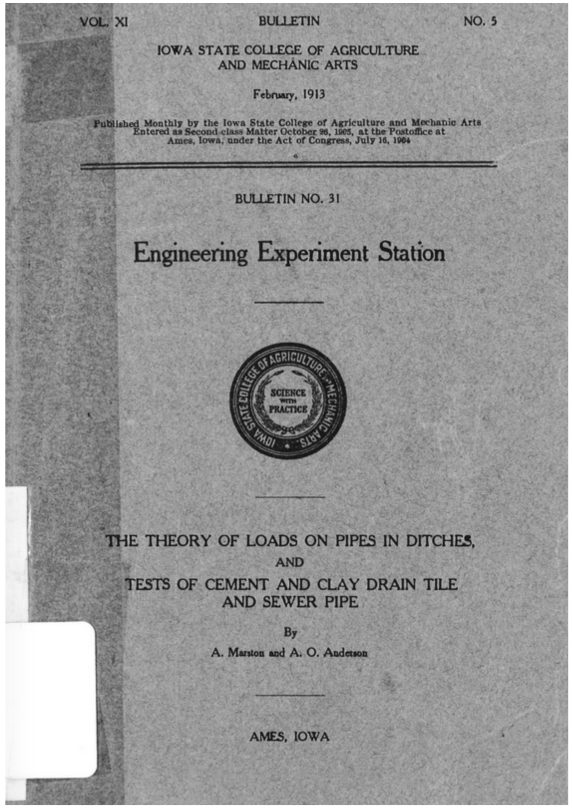
- Anson Marston started research into rigid pipe in "ditches" in about 1910
- Long before we ever knew the difference between active and passive soil pressures, we needed to know why many pipes would crack/fracture/break under the *"weight of the earth"*
  - After all, we could reasonably estimate the weight of displaced earth over the pipe and directly measure its load carrying capacity
- Two common problems encountered:
  - Cracking that occurred during construction
  - Cracking that occurred a "considerable time period" after construction
    - A period we now know is reasonably assessed in about 30 days to a year



48-inch diameter pipe, 3½ feet long, at Columbia, S. C., loaded to 30,000 pounds with knife-edge loading. No crack shown in the pipe.

What design looked like ~ 1918

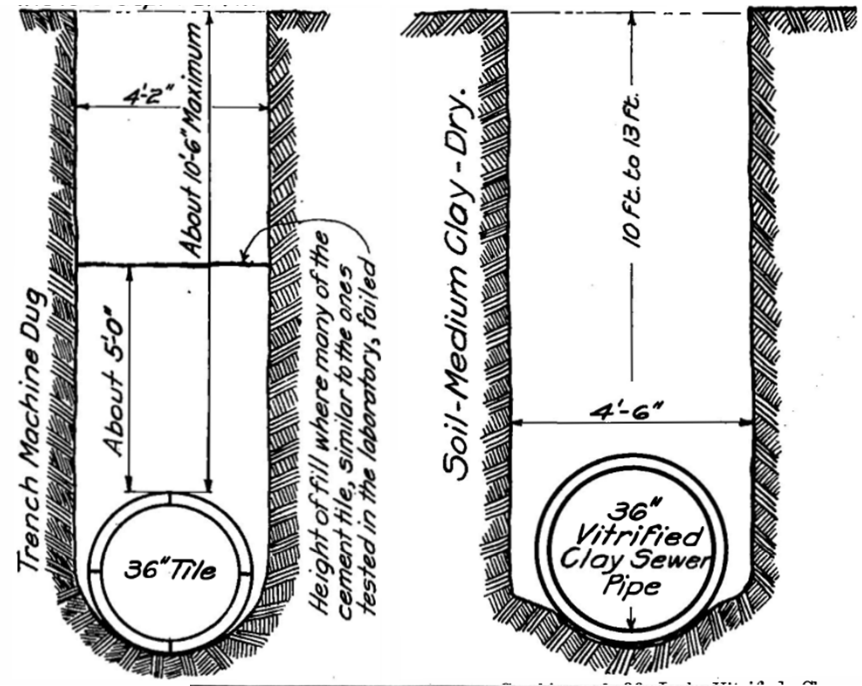
The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe

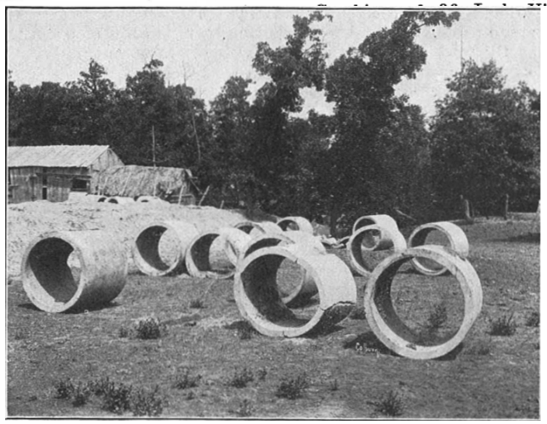

VOL. XI BULLETIN NO. 5
IOWA STATE COLLEGE OF AGRICULTURE AND MECHANIC ARTS
February, 1913
Published Monthly by the Iowa State College of Agriculture and Mechanic Arts
Entered as Second-class Matter October 26, 1905, at the Postoffice at Ames, Iowa, under the Act of Congress, July 16, 1894
BULLETIN NO. 31
Engineering Experiment Station
THE THEORY OF LOADS ON PIPES IN DITCHES, AND TESTS OF CEMENT AND CLAY DRAIN TILE AND SEWER PIPE
By
A. Marston and A. O. Anderson
AMES, IOWA

- Published in 1913 by the Iowa State College of Agriculture and Mechanical Arts
- Authors:
  - Anson Marston
  - A. O. Anderson
- New theories for calculating soil loads on buried pipes in narrow trenches

What were some of Marston's initial findings?

- Clay tile pipe and concrete pipe both cracked under loads less than the displaced earth and the pipe's known supporting strength
  - Many of the failures occurred long after installation and backfilling
- The wider the trench at the top of the pipe the easier the pipes cracked under the same load
- Soil support impacted cracking as load carrying capacity could be increased considerably by shaped bedding and tamped side fill
- Larger pipes (>15") needed considerably more structural capacity than original manufacturing standards could deliver (why was this???)
- Concrete, as a backfill material, greatly increased load carrying capacity (lean concrete to springline only)
- ***While cracks were easily initiated (even from tamping), a properly supported and backfilled pipe was almost impossible to collapse***

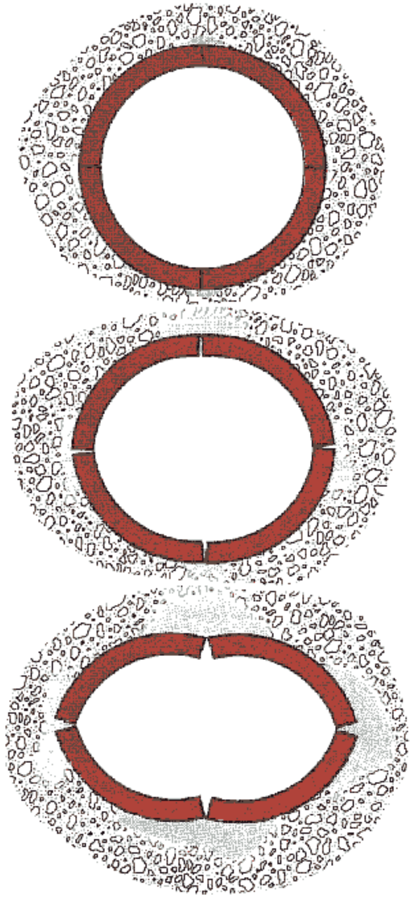




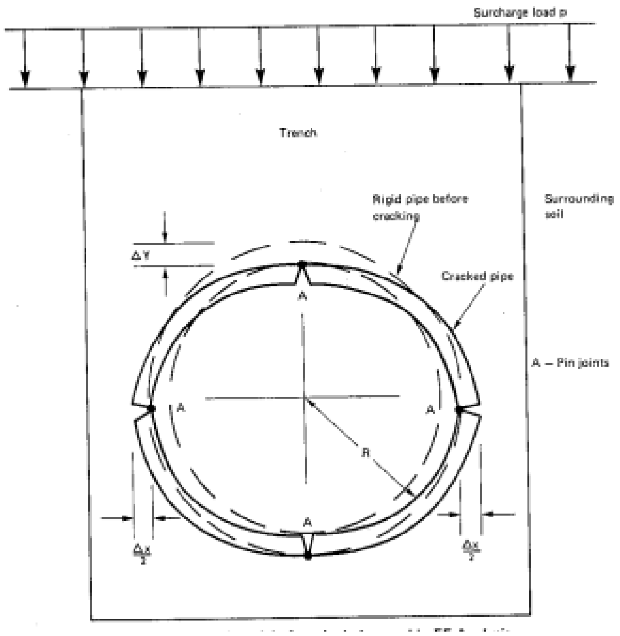
This ability to break but not collapse is a unique property of concrete/clay tile pipe (much more relevant today)

Classic 4 point cracking of rigid pipes was studied in the UK in the 1980's (Trott-1981)

- Cracks progress to fractures, rigid pipe functioning on hinges
- Load to collapse the pipe had to be increased by a factor of 6 or more due to mobilization of passive versus active lateral support (used Spangler's work from the late 1960's to verify)
- Structure considered stable with up to 10% vertical deformation
- Deterioration occurs due to soil migration and loss of lateral support
- Concern of failure largely due to stability of structure at the hinges

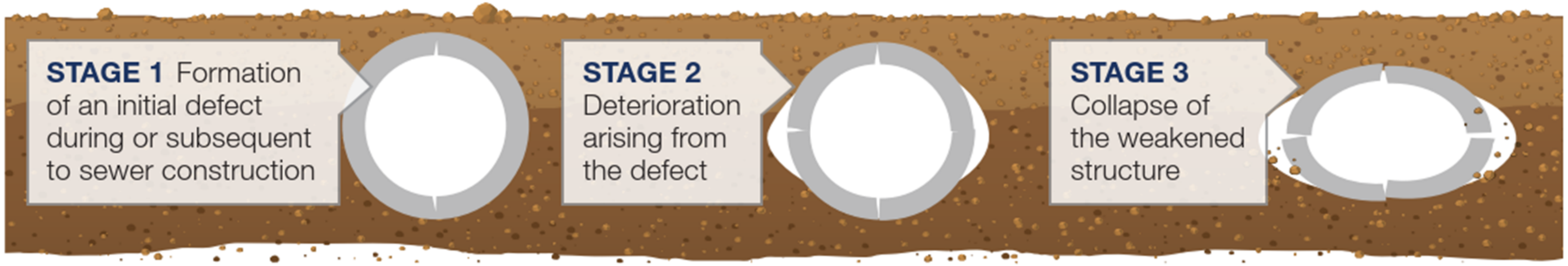


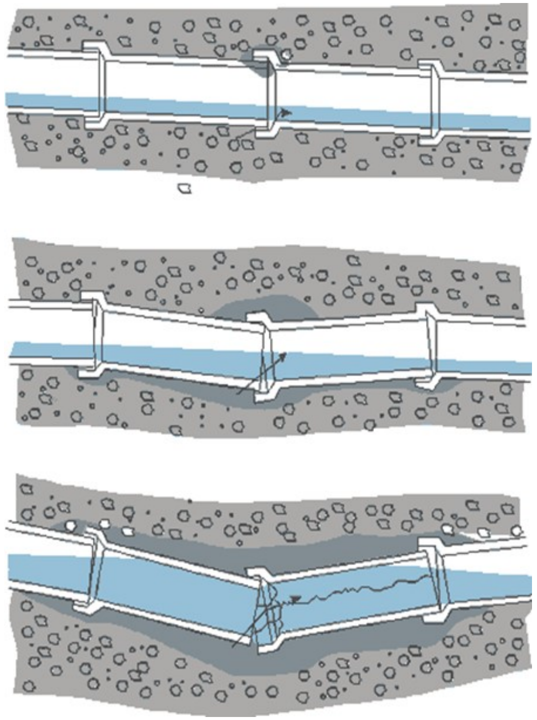
Source: WRc SRM

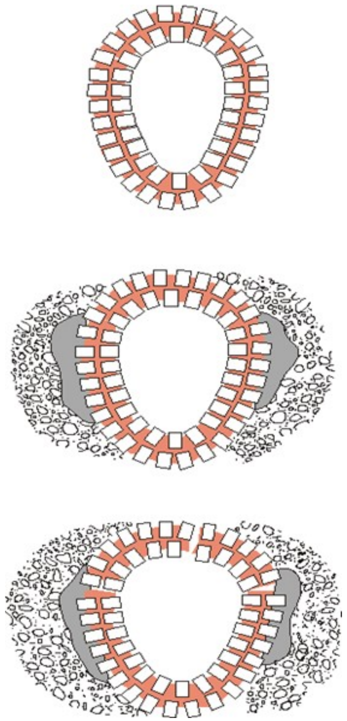


Source: Trott et al - 1981

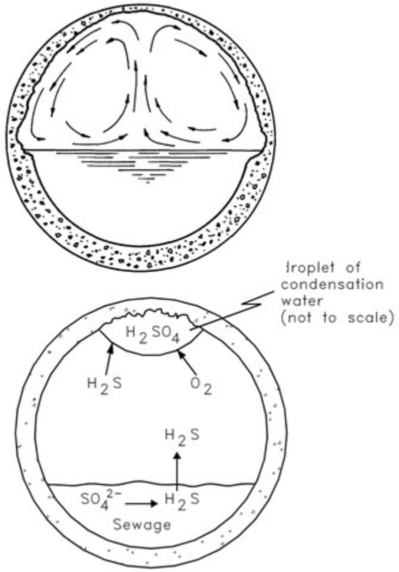
So for pipes that break, it's primarily the movement of soil around the pipe that impacts remaining useful life

