Civil & Environmental Engineering
University of Missouri

Methodology for Risk Assessment of Post-Tensioning Tendons
Webinar

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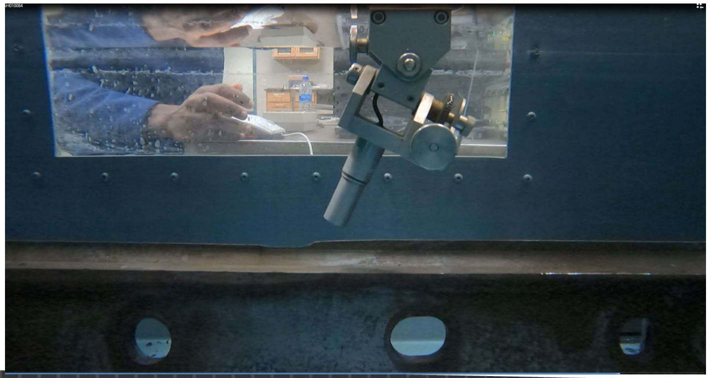
Introduction

- Professor, University of Missouri, 2004 – present
- FHWA NDE program manager 1991-2004
- PhD Johns Hopkins University Center for Nondestructive Evaluation
- Research interest: Bridge inspection reliability, risk assessment, ultrasonic testing, stress measurement, transient thermography



Agenda

- Background
  - –Risk-Based Decision-Making
- Introduction
  - –Methodology for Risk Assessment of PT tendons
- Risk Assessment Process
  - –Steps for conducting the risk assessment
- Attributes for PT Tendons
  - –Descriptions of individual attributes
- Example Bridge
  - –Application of the Methodology to an example bridge

Post Tensioning Technology Selection for Durability Guidance

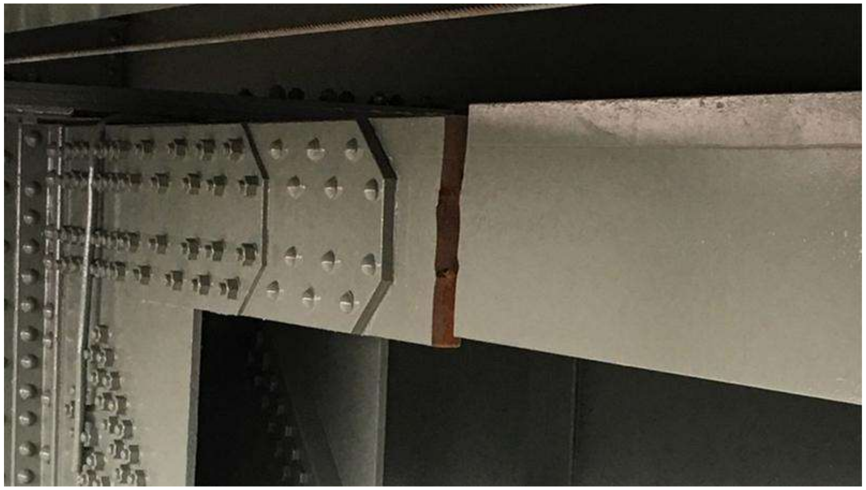
BACKGROUND
RISK-BASED DECISION-MAKING

Background on Project

- **Goal:** Improve the durability of PT bridges
- **Objective:** Develop a guideline for conducting risk assessment of PT tendons to aid designers in selecting corrosion protection strategies for PT systems in bridges
- Scope: Methodology developed for assessing risk of corrosion damage for PT tendons
  - For use during design/project development for selection of corrosion protection strategies
- Methodology developed based on NCHRP Report 782
  - *Reliability-Based Bridge Inspection Practices*
- Advanced Concrete Bridge Technology to Improve Infrastructure Performance Program
  - WSP
  - rosap.ntl.bts.gov

Background

- Risk-Based Decision-making
- Learning Objectives:
  - Understand the concept of risk-based decision making



Risk-Based Decisions

- Risk-based decision are made by engineers every day
  - Risk-based methodologies formalize and document the process
    - What can go wrong?
      - e.g., Cracking in a steel member
    - What are the chances of that happening in the next 1 yr, 2 yrs, etc.?
      - Depends on
        - » Magnitude and frequency of loading
        - » Existing damage
        - » Resistance to cracking of the member
    - What is the consequence?
      - Catastrophic collapse, service interruption or benign?

Risk-Based Decisions (cont.)

- Risk-based methods generally consider the *likelihood (i.e. probability)* of failure and the associated *consequences*
- **R = POF x C**
  - –R = Risk
  - –POF = Probability of failure
  - –C = Consequence of the failure
  - –Different terms may be used for the POF

R = Likelihood x C
R = Frequency x C
R = Occurrence x C

Risk – Based Decisions (cont.)

Probability of Failure (POF)

- Estimate of the likelihood of "failure"
  - "Failure" needs to be defined
    - Loss of service or bridge collapse?
- "Occurrence factor" (OF) is a POF measure that considers the likelihood of failure, i.e., the POF

How can the POF be determined?

- Testing to failure of components
- Deterioration models
- Experience and engineering judgement (expert knowledge)
  - What are the characteristics of a reliable tendon?
  - What characteristics increase the POF for a component?
- Point estimates and order-of magnitude estimates

Risk – Based Decisions (cont.)

Typical Consequences

- Economic
  - Cost of replacement, repair, accident costs, cost of service loss
    - Quantitative
- Environmental
  - Measure of the environmental impact of a failure – quantitative cost or qualitative impact
- Safety
  - Consequence in terms of injury or death, qualitative safety measure

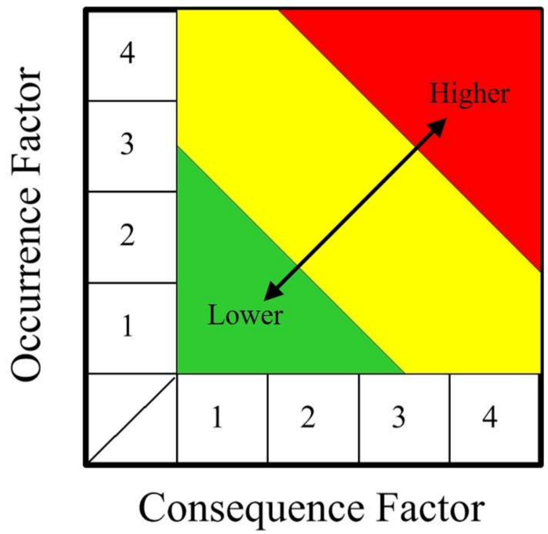
Risk – Based Decisions (cont.)