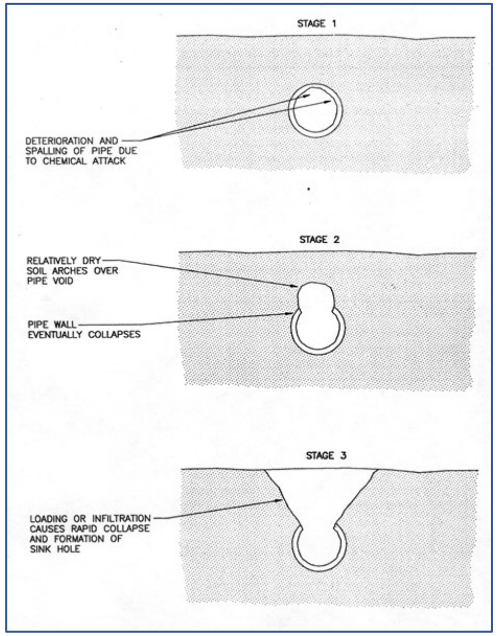




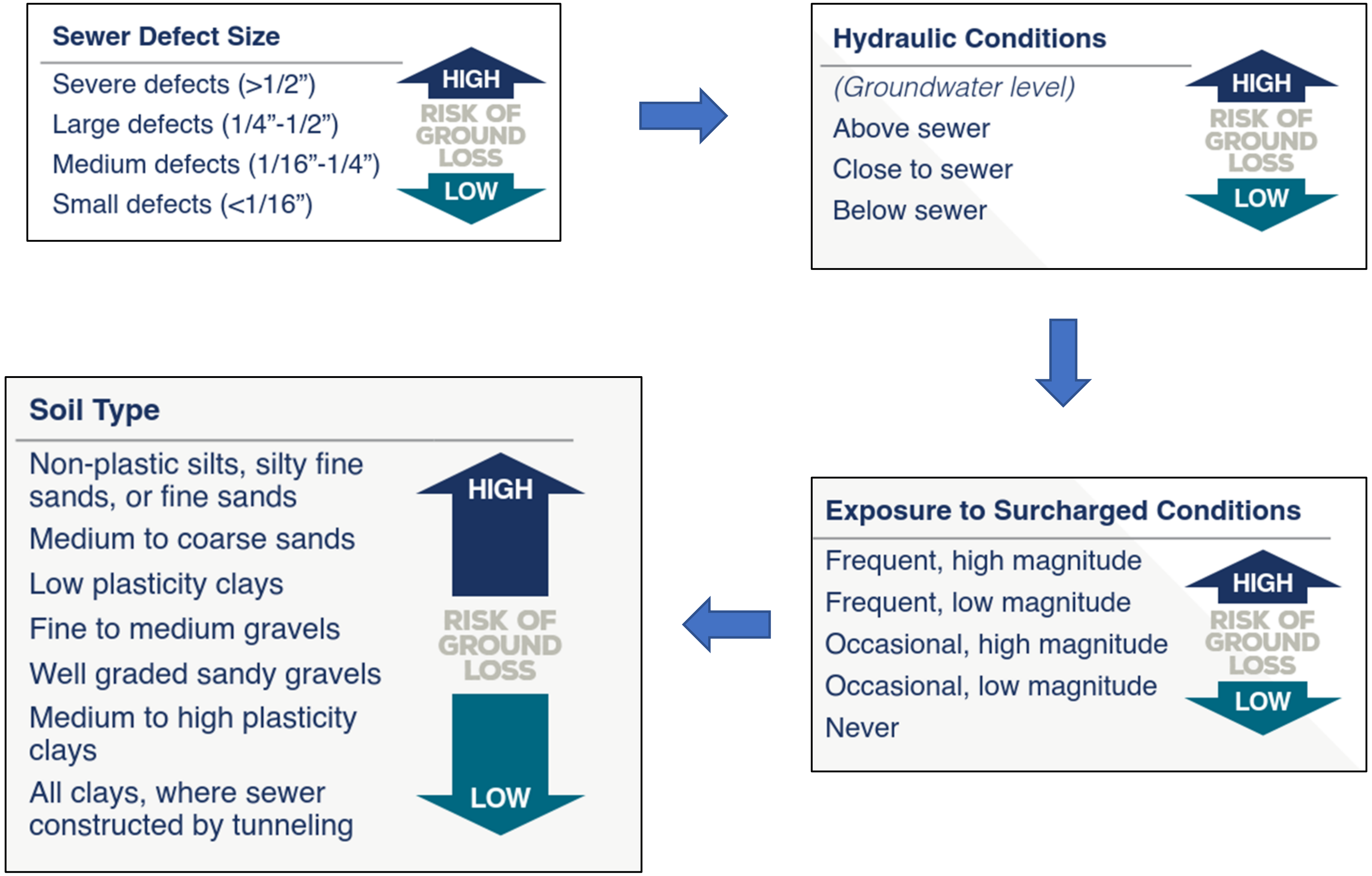


What about H_2S or other Material Breakdown Phenomena?





So what things affect the rate of soil loss around a pipe?



STRUCTURAL CONDITION STATES - SEWERS

- Implications of PACP structural condition states
  - Need to adjust up or down a grade based on the Supplementary Data
  - Hard procedure for this is documented in SRM Version 2-5

Condition Grade	Implication	Typical Description Concrete – Clay Tile Pipe
5	Collapsed or collapse imminent	Already collapsed; or Deformation >10% and cracked or fractured or broken; or Extensive areas of missing fabric.
4	Collapse likely in the near future	Deformation 5 – 10% and cracked or fractured or broken; or Broken or fractured; or Serious loss of level.
3	Collapse unlikely in the near future but further deterioration likely	Deformation 0 – 5% and cracked; or fractured; or Longitudinal/multiple cracking; or Occasional fractures; or Minor loss of level; or Badly made connections.
2	Minimal collapse risk in the short term but potential for further deterioration	Circumferential cracking; or Moderate joint defects.
1	Acceptable structural condition	No structural defects.

PACP Quick Rating

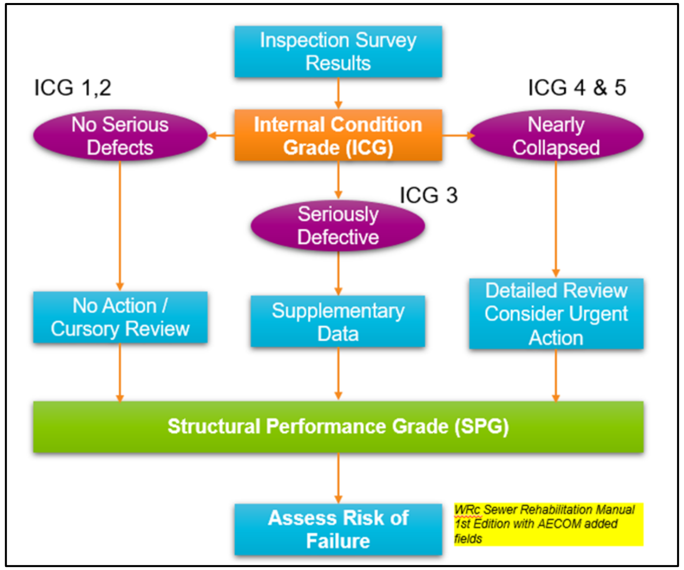
- Structural & O&M
- Initial Condition Grade (ICG)

543D

1. Worst defect
2. Number of occurrences
3. 2nd worst defect
4. Number of occurrences of 2nd worst defect

A = 10 to 14
B = 15 to 19
C = 20 to 24
D = 25 to 29…

Turning our ICG's into SPG's by considering the Ground Around the Pipe

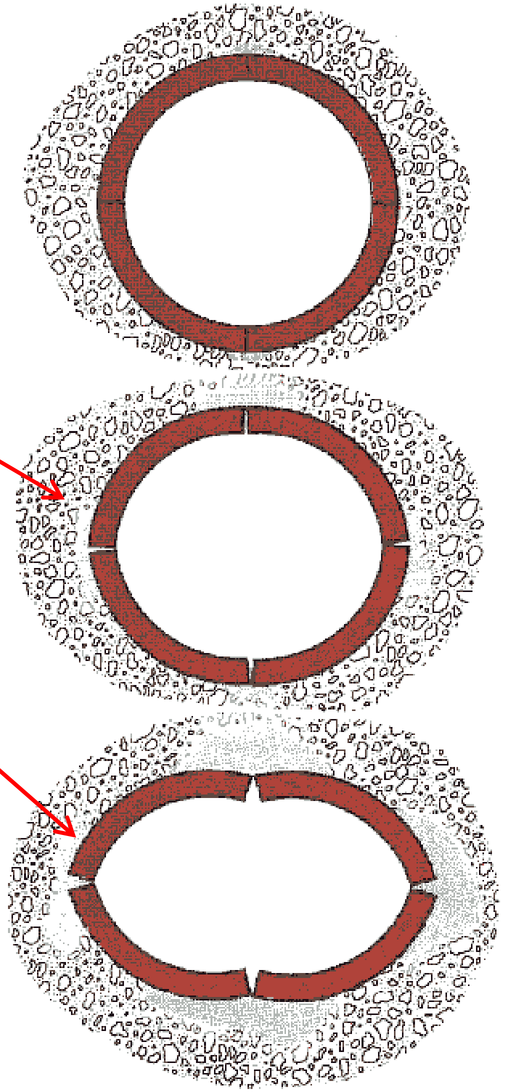


Effect of Soil Type and Frequency of Surcharge on SPG

INTERNAL CONDITION GRADE	SOIL TYPE	STRUCTURAL PERFORMANCE GRADE		
		FREQUENCY OF SURCHARGE		
		RARELY	FREQUENTLY	DAILY
4	High risk	4	5	5
3		3	4	5
2		2	3	3
4	Medium risk	4	4	5
3		3	4	4
2		2	2	3
4	Low risk	4	4	5
3		3	3	3
2		2	2	2

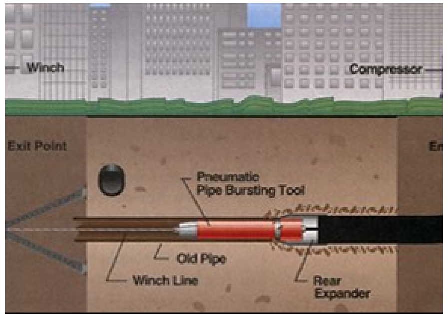
PRACTICAL RAMIFICATIONS OF STRUCTURAL SCORES (once resolved)

- SPG 3 = next generation of rehab
  - 3-10 years and beyond based on criticality
- SPG 4 = waiting for a random event to fail
  - 2-5 year capital program
- SPG 5 = broken and need to fix
  - Assess for emergency and either fix or schedule for immediate capital (1-2 years)



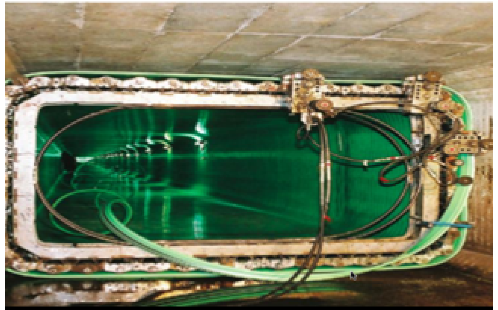
We use our rehabilitation program to fix what we need
- In Part 3, we'll discuss how to predict and manage backlog
- Plenty of ways to restore RUL without replacing the asset


Continuous Sliplining



Pipe Bursting


Fold and form Liners


Spiral Wound PVC Liners

Carbon Fibre Reinforced Polymers (CFRP)



Segmental GRP Liners


Cured-in-place pipe (CIPP)


Discrete Pipe Sliplining


Compression Fit Liners


Spray-applied Geopolymers

Apply your Risk Model and Adjust your Monitoring Frequency to Make Sure what you don't fix does not come back to bite you!