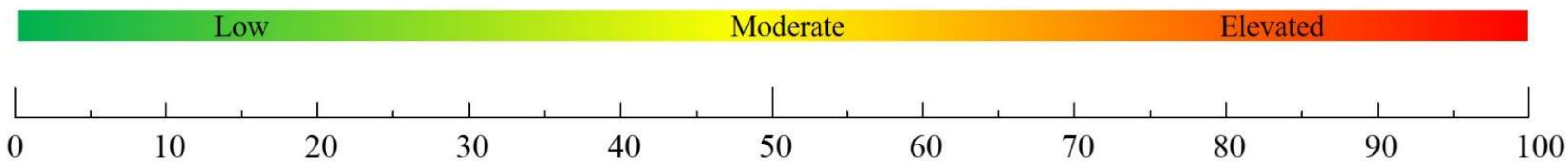
- **Combine POF and Consequence measures**
- **R = POF x C**
  - –R = Risk
  - –POF = Probability of failure
  - –C = Consequence of the failure
- Determine level of risk
  - –Qualitative (low, moderate, or high risk)
  - –Quantitative
    - Relative risk value
    - Product of POF and consequence

Risk – Based Decisions (cont.)

Risk measures

- Risk Matrix
  - Matrix with a defined number of levels for POF and C
    - 4, 6, 8… etc. levels
    - Increased risk toward upper right
- Risk Scale
  - Product of POF x C on a 100 point scale
  - Define threshold for low, moderate or elevated risk.





Methodology for Risk Assessment of PT Tendons

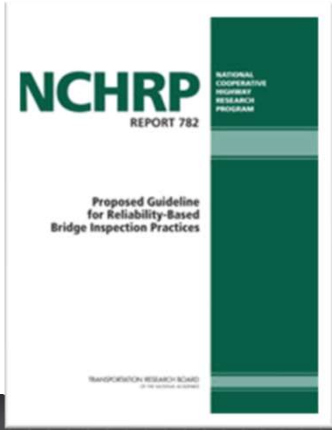
INTRODUCTION
METHODOLOGY FOR RISK ASSESSMENT OF PT TENDONS

Introduction

- Learning Objectives
  - Understand the guidelines for risk assessment of PT tendons
  - Apply the process for risk assessment of tendons
  - Evaluate the CF and OF for risk assessment of PT Tendons

Background

- Process / Strategy:
  - –Using the processes developed for NCHRP Report 782
    - Form a risk model to assess corrosion damage in PT tendons
      - –Scoring process based on attributes and criteria formed from expert knowledge and input
        - »Identify attributes of PT tendons/bridges that affect likelihood of corrosion damage
        - »Assess consequences associated with an adverse event
          - Redundancy, replaceability (cost), importance
  - –Provide guidance on risk reduction / mitigation strategies based on risk assessment



Expert Elicitation Process

- Expert elicitation is used when data to determine a quantitative POF and consequence measures are unavailable
- Elicitation of expert knowledge:
  - Present scenarios to identify
    - Credible damage modes and deterioration mechanisms
      - Damage mechanisms that will increase the likelihood of corrosion damage
    - Identify Key attributes for reliability/durability
      - Rank attributes in terms of impact on likelihood of corrosion damage
  - Consequence factors
- Consensus process

Expert elicitation: Synthesis of opinions of experts of a subject where there is uncertainty due to insufficient data, or when such data is unattainable.

Reliability Assessment Panel (RAP)

- Analysis was conducted by and expert panel
  - Expert knowledge and experience was used to develop a model for estimating risk
    - Lack of quantitative POF data
  - Familiarity with specific design and construction practices
    - Designs, history, unique circumstances, etc.

RAP team:
ASBI, PCI, FHWA, State DOT, consultants

Risk-Based Inspection (RBI) Process

- **What can go wrong?**
  - –Identify damage modes and deterioration mechanisms
- **How likely is it?**
  - Categorization based on reliability characteristics of bridge elements
  - Based on expert judgment and expert elicitations
    - –Past experience
    - –Analysis of existing or potential damage modes
- **What are the consequences?**
  - –How important is it?
- Semi-quantitative methodology
  - –Results in a “risk model,” i.e. criteria for inspection interval
  - –Rational, based on engineering judgement, data, past experience

Risk-Based Inspection (RBI) Process

- **What can go wrong?**
  - Identify damage modes and deterioration mechanisms
    - ***Corrosion damage requiring tendon replacement*** *was* assumed damage / deterioration mode for PT tendons
    - Damage mechanisms considered in the analysis
      - Breached duct or anchorage
      - Construction and workmanship quality
      - Environment
      - Inadequate specifications and detailing
      - Poor or improper materials
      - Voids in grouted tendons

How likely is it?

- How likely is it that will corrosion damage will occur during normal service life of a tendon?
  - What are its durability/reliability **attributes**?
    - Design characteristics, specifications, exposure, environment, etc.
- Attributes are ranked to develop a scoring process
  - High impact on likelihood of corrosion damage (20 pt scale)
  - Moderate impact on likelihood of corrosion damage (15 pt scale)
  - Low – has a small impact (these attributes were neglected)

Example of Attributes for Risk Assessment

- Damage Mechanism: Voids in grouted tendons
  - –What characteristics (i.e., attributes) of a PT tendon increase the likelihood that a void could form?
    - Tendon profile
    - Proper venting
    - Quality of grout used
    - Grouting procedures used
- RAP identified the most relevant attributes and ranked their impact on the likelihood of a grout void forming

Likelihood Attributes

- 19 Attributes were identified as having a moderate or high impact
- Attributes were divided into 5 categories
  - PT Tendon and Profile
  - PT Tendon Joint and Closure
  - PT System Materials and Components
  - PT Installation Quality
  - Environment