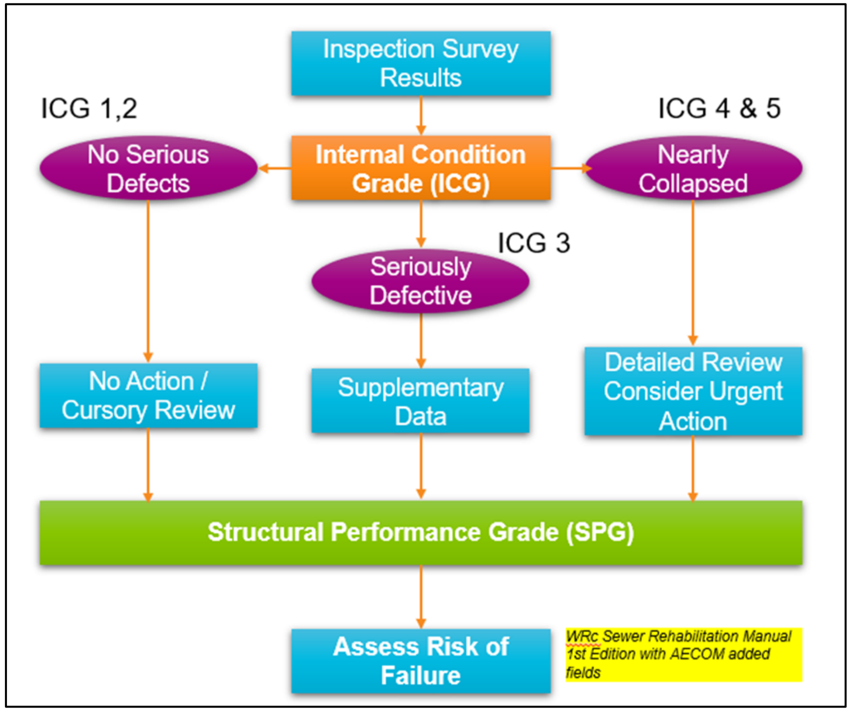
1. Build Capital Programs to take Risk where you can
2. Adjust your Re-inspection Periodicity to eliminate surprises

Structural Performance Grade	High Criticality	Medium Criticality	Low Criticality
5	*	*	*
4	1 year	5 year	10 years
3	3 years	15 years	20 years
2	5 years	20 years	25 years
1	10 years	25 years	30 years

*Note: * Where rehabilitation is not planned in the immediate future sewer condition should be monitored frequently to prevent unanticipated failure.*

Summary: Part 2

- For rigid pipes that break, deterioration largely occurs due to a loss of ground around the pipe
- PACP is the start of the Condition Assessment process but we need to consider other factors to estimate RUL
- As the events that ultimately drive failure are random, we can't predict failure timing exactly
- With good judgement, we can be close enough
  - Let risk determine where failure can occur
  - Intervene early enough where failure can't occur



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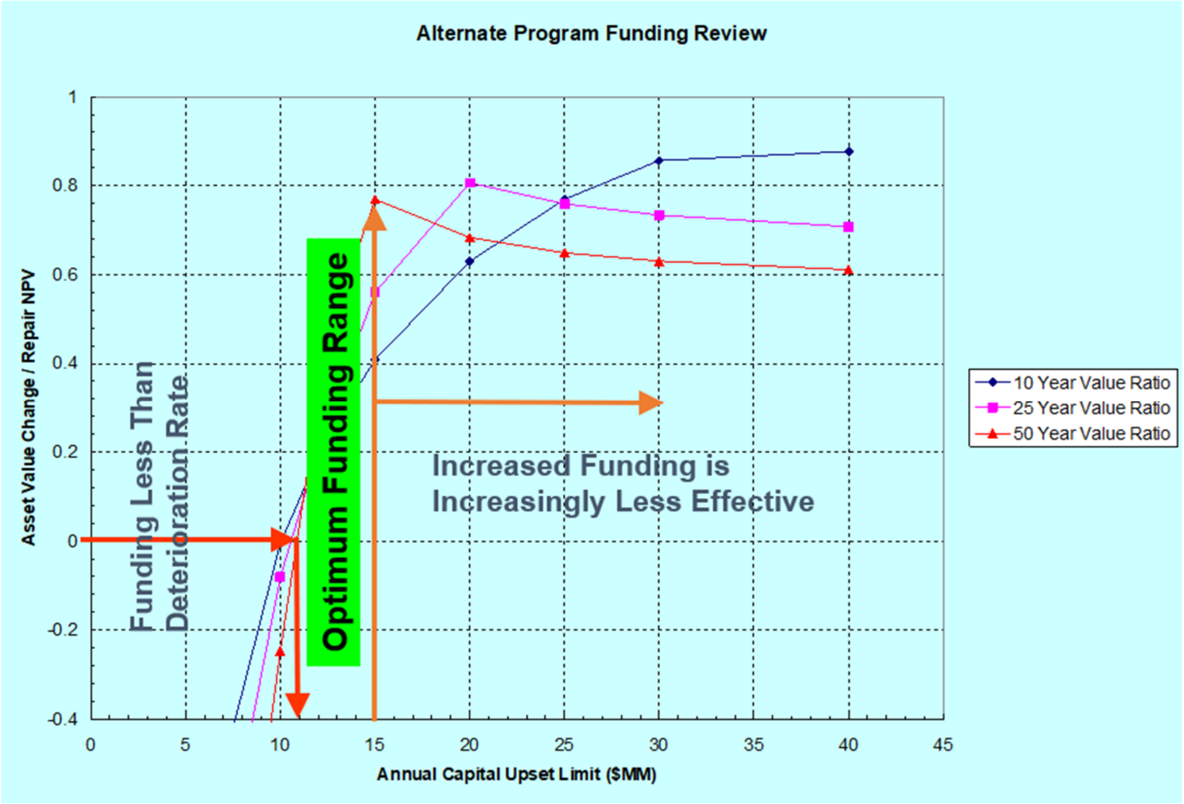
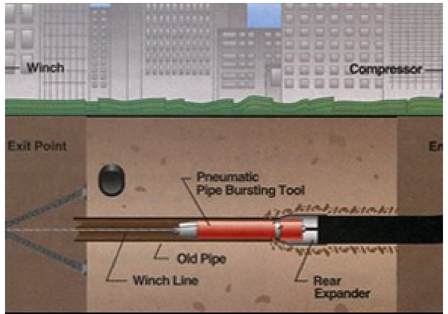
Part 3 – The Big RUL Picture - Modeling Deterioration with a PACP Database to Better Understand Short and Long Term Funding Ramifications

- We can do a lot more with clean PACP databases than we think we can.
- They form the fundamental basis for:
  - How we should fix things
  - When we should fix things
  - Capital planning spends
- On the capital planning side of this what questions should we be asking ourselves?
  - *How much should we spend?*
  - *When do we need to reinspect?*
  - *What happens if spend more or less?*
  - *What happens if we don't carry out planned re-inspections?*



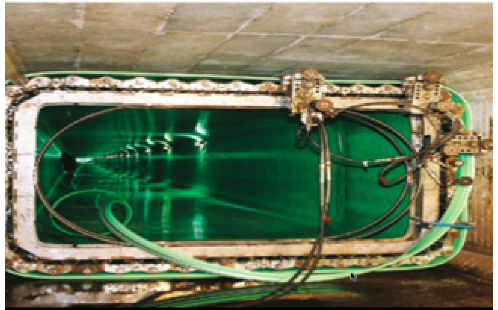
Using PACP to Ascertain How We Fix Things


Continuous Sliplining



Pipe Bursting


Fold and form Liners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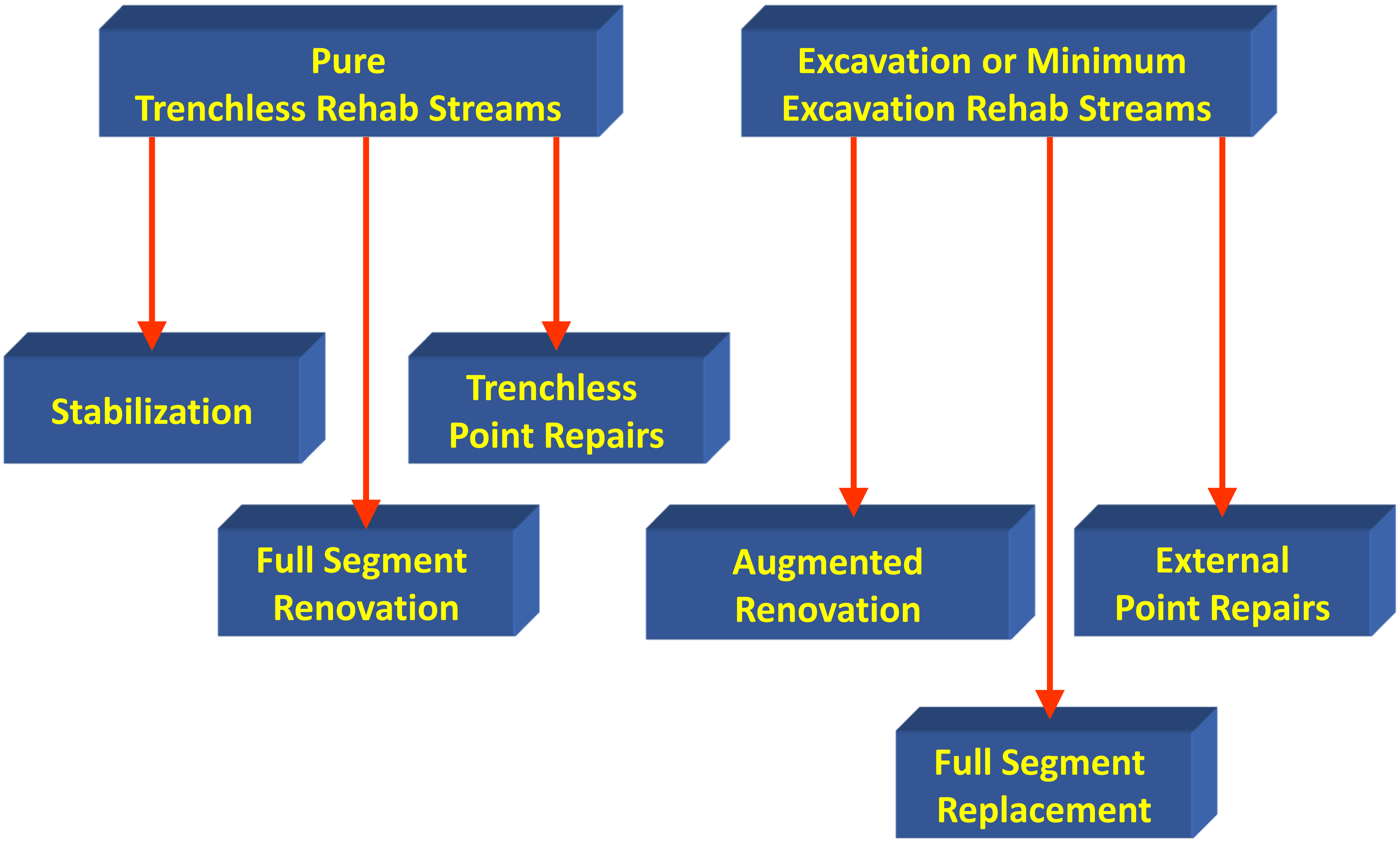
Typical Sewer Rehabilitation Work Streams



Rationalizing Work Streams Based on Defect Characterizations

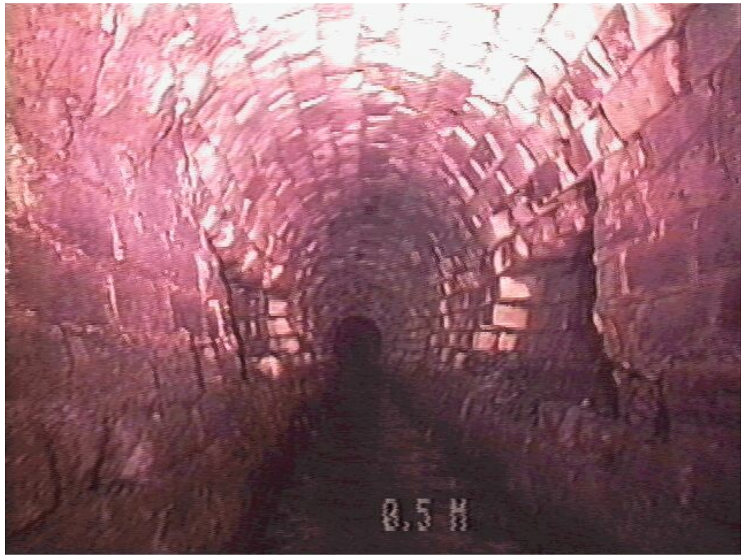
- It is often best to develop simple rules relative to defect patterns to characterize what rehabilitation work stream is applicable
- Rules are market driven and require verification on a jurisdiction-by-jurisdiction basis
- Rules are developed based on life cycle costing and should be tested annually using local market conditions

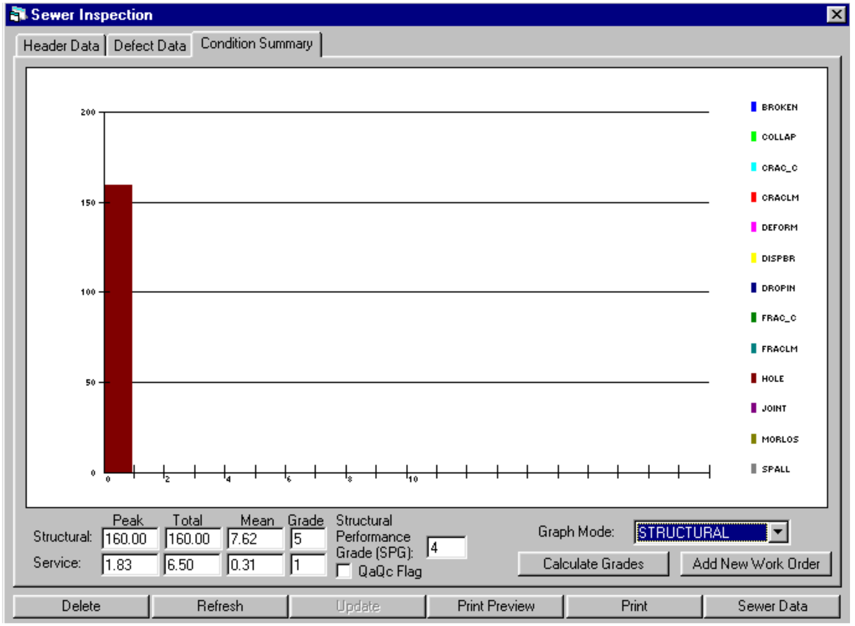
A sample set for small to intermediate diameter sewers will be reviewed for illustrative purposes

Evaluation Criteria -Trenchless Renovation

Stabilization (typically patching in large diameter and grouting in smaller diameters):

- man accessible (900-1200 mm ~ 36”-48”)
  - location of repair (close to point of entry)
  - extent of repairs (5-10% of MH-to-MH length - max)
- man entry (>1200 ~ 48”)
  - extent of repairs