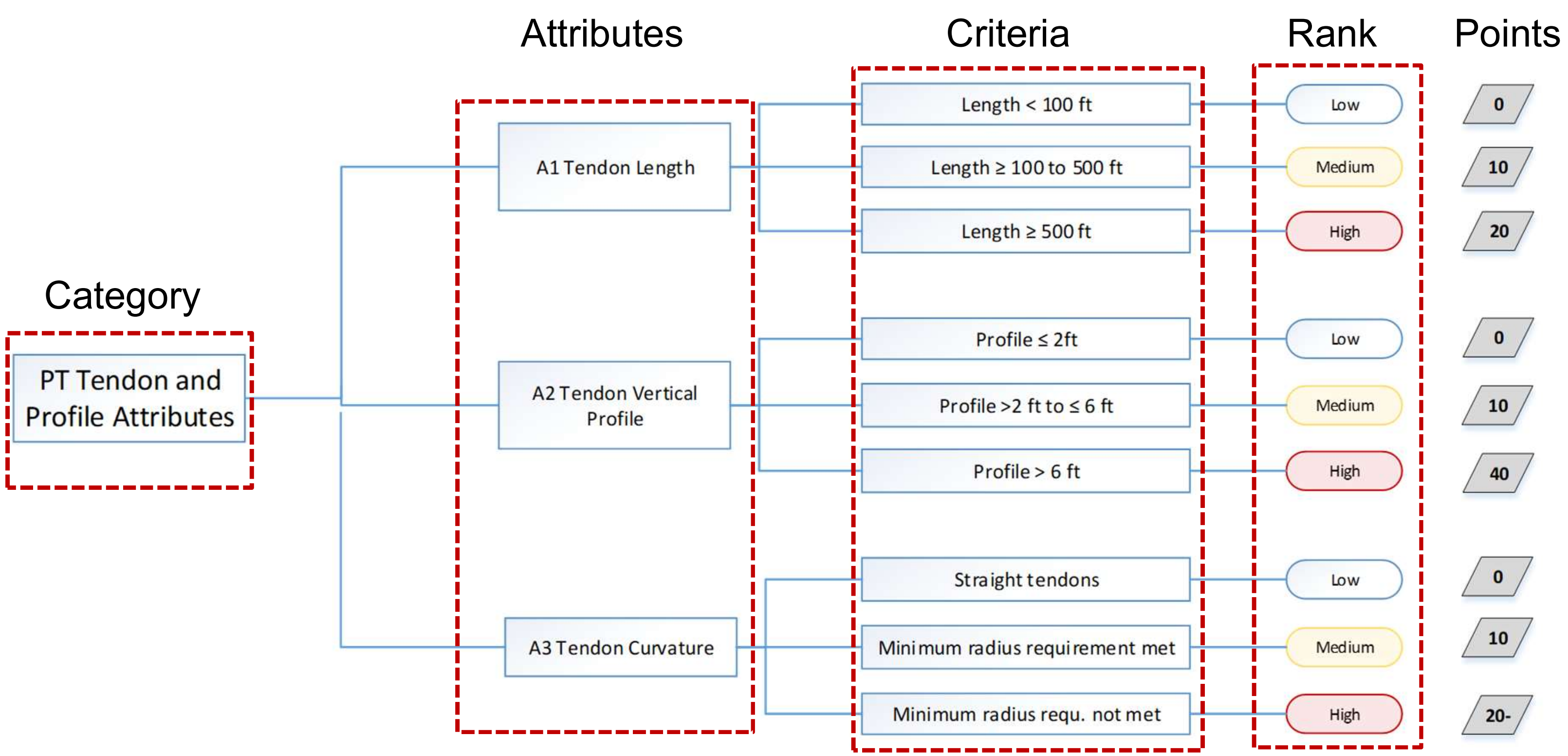
No.	Attributes	Rank
	PT Tendon and Profile Attributes	
A1	Tendon Length	High
A2	Tendon Vertical Profile	Very High
A3	Tendon Curvature	High
A4	Profile Conflict Avoidance	Moderate
	PT Tendon Joint and Closure Attributes	
A5	Cold Joints, Precast Segments	High
A6	Cold Joint, Cast-in-Place (CIP) Segments	Moderate
A7	Closure Pours	High
	PT System Materials and Components Attributes	
A8	Anchorage Protection, Interior	High
A9	Anchorage Protection, Exposed	High
A10	Venting Protection	High
A11	Grout Material Performance	High
A12	Materials Specification	Moderate
A13	Venting	High
A14	Use of Diabolos	High
	PT Installation Quality Attributes	
A15	Construction Quality	High
A16	Quality Assurance	Moderate
A17	Grouting Procedures	High
	Environmental Attributes	
A18	Macro Environment	Very High
A19	Micro or Local Environment	High

Attributes for PT Tendons

- Criteria were developed for each attribute
  - Points assigned again on high, medium, and low scale (generally 100%, 50%, or 0 to start)
- Some changes were made to the weights of certain attributes
  - e.g., Vertical profile, microenvironment, etc.
- Add-ons were used
  - To calibrate and apply engineering judgement
    - Add-ons are additional points assigned to address a situation increasing likelihood
      - E.g., More than two closure pours

No.	Attributes	Rank
	PT Tendon and Profile Attributes	
A1	Tendon Length	High
A2	Tendon Vertical Profile	Very High
A3	Tendon Curvature	High
A4	Profile Conflict Avoidance	Moderate
	PT Tendon Joint and Closure Attributes	
A5	Cold Joints, Precast Segments	High
A6	Cold Joint, Cast-in-Place (CIP) Segments	Moderate
A7	Closure Pours	High
	PT System Materials and Components Attributes	
A8	Anchorage Protection, Interior	High
A9	Anchorage Protection, Exposed	High
A10	Venting Protection	High
A11	Grout Material Performance	High
A12	Materials Specification	Moderate
A13	Venting	High
A14	Use of Diabolos	High
	PT Installation Quality Attributes	
A15	Construction Quality	High
A16	Quality Assurance	Moderate
A17	Grouting Procedures	High
	Environmental Attributes	
A18	Macro Environment	Very High
A19	Micro or Local Environment	High

Example RBI Attributes flow chart



Scoring tool for PT Risk Assessment

- Results were formed into a spreadsheet tool that can be used to score a given tendon attributes
- Drop-down lists are used to select criteria, fills the appropriate score
- Links to commentary are available
  - Describes the purpose of the attribute and how to assign scores