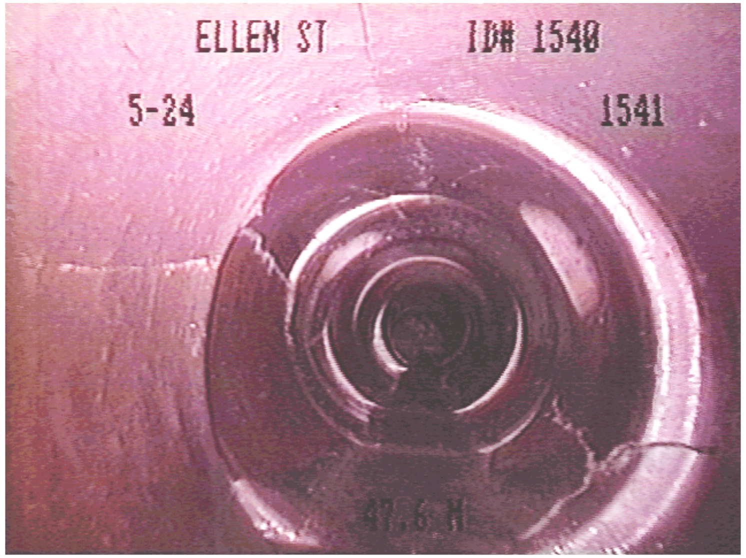


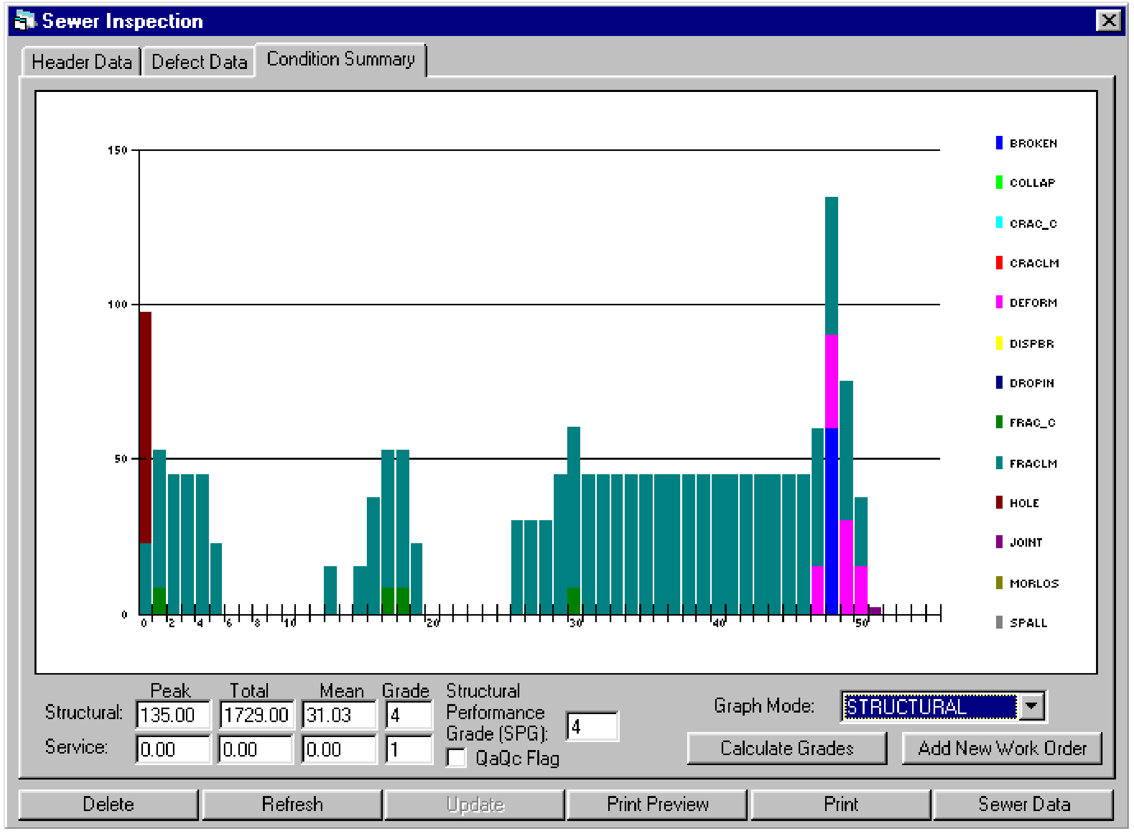


Evaluation Criteria - Trenchless Renovation

Full segment renovation:

- Nature of defects
  - deformation (<10%)
  - No offset fractures
- Extent of defects
  - >20-25% of MH-to-MH length

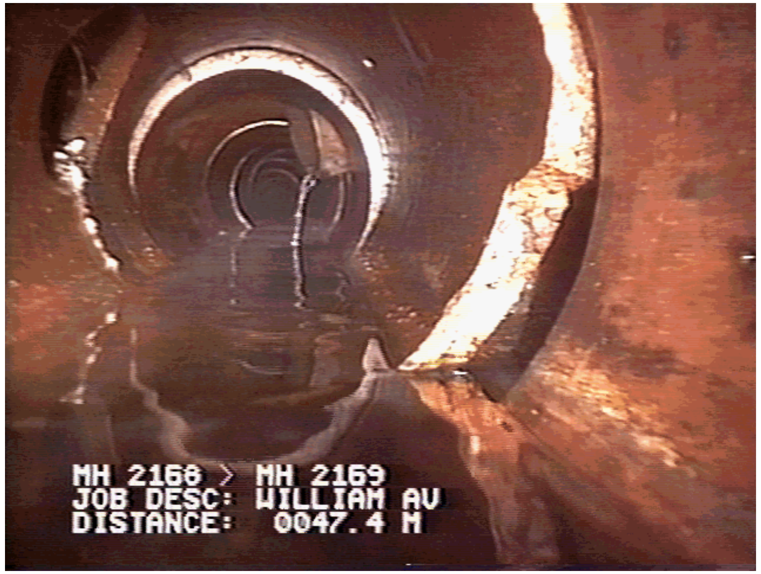


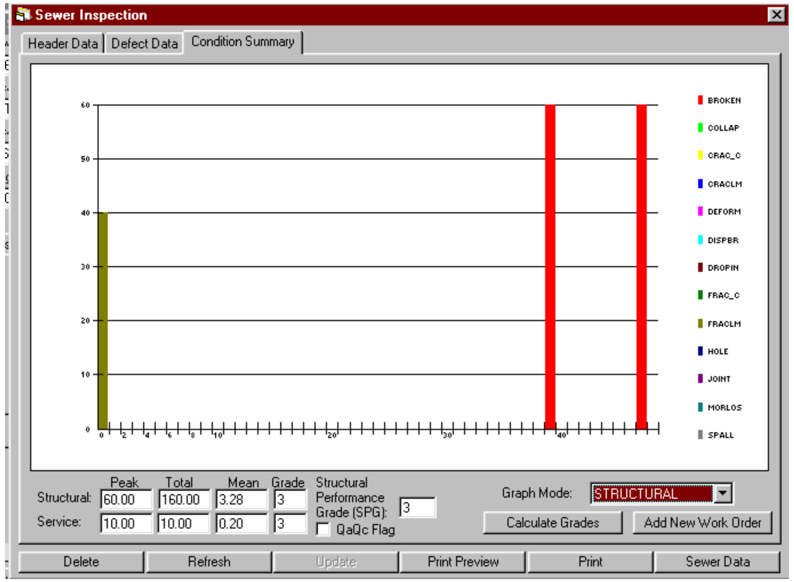


Evaluation Criteria -Trenchless Renovation

Trenchless point repairs:

- Nature of defects
  - deformation (<10%), no offset fractures
- Extent/length of defects
  - 3-10 feet or multiples thereof, < 20-25% of MH-to-MH length, limit of 3-4 repairs in any one sewer segment.

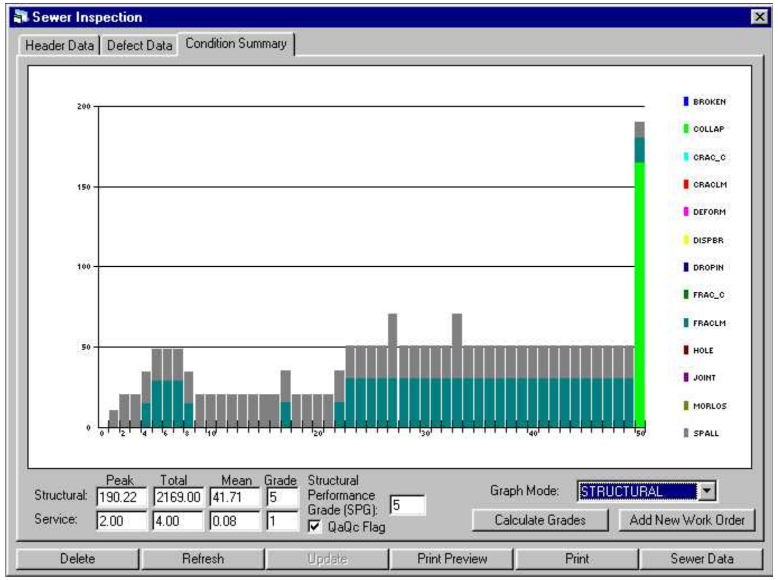




Evaluation Criteria - Min. Excavation

Augmented renovation:

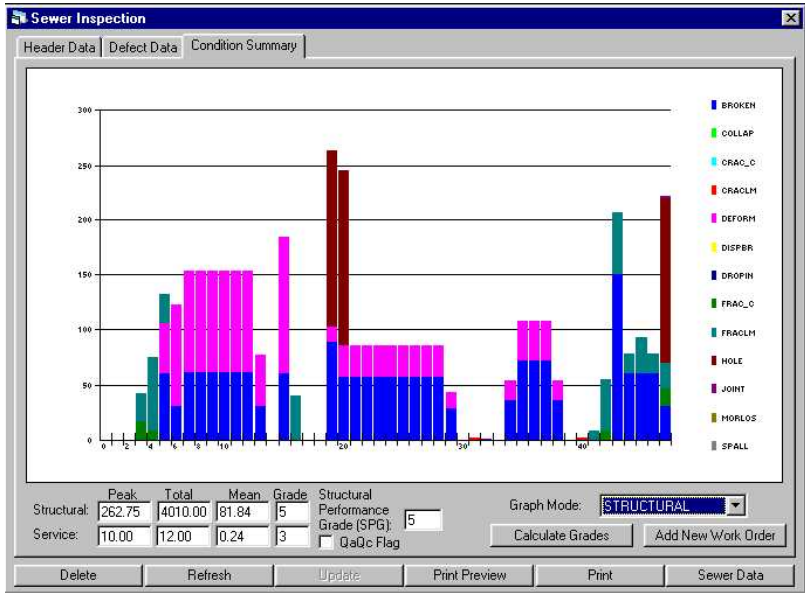
- renovation possible, with:
  - subsequent to external point repairs
  - with localized or extensive liner strengthening
  - with fully deteriorated design.



Evaluation Criteria - Min. Excavation

Full segment replacement:

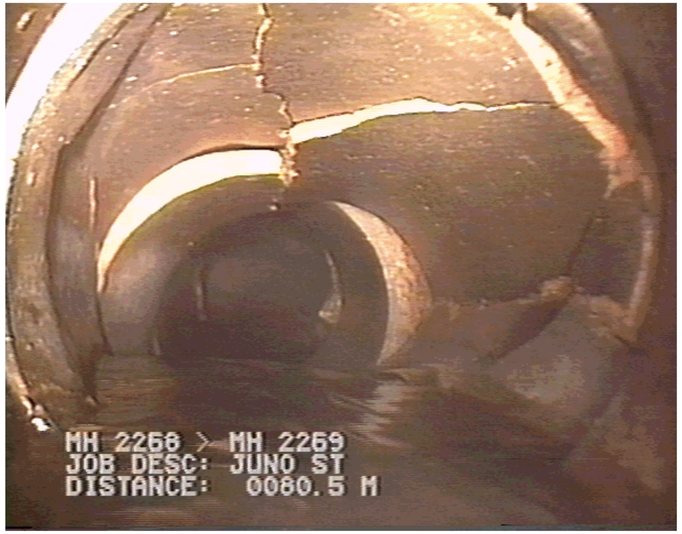
- Significant hydraulic upgrading required
- Nature of defects
  - Significantly > 10% deformation
  - Offset fractures
- Extent of defects: > 30-40% MH-to-MH length

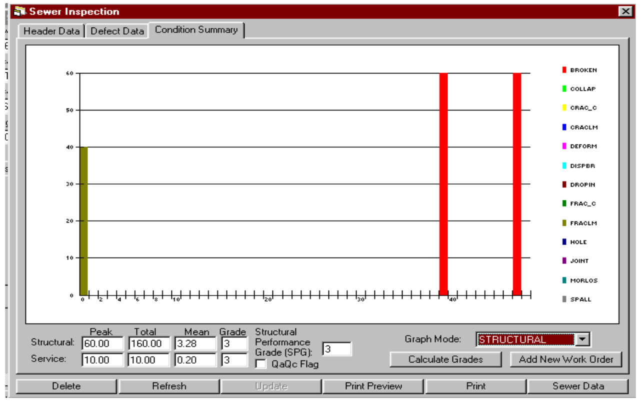


Evaluation Criteria - Min. Excavation

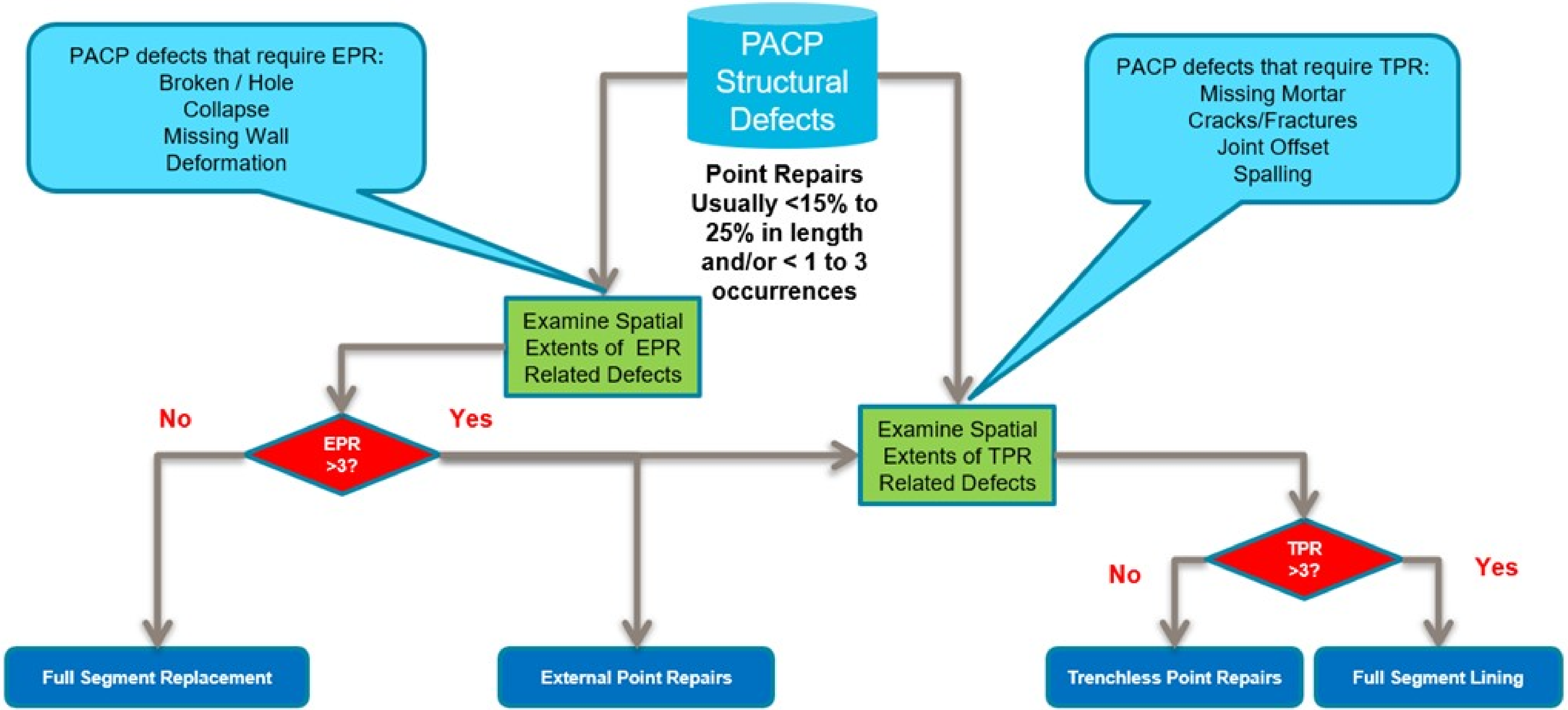
External Point Repairs:

- Nature of defects
  - Significantly greater than 10% deformation
  - Offset fractures
  - Non-removable obstructions (cross bores)
- Extent/length of defects
  - < 20-25% of MH-to-MH length
  - rule-of-thumb limit of 3 repairs in any one sewer





Automated Process for initial screening of Rehab Assignment

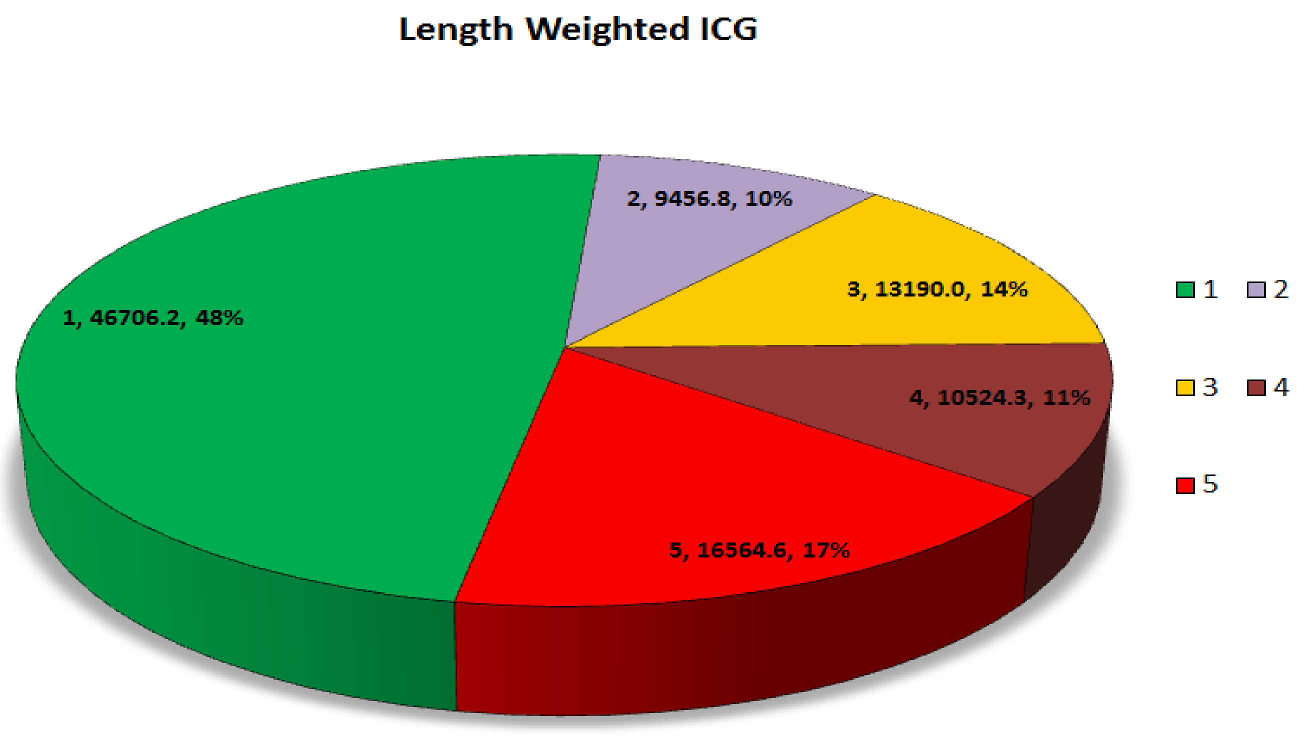


Initial Rehab Selection Process
- A series of automated algorithms for initial assessment
- Engineered review to confirm assignment

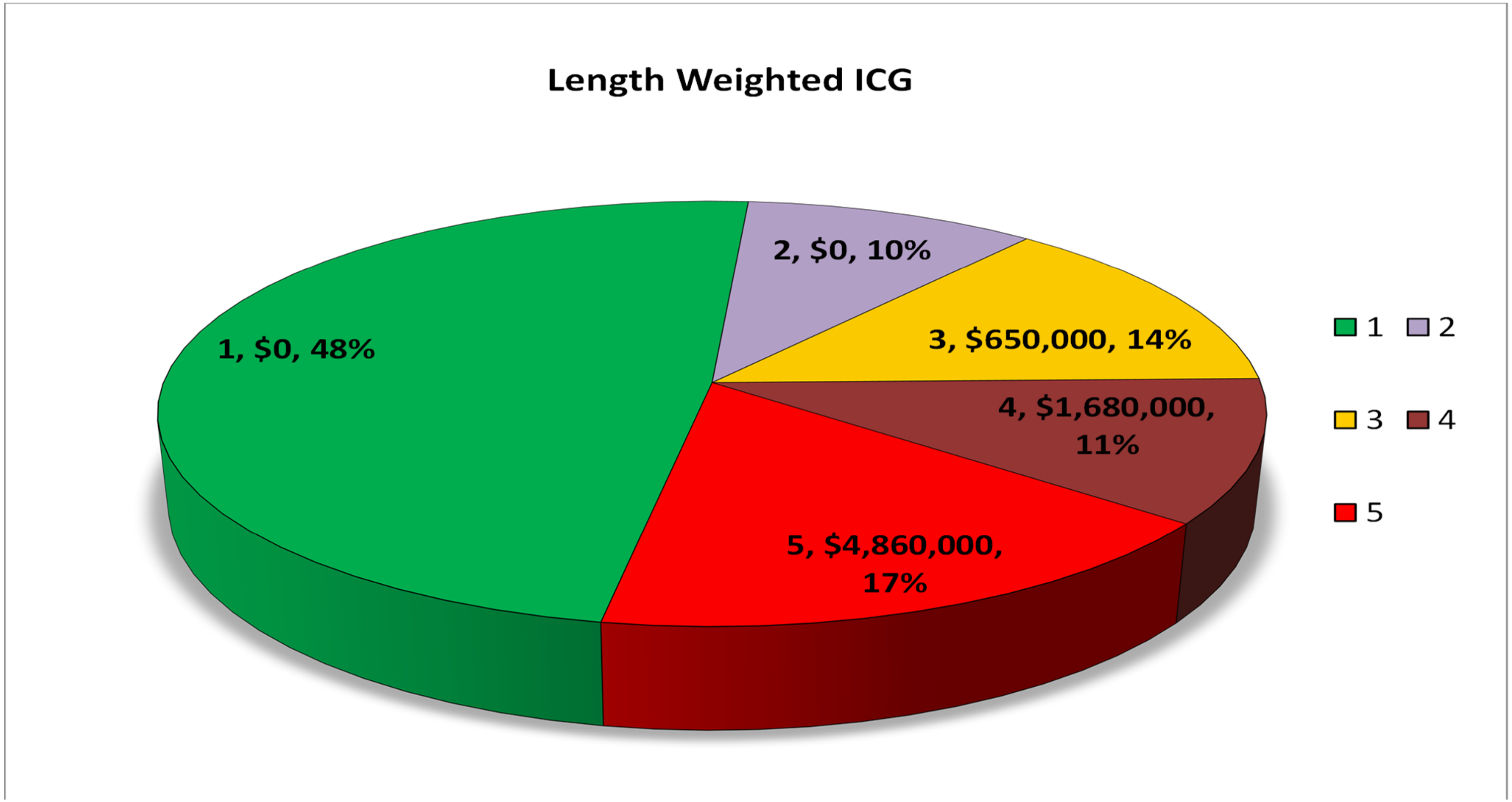
- Attach a cost model to workflow streams in your Database
  - Instantaneous generate financial ramifications of inspection program
  - Updated as Engineering review is completed
  - Evolves as rehab streams reach implementation

However, an initial understanding of the technical requirements and financial ramifications is immediate and can facilitate discussions between all stakeholders

KNOWLEDGE OF CONDITION = KNOWLEDGE OF COST AND UPGRADING



KNOWLEDGE OF CONDITION = KNOWLEDGE OF COST AND UPGRADING

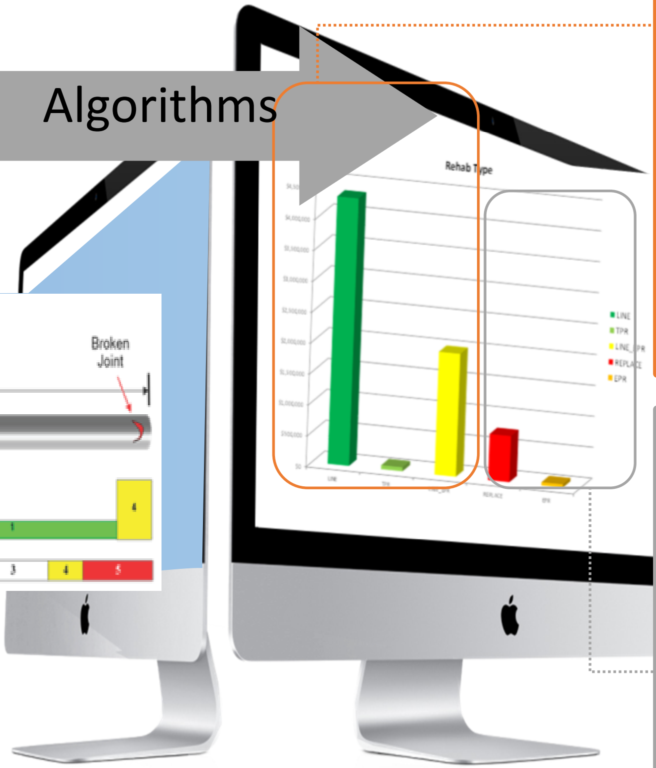


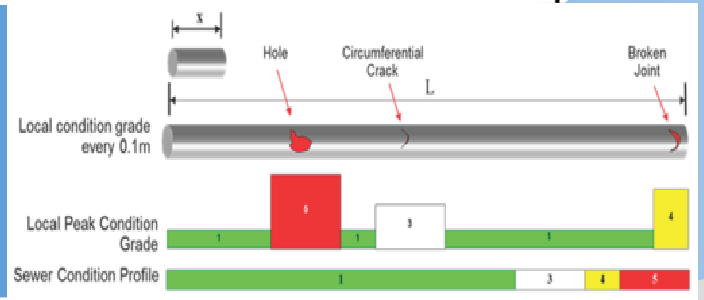
Quality PACP Data Can be Turned Into a Solid Understanding of the Present and Clarity of Vision for the Future