	ANALYSIS NAME:			
	NOTES:			
PT TENDON OCCURRENCE FACTOR				
	PT TENDON GEOMETRY AND PROFILE ATTRIBUTE DATA			
	Attribute	Attribute Characteristic	Score	MAX
A1	Tendon Length	length < 100-ft	0	20
A2	Vertical Profile	2-ft < profile < = 6-ft	20	40
A3	Tendon Curvature	Straight tendon	0	15
A4	Profile Conflict Avoidance	Limited or undesirable detailing	15	15
	PT TENDON JOINT & CLOSURE ATTRIBUTE DATA			
	Attribute	Attribute Characteristic	Score	MAX
A5	Cold Joints, Precast	Continuous duct or bridge without segmental joints	0	20
A6	Cold Joints, CIP	Plastic ducts without duct coupling or metal ducts	15	15
A7	Closure Pours	Adequate spacing for plastic duct couplers, recommended clearance, and resolving alignment	0	20
Q	Number of closure pours crossed:	4+ closure pours	0	
	PT SYSTEM MATERIALS AND COMPONENTS ATTRIBUTE DATA			
	Attribute	Attribute Characteristic	Score	MAX
A8	Anchorage Prot., Interior	Four or more layers of protection	0	15
A9	Anchorage Prot., Exposed	Four layers of protection	0	20
A10	Venting Protection	PTI/ASBI M50, PTI M55 PL-2 is specified	0	20
A11	Grout Materials Performance, Internal	Class B grout	10	20
A11	Grout Materials Performance, External	Class C grout	0	30
A12	Materials Specification	PTI/ASBI M50, PTI M55 specified for duct materials and handling of grout	0	15
A13	Venting	External tendons with proper venting according to PTI/ASBI but high point not vented	10	20
A14	Use of Diablos	Diablos used	0	20
	PT INSTALLATION QUALITY ATTRIBUTE DATA			
	Attribute	Attribute Characteristic	Score	MAX
A15	Construction Quality	PTI/ASBI M50, PTI M55 not specified, without certified personnel for installation, grouting, and inspection	20	20
A16	Quality Assurance	Effective QA to verify materials, records, installation, and personnel qualifications	0	15
A17	Grouting Procedures	PTI/ASBI M50, PTI M55 not specified, no pressure testing of ducts	20	20
	ENVIRONMENTAL ATTRIBUTE DATA			
	Attribute	Attribute Characteristic	Score	MAX
A18	Macro environment	Non-aggressive C-NA1, 2, C-B	0	40
A19	Micro environment	Not applicable	0	0
		LIKELIHOOD OF CORROSION TOTAL SCORE	110	400
		Occurance Factor	0.28	Low
CONSEQUENCE FACTOR				
	Attribute	Attribute Characteristic	Score	MAX
C1	Tendon Importance (System)	System factor > 1.05	10	30
C2	Ease of Tendon Replacement	Bonded internal tendon	30	30
C3	Bridge Importance	Not applicable	NA	0
		CONSEQUENCE TOTAL SCORE	40	60
		CONSEQUENCE FACTOR	0.67	High
		Risk Factor	18	

Example Commentary

A1 Tendon Length (H): Increased tendon length creates an increased likelihood that grout voids may be formed, particularly at intermediate high points. Tendon and grout installation are more challenging for a longer tendon as compared with a shorter tendon; tendons in excess of 500 ft in length can be especially difficult to grout without voids, segregation, or development of soft grout.

Table 1. Table of criteria for A1, Tendon Length.

Criteria	Rank	Score
Tendons length < 100 ft	Low	0
Tendons length ≥100 to <500 ft	Moderate	10
Tendon length ≥ 500 ft	High	20

ANALYSIS NAME:	
NOTES:	

PT TENDON OCCURRENCE FACTOR				
	PT TENDON GEOMETRY AND PROFILE ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A1	Tendon Length	length < 100-ft	0	20
A2	Vertical Profile	2-ft < profile <= 6-ft	20	40
A3	Tendon Curvature	Straight tendon	0	15
A4	Profile Conflict Avoidance	Limited or undesirable detailing	15	15
	PT TENDON JOINT & CLOSURE ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A5	Cold Joints, Precast	Continuous duct or bridge without segmental joints	0	20
A6	Cold Joints, CIP	Plastic ducts without duct coupling or metal ducts	15	15
A7	Closure Pours	Adequate spacing for plastic duct couplers, recommended clearance, and resolving alignment	0	20
Q	Number of closure pours crossed:	4+ closure pours	0	
	PT SYSTEM MATERIALS AND COMPONENTS ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A8	Anchorage Prot., Interior	Four or more layers of protection	0	15
A9	Anchorage Prot., Exposed	Four layers of protection	0	20
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A19	Micro environment	Not applicable	0	0
		LIKELIHOOD OF CORROSION TOTAL SCORE	110	400
		Occurance Factor	0.28	**Low**
CONSEQUENCE FACTOR				
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
C1	Tendon Importance (System)	System factor > 1.05	10	30
C2	Ease of Tendon Replacement	Bonded internal tendon	30	30
C3	Bridge Importance	Not applicable	NA	0
		CONSEQUENCE TOTAL SCORE	40	60
		CONSEQUENCE FACTOR	0.67	High
		Risk Factor	**18**	

Calculating the likelihood

- Individual attribute scores are summed to provide an relative estimate of the likelihood of corrosion damage

$$OF = \sum S_i / \sum S_0$$

- S_i is the score recorded for each attribute and S_0 is the maximum score for each attribute
  - The ratio is a value between 0 and 1
- This score can be placed in 1 of 4 categories for using a risk matrix, or combined with the consequence value if using a risk scale

Consequence Factors

- Presuming the damage occurs, what are the possible consequences?
  - Focuses attention on the damage that is most important
- RAP considered the consequences of tendon corrosion damage in terms of
  - Tendon importance based on system redundancy factors
  - Ease of replacement of a damaged tendon
  - Importance of bridge
    - Key transportation corridor, ADT, etc.
    - Essential bridges, typical, or relatively less important

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Consequence Attributes

- Only 3 consequence attributes were used
  - Redundancy measure
    - Based on available analysis
    - *Tendon importance, system level*
      - *MBE load rating data*
  - Replaceability measure
  - Bridge importance
- Two attributes scored on 30-20-10 scale
  - Nothing has 0 consequence
- Third consequence describes the importance of the bridge in terms of the transportation corridor (ADT, emergency vehicles, key evaluation routes, etc.
  - Scored on a 20-10-0 scale
  - Optional use