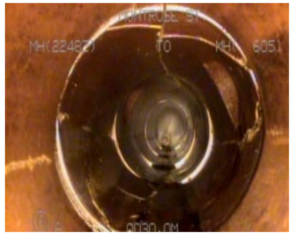
Quality Inspection Data → **Directly Processed into Initial Work Ramifications** → **Final Review of Rehab and Work Stream Assignments** → **5 Yr, 10 Yr CIP, O&M Programs And Beyond**

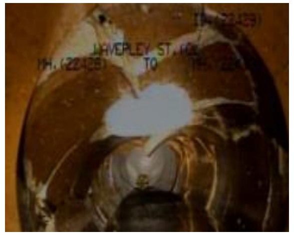
INPUT

Algorithms









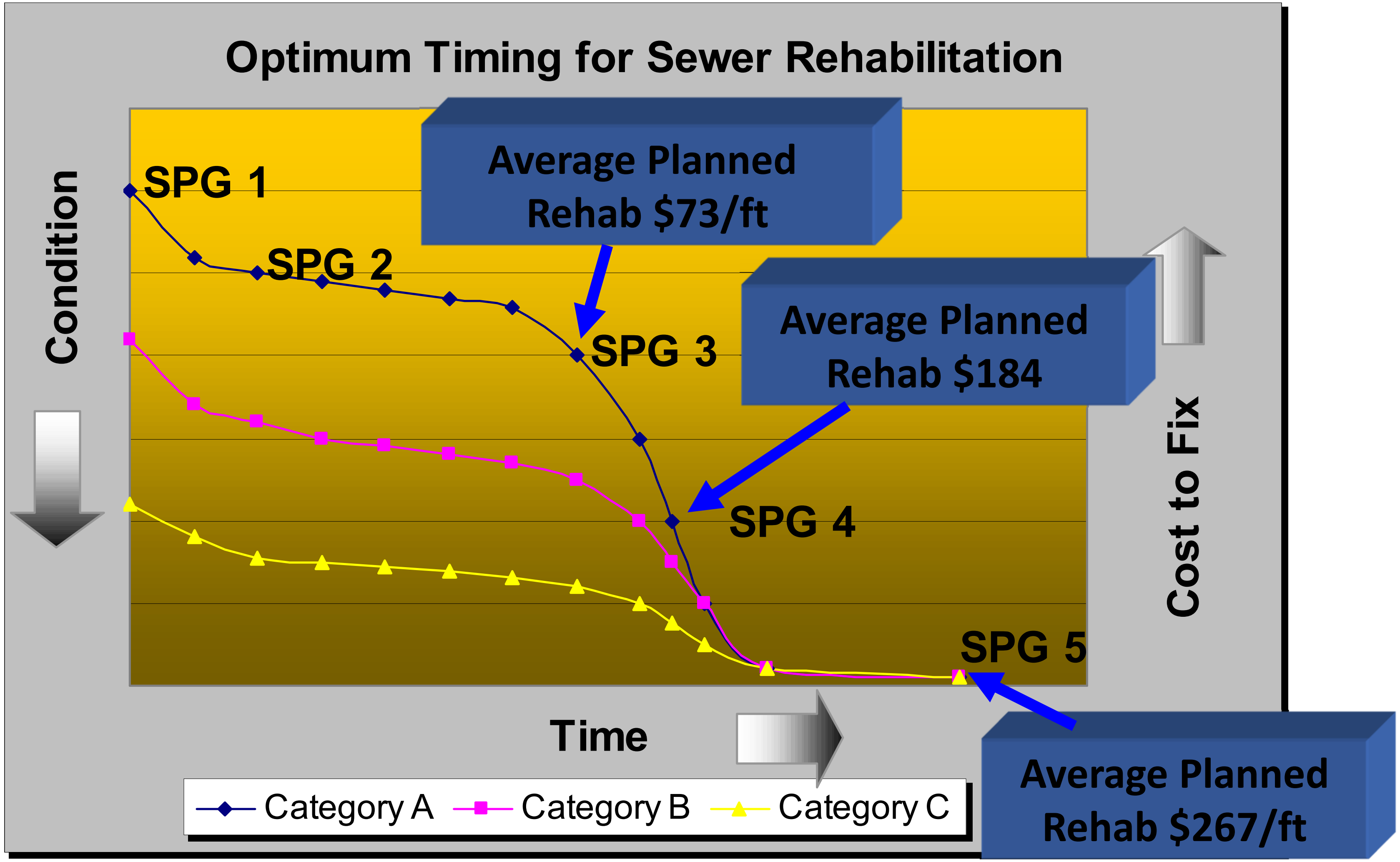
Capital Treatment Option Implementation
Action / No Action vs. Reaction

- We need to factor in the significance of intervening at various points in the deterioration cycle and account for the consequences of action, no action and reaction!

- Three categories of rehabilitation work:
  - Planned Rehabilitation Work
    - Cost increasing with increasing condition state
  - Emergency Repairs
    - Costs greater than planned rehab but repairs can't wait
  - Catastrophic Repairs
    - Greatest cost and public safety could be compromised

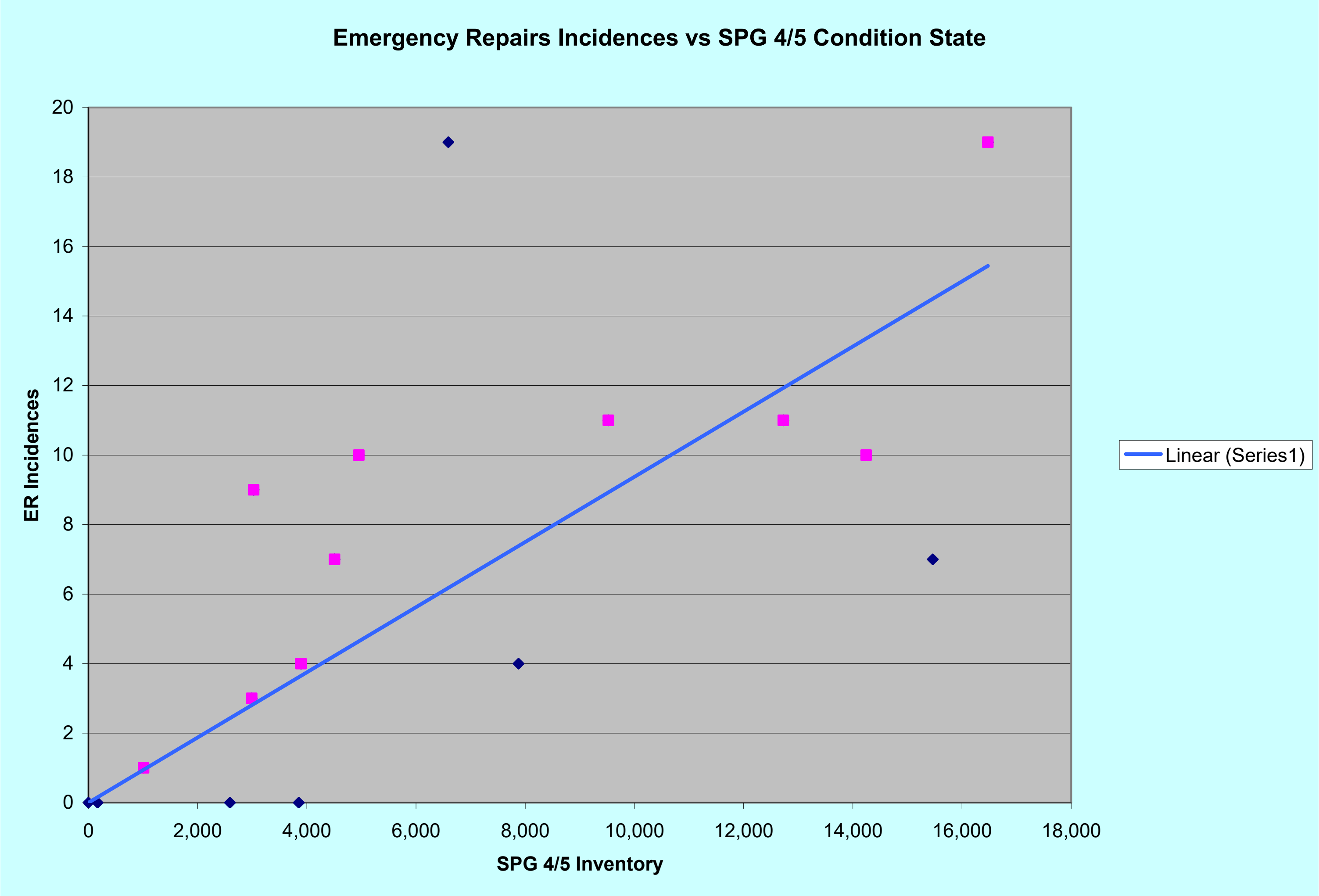
Action / No Action vs. Reaction

Planned Rehabilitation Works - Sewers



Action / No Action vs. Reaction

Emergency Repairs – if our backlog is too large



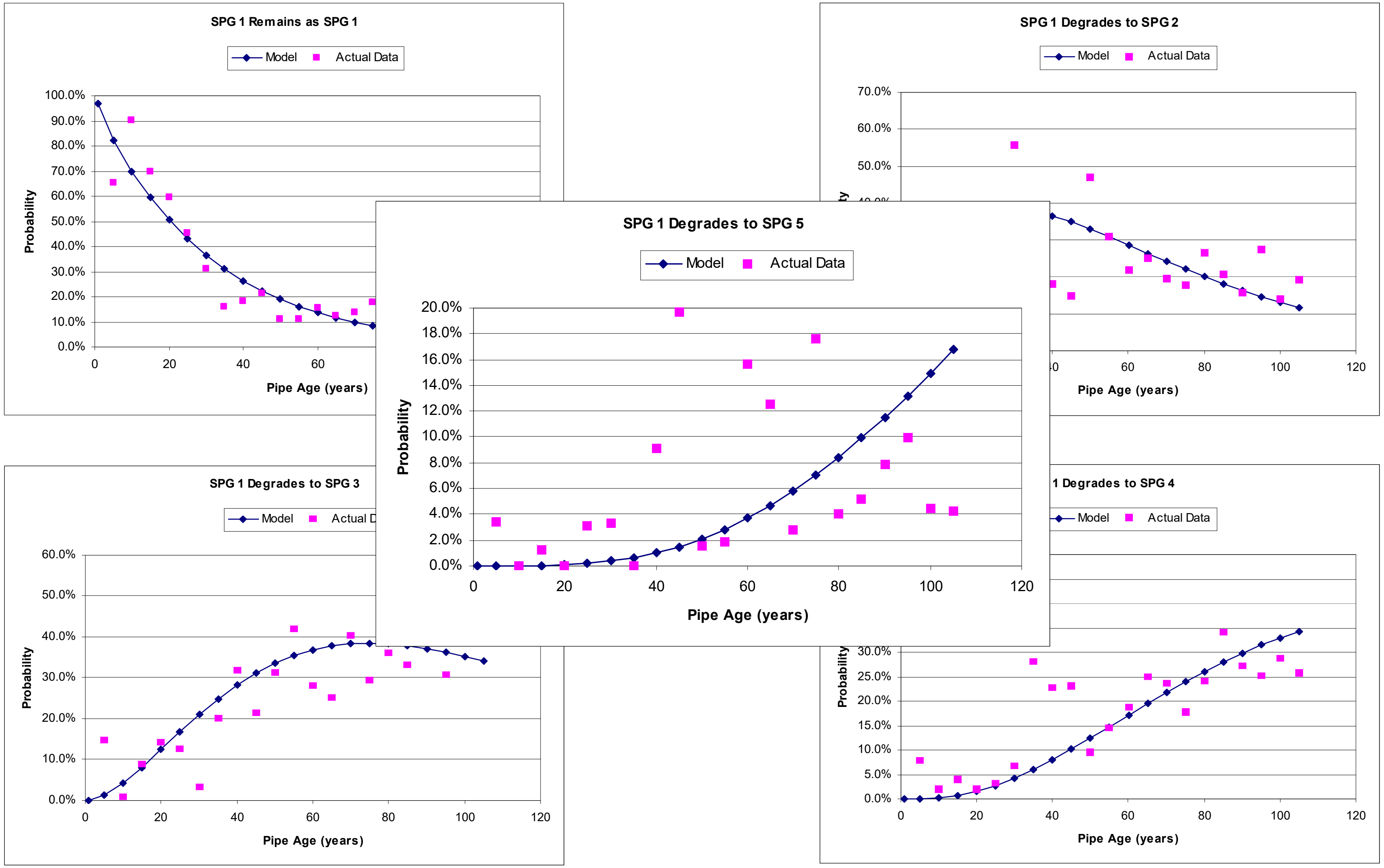
Action / No Action vs. Reaction

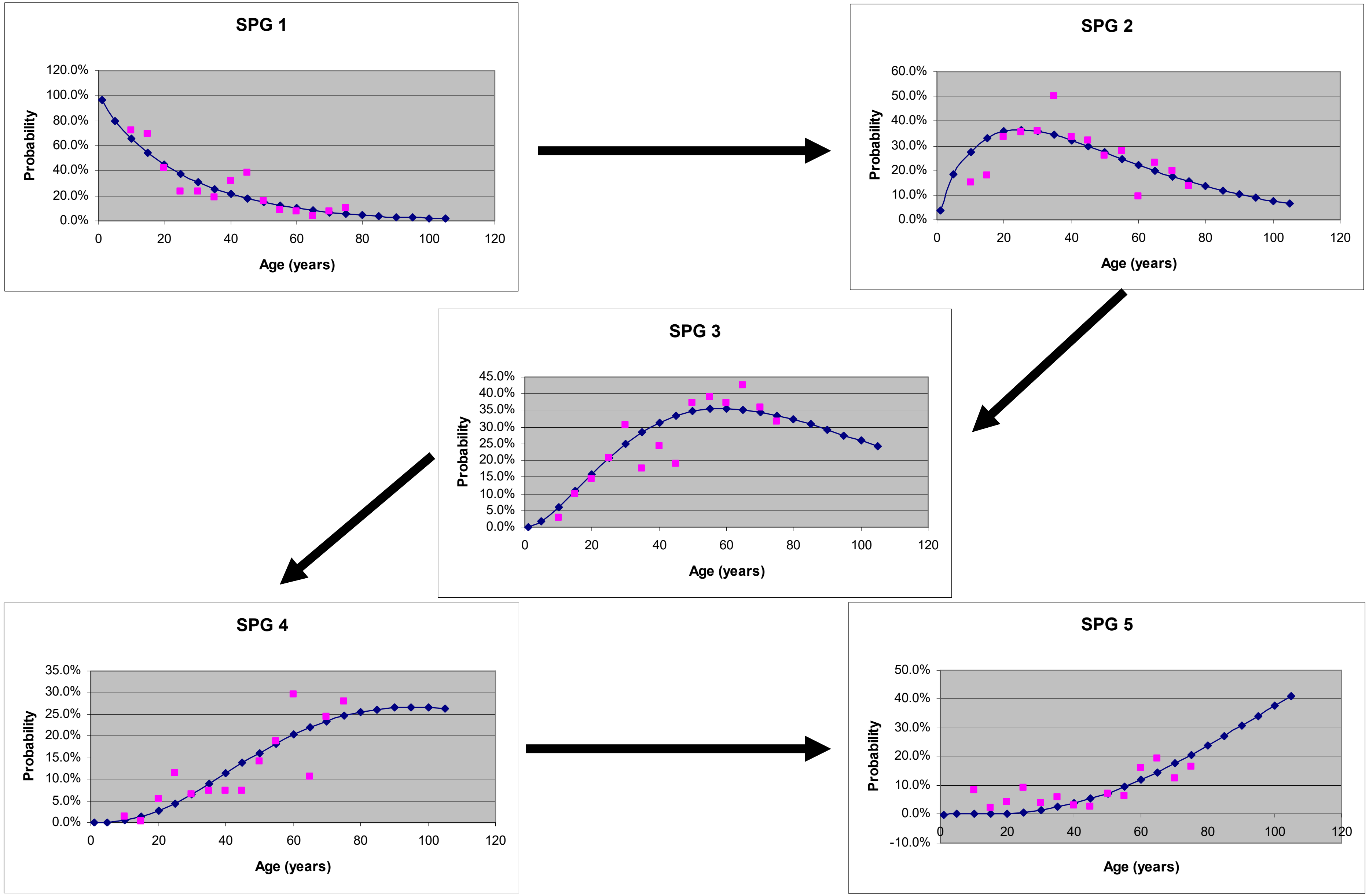
Catastrophic repairs – if we don't inspect frequently enough

Understanding the Deterioration Process – Sewers – the key in determining how much to spend and when

- We need to put deterioration timelines into perspective
- Deterioration modeling
  - Most commonly use a simple Markov chain type model
  - Initial model development based on a review of existing distribution of condition state versus age
    - Evolution of model is based on actual observations through re-inspection to refine the probability distribution associated with each condition state transition
  - Initial models averaged condition of all sewer plant
    - Advanced model can small, intermediate, and large diameter chains for each material type

Understanding the Deterioration Process - Sewers



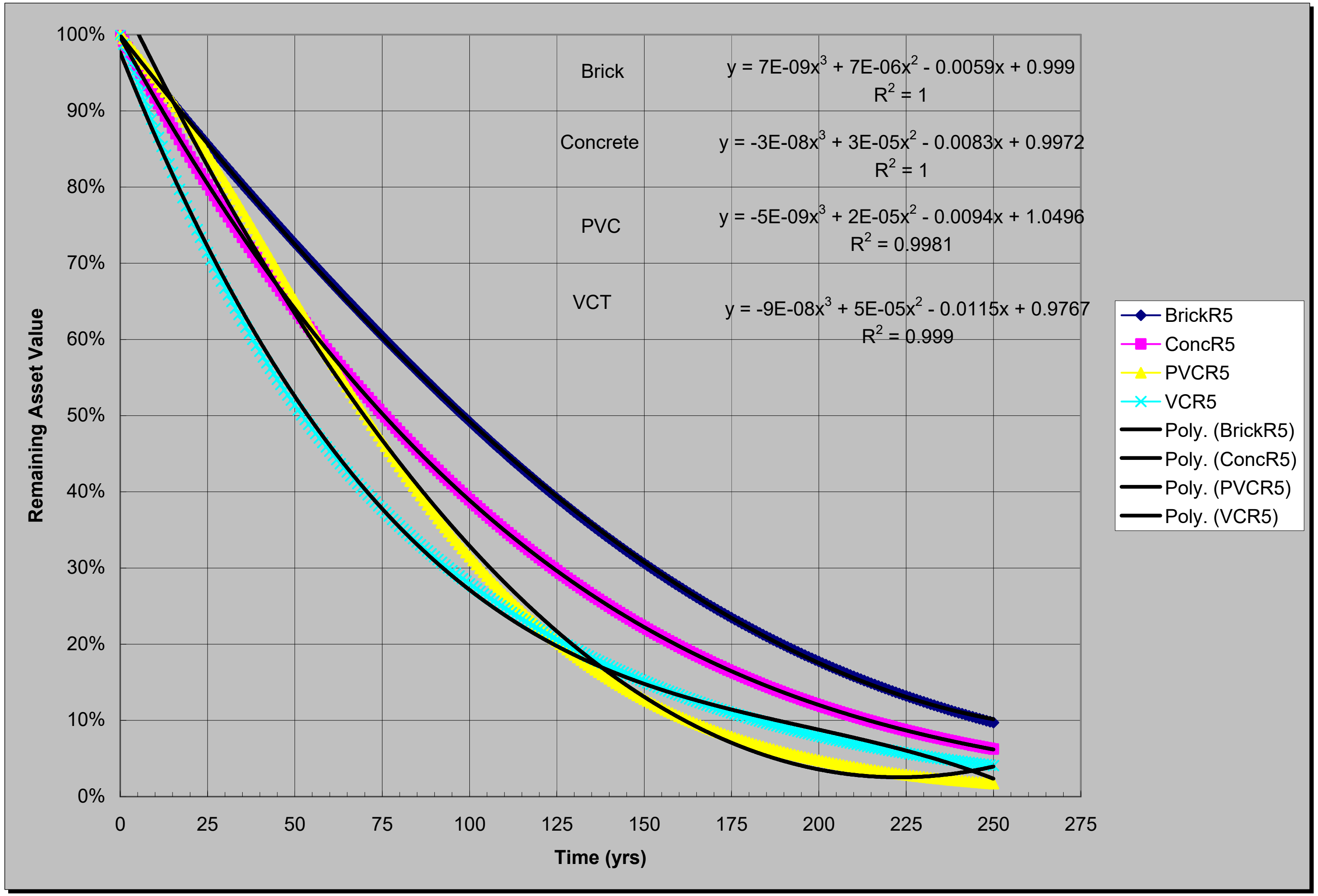

SPG 1
Probability
120.0%
100.0%
80.0%
60.0%
40.0%
20.0%
0.0%
0
20
40
60
80
100
120
Age (years)
SPG 2
Probability
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
0
20
40
60
80
100
120
Age (years)
SPG 3
Probability
45.0%
40.0%
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
0
20
40
60
80
100
120
Age (years)
SPG 4
Probability
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
0
20
40
60
80
100
120
Age (years)
SPG 5
Probability
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
-10.0%
0
20
40
60
80
100
120
Age (years)

Understanding the Deterioration Process - Sewers

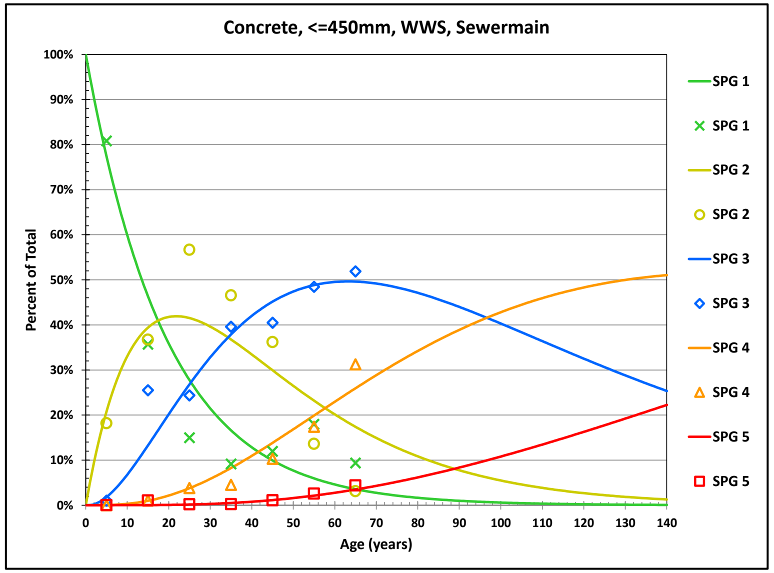
Markov Chains

	To SPG				
From SPG	1	2	3	4	5
1	96.3%	3.7%	0.0%	0.0%	0.0%
2	0.0%	96.1%	3.9%	0.0%	0.0%
3	0.0%	0.0%	97.5%	2.5%	0.0%
4	0.0%	0.0%	0.0%	97.0%	3.0%
5	0.0%	0.0%	0.0%	0.0%	100.0%