Consequence Factors

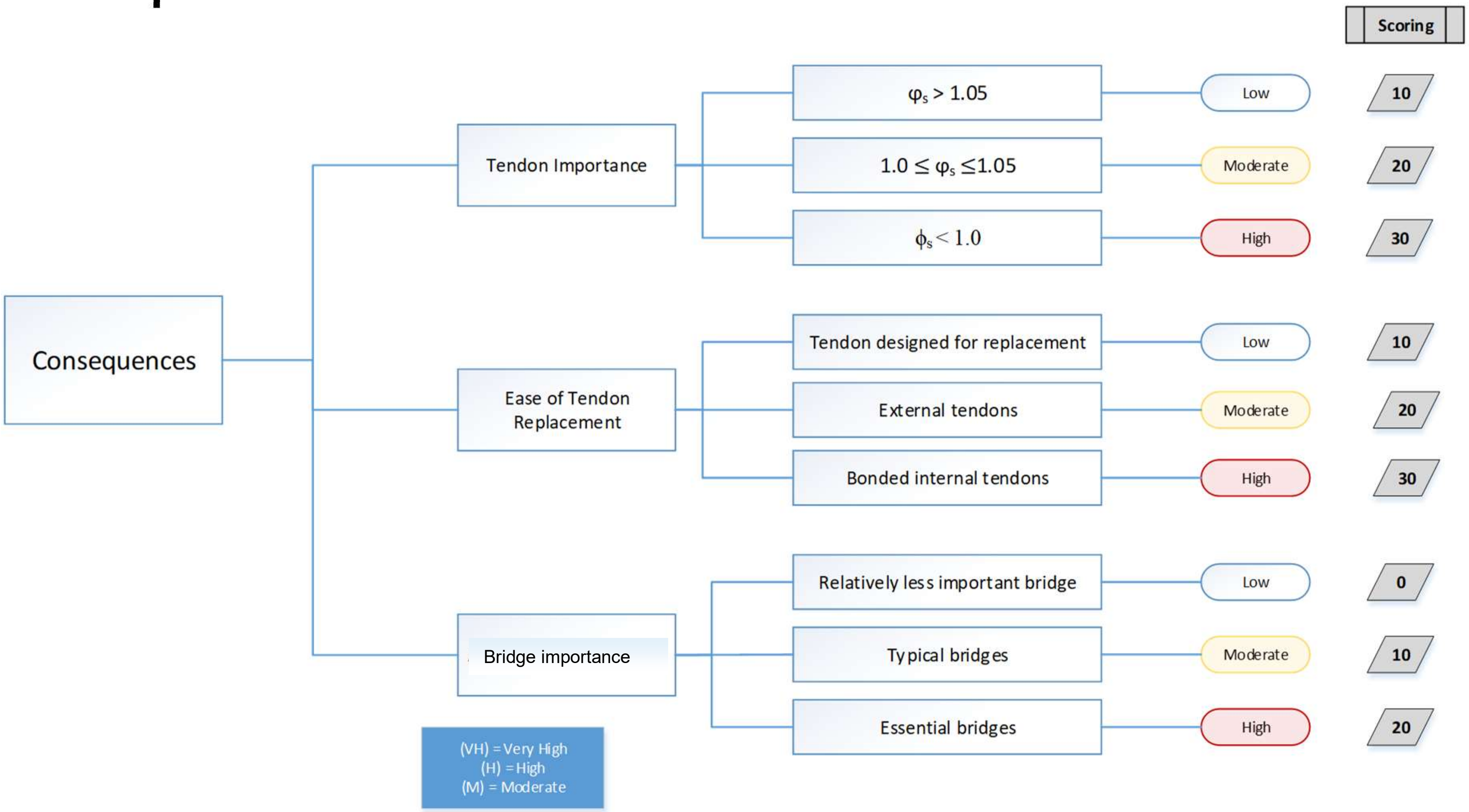
- Consequence Factors
  - C1 and C2 are scored on a 30 pt scale (10, 20, 30)
  - C3 relatively less important, 20 pt scale

CONSEQUENCE FACTOR ATTRIBUTES			
C1	**Tendon Importance (System)**	**Value**	**Max Value**
	System factor > 1.05	10	**30**
	1.0 < System Factor < 1.05	20	
	System Factor < 1.0	30	
C2	**Ease of Tendon Replacement**		
	Tendon designed for replacemer	10	**30**
	External tendon	20	
	Bonded internal tendon	30	
C3	**Bridge Importance**		
	Relatively less important bridge	0	**20**
	Typical Bridges	10	
	Essential Bridges	20	
	Not applicable	NA	

$$CF = \sum C_i \Big/ \sum C_0$$

- C_i is the score recorded for each attribute
- C_0 is the maximum score for each attribute

Consequence Factors

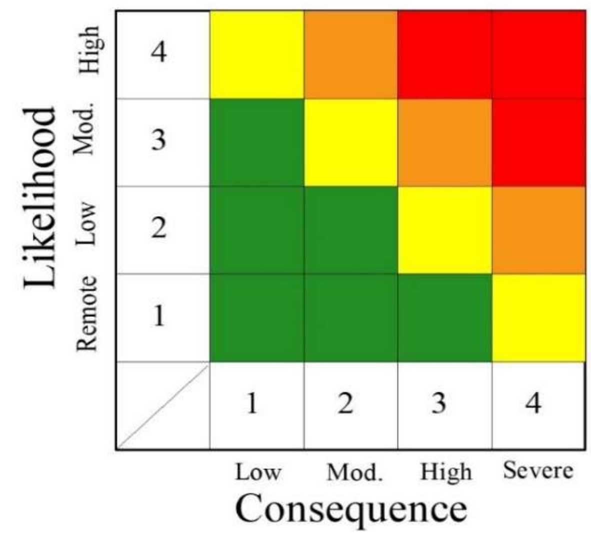


Risk Matrix

$$CF = \sum C_i \Big/ \sum C_0 * 4$$

$$OF = \sum S_i \Big/ \sum S_0 * 4$$

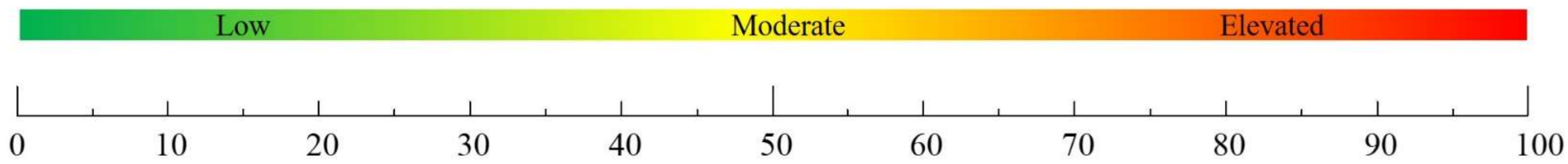
- Results can be plotted on a risk matrix
  - Components in the top right corner are "high risk"
- OF plotted on the vertical axis, consequence on the horizontal
- Increased risk toward upper right, reduced risk toward lower left