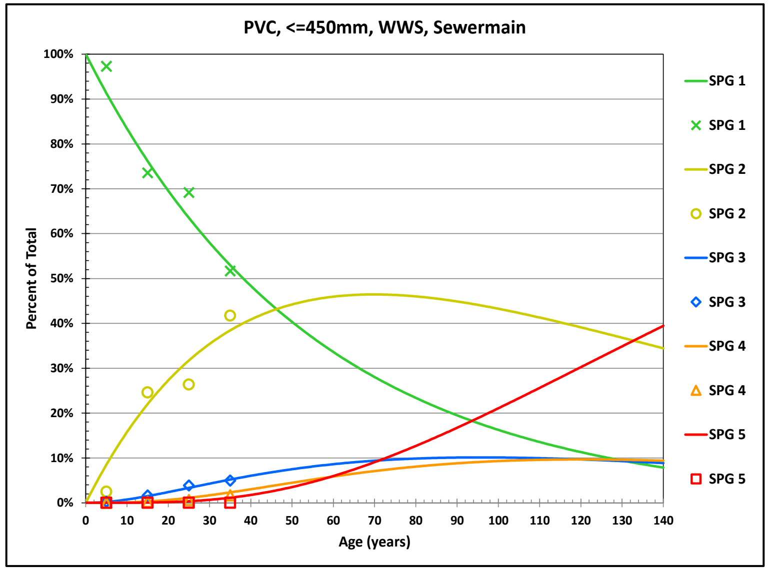
Material Type is significant



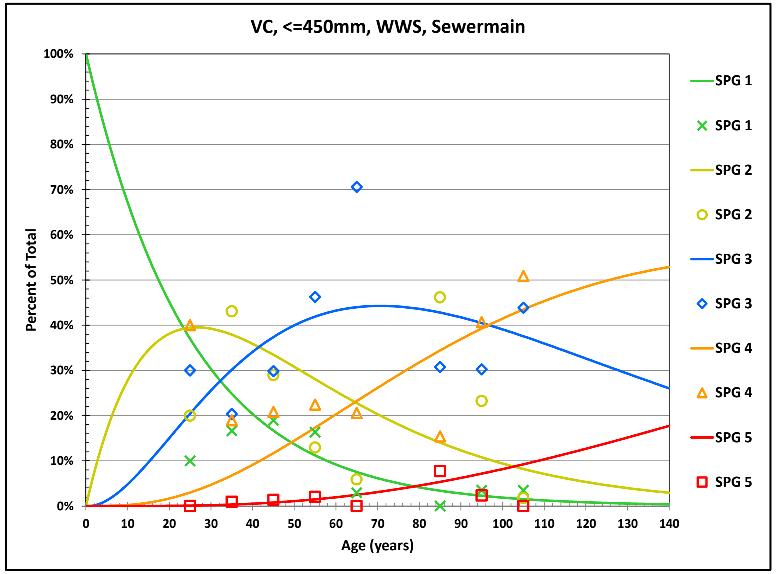
Material Type Impacts



≤ 18” CONC



≤ 18” PVC



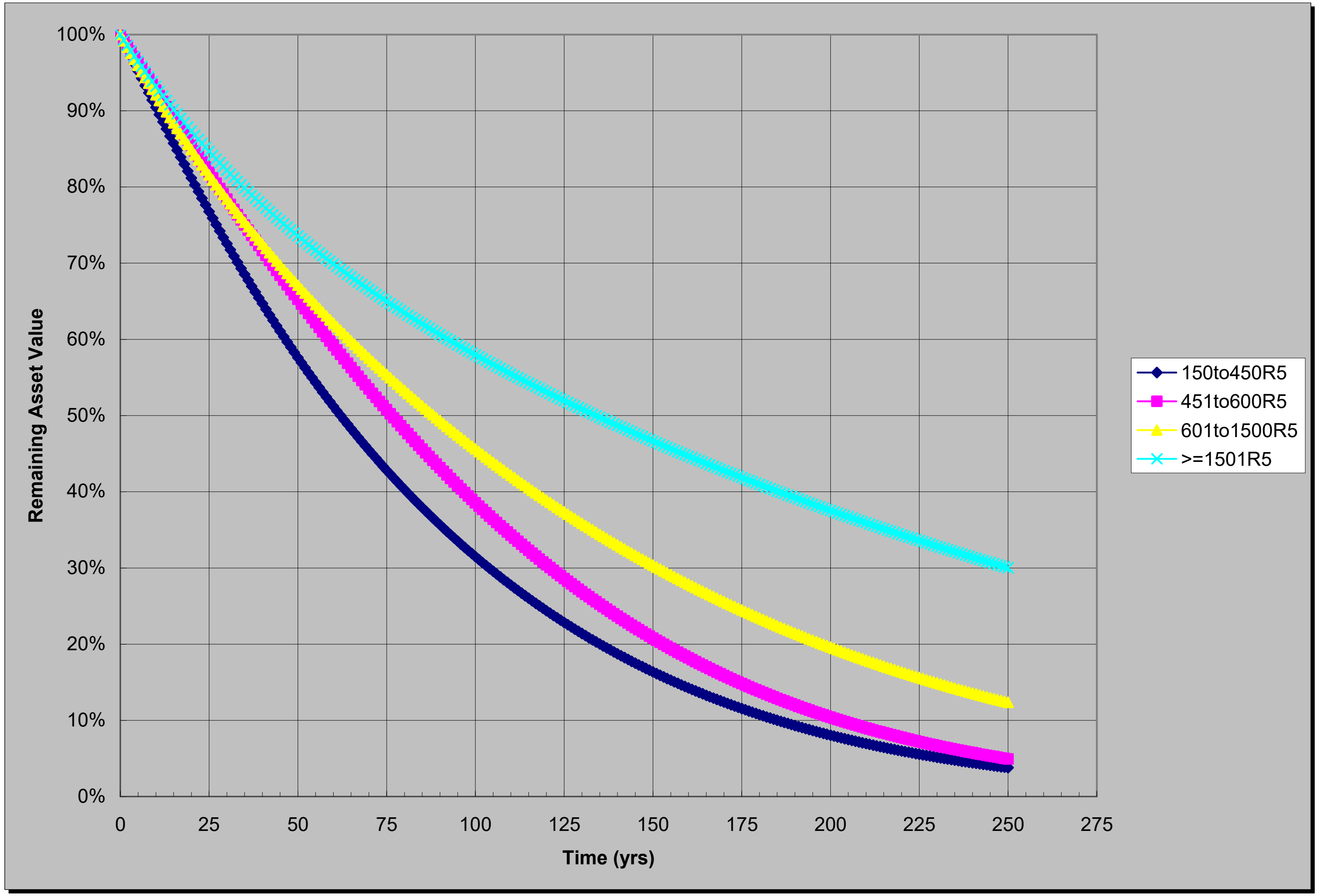
≤ 18” VC

3625	0.982	0.018	0	0	0
	0	0.989	0.011	0	0
	0	0	0.952	0.048	0
	0	0	0	0.952	0.048
	0	0	0	0	1

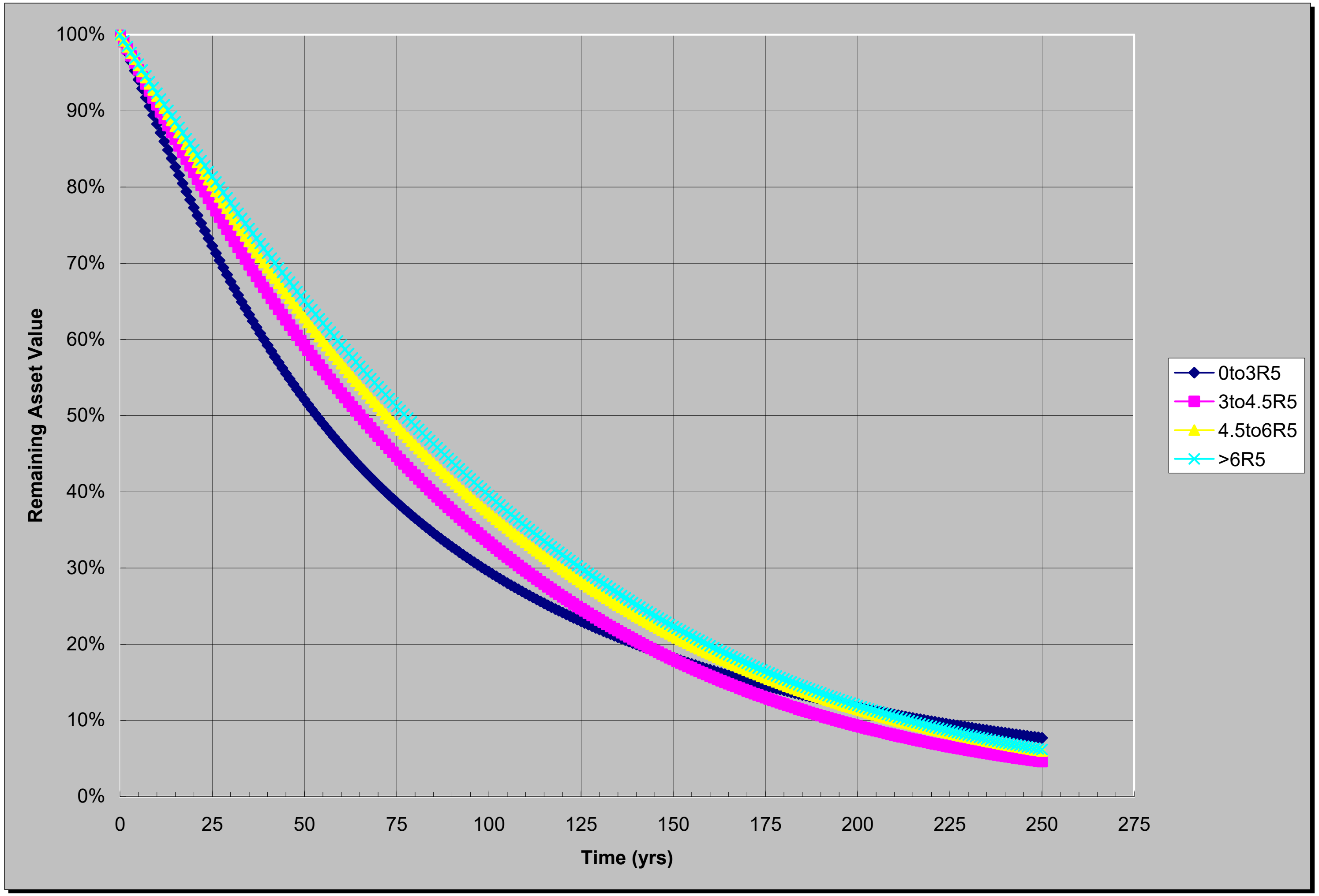
12878	0.95	0.05	0	0	0
	0	0.96	0.04	0	0
	0	0	0.985	0.015	0
	0	0	0	0.994	0.006
	0	0	0	0	1

806	0.961	0.039	0	0	0
	0	0.965	0.035	0	0
	0	0	0.984	0.016	0
	0	0	0	0.995	0.005
	0	0	0	0	1

Diameter is significant



Depth often is not



Markov Chain Deterioration and Sustainable Funding Model for Sewers
- brief demo on real data

(example provided using proprietary spreadsheet demonstrating Markov Chain)

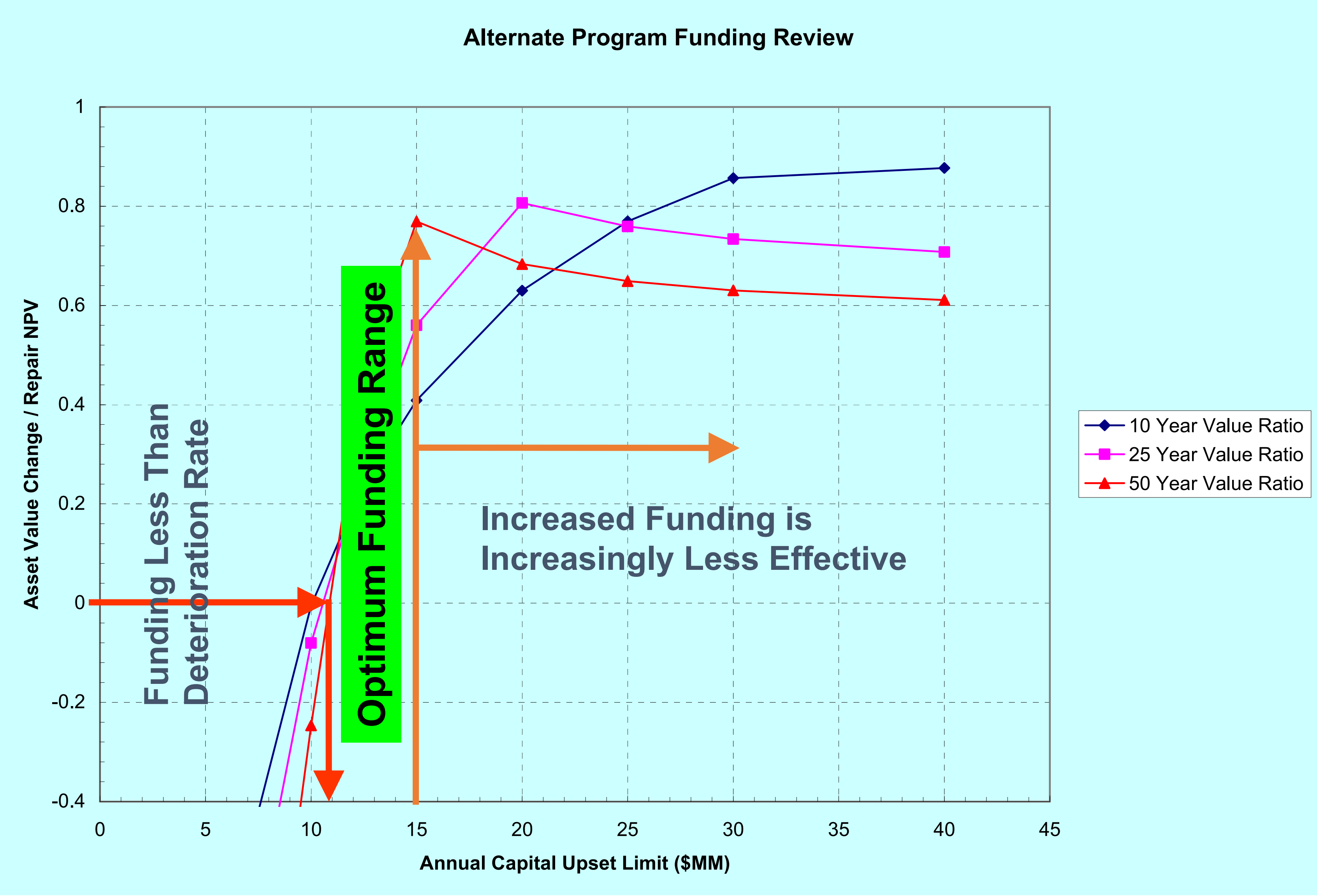
Average Condition Index				
Category	A	B	C	All
Beginning of Analysis	2.889	2.754	2.506	2.703
End of Analysis	2.401	2.378	2.375	2.386
% Change	16.9%	13.6%	5.3%	11.7%

Cost of All Backlogged Repairs	
Beginning of Analysis	$244.3
End of Analysis	$113.2

Asset Value	
Beginning of Analysis	$946.8
End of Analysis	$1,077.9
Difference	$131.1

Asset Value Change / NPV of Repairs	0.56
Asset Value Change - Total Repair Cost	-$243.9
Asset Value Change/Total Repair Cost	0.35
Asset Value Change/(Repair + Reinsp)	0.34

What Else Can This Tell Us About Sustainable Funding Levels?

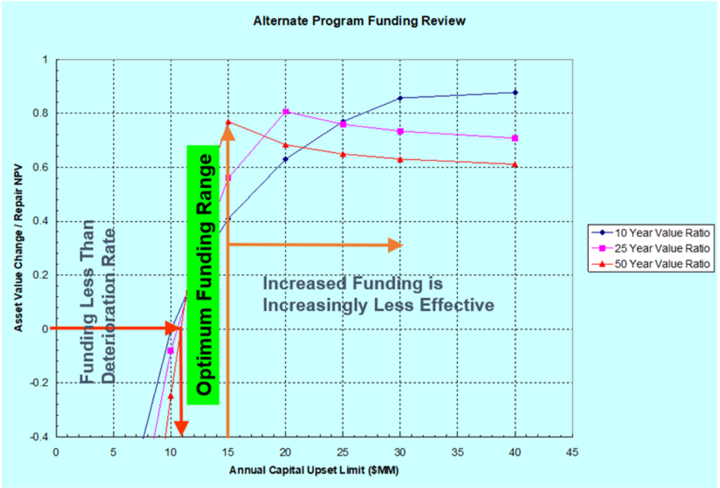


Summary: Part 3

- With quality PACP data and proper interpretation of RUL
  - We can determine what to fix and when
  - We can determine how to fix things
  - By overlaying Risk Models we can determine where we can tolerate failure and where we can't
  - We can determine much time and money we should spend on fixing things
  - We can illustrate what happens if we have more or if we have less

Structural Performance Grade	High Criticality	Medium Criticality	Low Criticality
5	*	*	*
4	1 year	5 year	10 years
3	3 years	15 years	20 years
2	5 years	20 years	25 years
1	10 years	25 years	30 years

Note: * Where rehabilitation is not planned in the immediate future sewer condition should be monitored frequently to prevent unanticipated failure.




Q&A

Thank you.

For additional questions, please contact TAC@NASSCO.org