Risk Scale

- Provides for a continuum of risk measures
  - Values from 1 to 100

  Risk Factor = $OF * CF * 100$
- Increased resolution as compared with a risk matrix
  - Matrix = 16 possible risk levels
  - Risk Factor Scale = Values from 1 to 100
- Risk levels defined by engineering judgement
  - Thresholds from low, moderate, or elevated risk



Methodology for Risk Assessment of PT Tendons

RISK ASSESSMENT CALIBRATION

How was the risk model calibrated?

- A **sensitivity study** was conducted to assess the scoring process and weights for individual attributes
  - 8 reference cases with different design and environmental conditions
    - Tendon length (A1)
    - Vertical profile (A2)
    - Tendon curvature (A3)
    - Profile conflict avoidance (A4)
    - Cold joints (A5, A6)
    - Closure pours (A7)
    - Macro Environment (A18)
    - Micro or local environment (A19)

Sensitivity Study

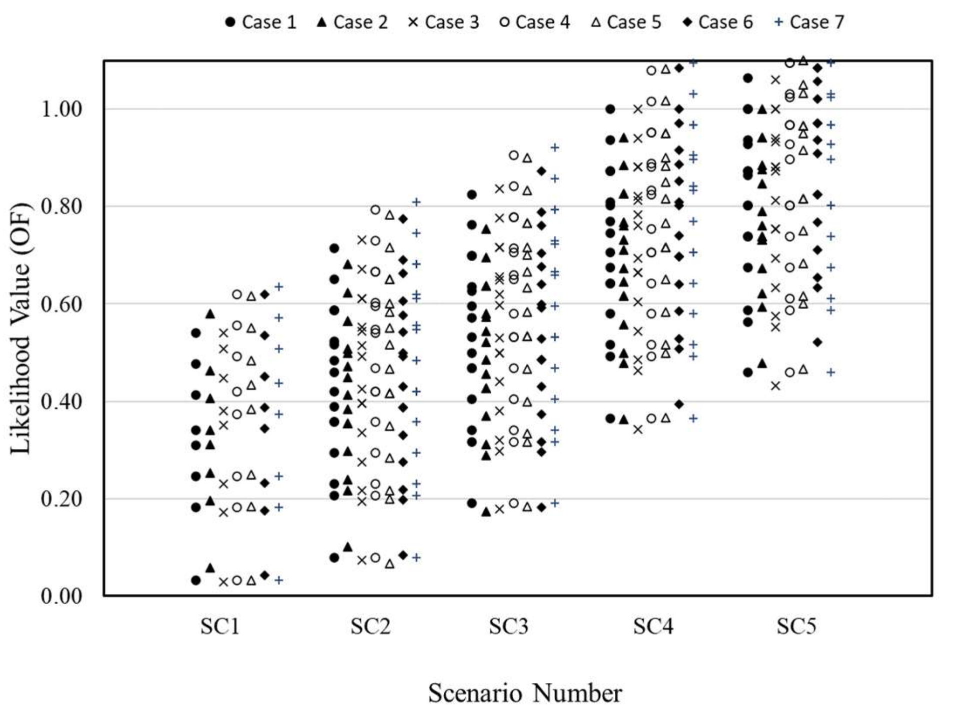
- 5 Different Scenarios were modeled
  - SC1: Base case, PL 2, PTI/ASBI specifications followed
  - SC2: PL2, poor quality attributes
  - SC3: PL2, PTI/ASBI specifications not followed, poor quality
  - SC4: PL1, PTI/ASBI specifications not followed, poor quality
  - SC5: PL1, PTI/ASBI specifications not followed, poor quality, metal ducts
- Generally, the scenarios described increasing risk of corrosion damage

Sensitivity Study

- 7 Different scoring approaches were tested
  - Different weights for key attributes
    - Increasing the weight of key attributes
    - Consider increase likelihood of corrosion damage as a result of
      - Multiple closure pours
      - Coupling of macro and micro environmental attributes
        - » Exposed anchorages have increased likelihood of corrosion damage in an aggressive environment as compared with a benign environment

Sensitivity Study

- In total, 504 different cases for the occurrence factor were studied
  - Increasing values of OF
  - Optimum scoring case identified (case 7)

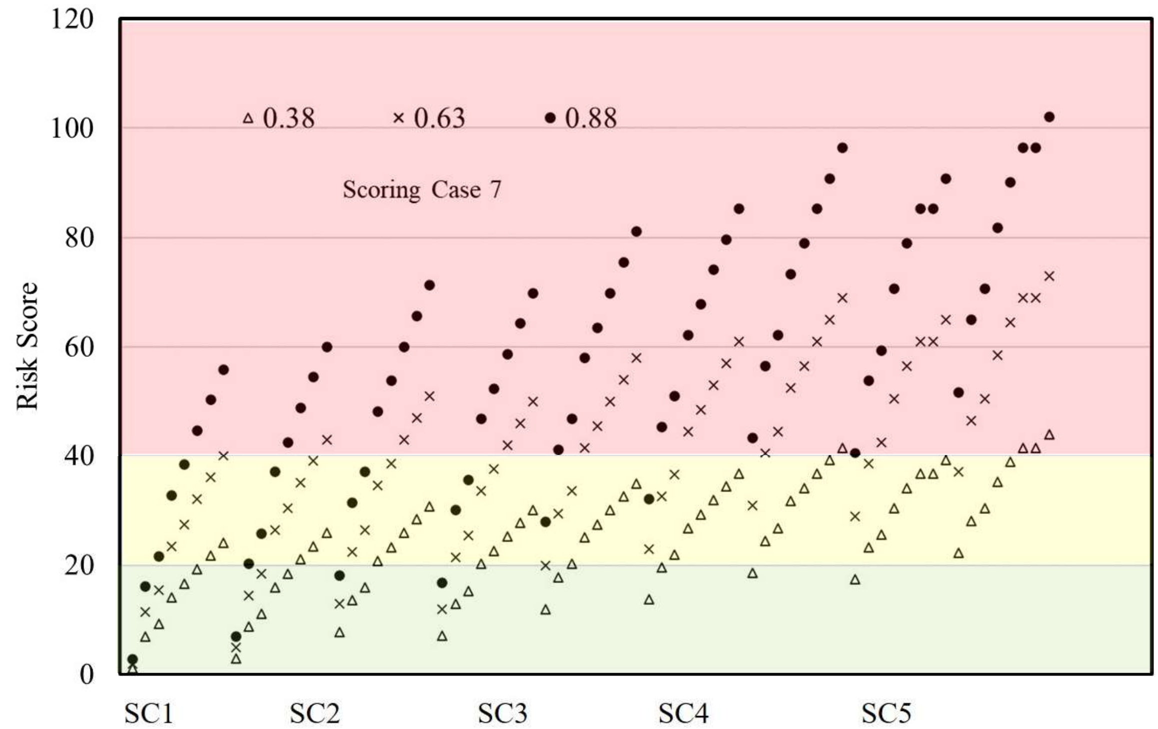


Sensitivity Study

- Different approaches for the Consequence factor examined
  - Different values for CF attributes
  - Different weights for CF attributes
  - Different number of CF attributes (2 or 3)
- Different levels of the resulting CF were considered (low, moderate and high)
- Combined with scoring case 7 and five scenarios of increasingly unprotected tendons
- Provide the range of possible risk levels
  - Select threshold values based on engineering judgement

Sensitivity Study

- Results were used to set risk thresholds
  - –Engineering judgement
  - –Experience
- Three different levels of consequence (low, moderate, and high)



Methodology for Risk Assessment of PT Tendons

RISK ASSESSMENT PROCESS
STEPS FOR CONDUCTING THE RISK ASSESSMENT

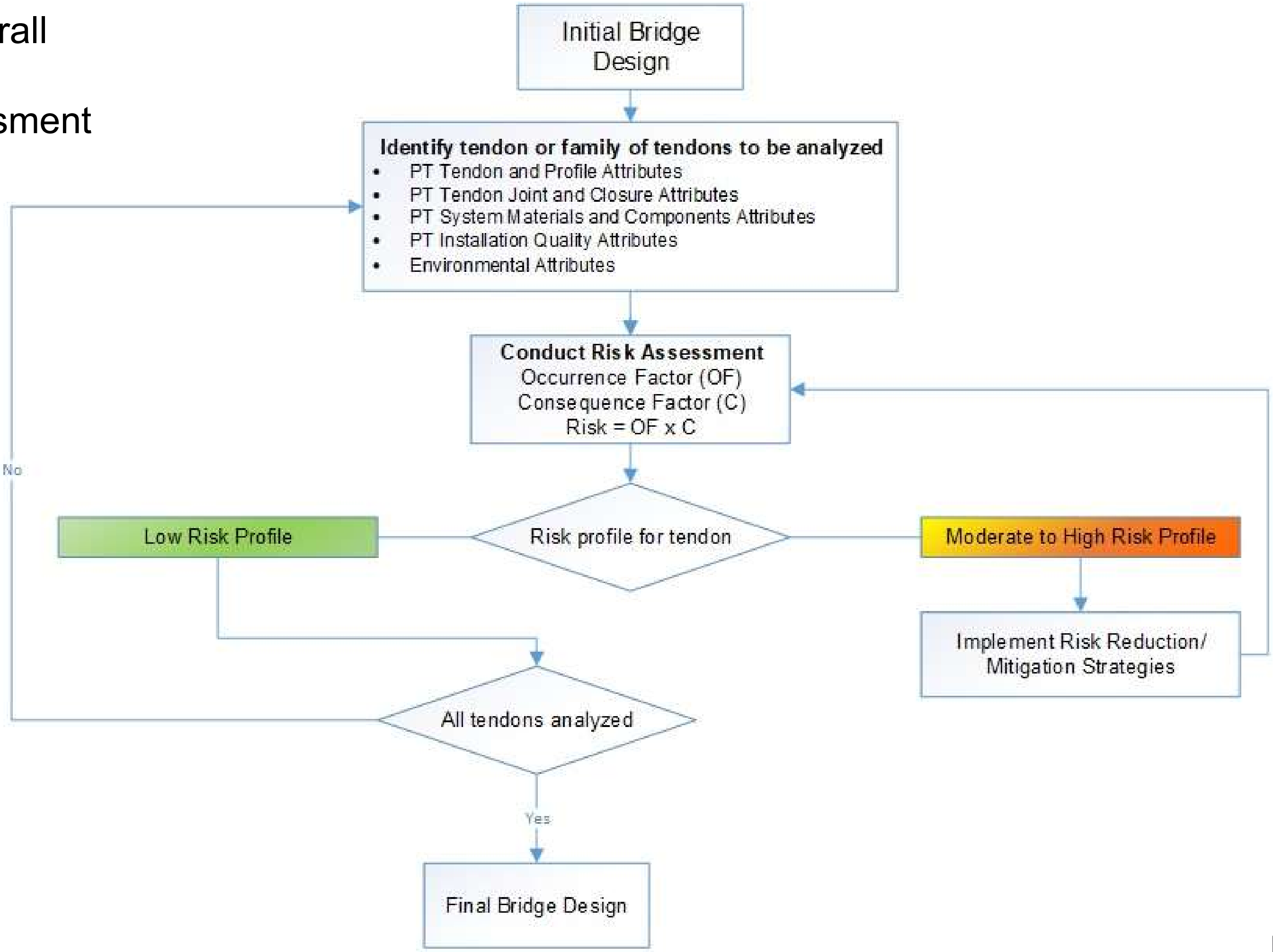
Risk Assessment Process

- Learning Objectives
  - Understands the steps required to complete a PT tendon risk assessment
  - Apply the methodology for risk assessment of PT tendons

Steps for Risk Assessment of PT Tendons

- Initial design of bridge including the specifications to be used in construction
- Select a tendon or family of tendons of similar design
  - Identify attributes
    - PT Tendon and Profile Attributes
    - PT Tendon Joint and Closure Attributes
    - PT System Materials and Components Attributes
    - PT Installation Quality Attributes
    - Environmental Attributes
- Conduct Risk Assessment
  - Risk = OF x C

Flow chart showing the overall process for using the methodology for risk assessment



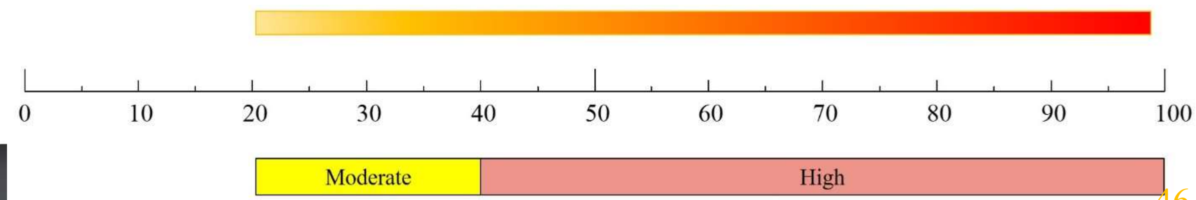
Scoring

- Likelihood attributes (Occurrence Factor)
  - Like golf, high score is bad, low score is good
  - Scoring is a simple summation
    - Points scored/total points available
  - Total available points for a given attribute expresses its weight
    - For example
      - Tendon vertical profile and Macro Environment was scored on a 40-point scale,
      - Quality assurance methods on a 15-point scale

PT TENDON OCCURRENCE FACTOR				
	PT TENDON GEOMETRY AND PROFILE ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A1	Tendon Length	length < 100-ft	0	20
A2	Vertical Profile	Profile > 6-ft	40	40
A3	Tendon Curvature	Straight tendon	0	15
A4	Profile Conflict Avoidance	Limited or undesirable detailing	15	15
	PT TENDON JOINT & CLOSURE ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A5	Cold Joints, Precast	Continuous duct or bridge without segmental joints	0	20
A6	Cold Joints, CIP	Plastic ducts without duct coupling or metal ducts	15	15
A7	Closure Pours	Adequate spacing for plastic duct couplers, recommended clearance, and resolving alignment	0	20
Q	Number of closure pours crossed:	4+ closure pours	0	
	PT SYSTEM MATERIALS AND COMPONENTS ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A8	Anchorage Prot., Interior	Four or more layers of protection	0	15
A9	Anchorage Prot., Exposed	Four layers of protection	0	20
A10	Venting Protection	PTI/ASBI M50, PTI M55 PL-2 is specified	0	20
A11	Grout Materials Performance, Internal	Class B grout	10	20
A11	Grout Materials Performance, External	Class C grout	0	30
A12	Materials Specification	PTI/ASBI M50, PTI M55 specified for duct materials and handling of grout	0	15
A13	Venting	External tendons with proper venting according to PTI/ASBI but high point not vented	10	20
A14	Use of Diablos	Diablos used	0	20
	PT INSTALLATION QUALITY ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A15	Construction Quality	PTI/ASBI M50, PTI M55 not specified, without certified personnel for installation, grouting, and inspection	20	20
A16	Quality Assurance	Effective QA to verify materials, records, installation, and personnel qualifications	0	15
A17	Grouting Procedures	PTI/ASBI M50, PTI M55 not specified, no pressure testing of ducts	20	20
	ENVIRONMENTAL ATTRIBUTE DATA			
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
A18	Macro environment	Non-aggressive C-NA1, 2, C-B	0	40
A19	Micro environment	Not applicable	0	0
		LIKELIHOOD OF CORROSION TOTAL SCORE	130	400
		Occurance Factor	0.33	Low
CONSEQUENCE FACTOR				
	Attribute	**Attribute Characteristic**	**Score**	**MAX**
C1	Tendon Importance (System)	System factor > 1.05	10	30
C2	Ease of Tendon Replacement	Bonded internal tendon	30	30
C3	Bridge Importance	Not applicable	NA	0
		CONSEQUENCE TOTAL SCORE	40	60
		CONSEQUENCE FACTOR	0.67	Moderate
		Risk Factor	22	

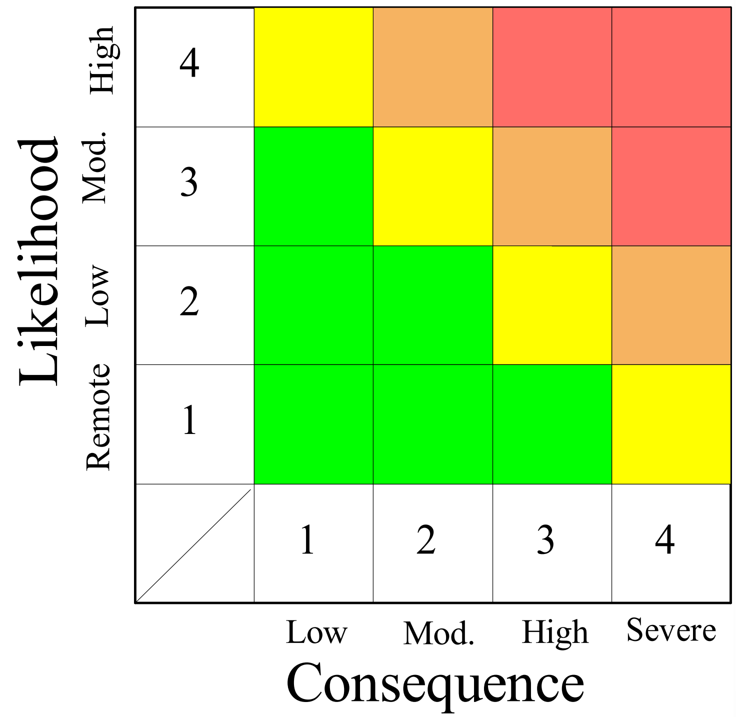
Steps for Risk Assessment of PT Tendons

- Determine the risk factor for each tendon or family of tendons with similar design characteristics
- Using the resulting risk factor, locate the tendon on the risk scale
- If moderate or high risk profile is found, consider risk mitigation or reduction technology
- *Risk Factor* = $OF * CF * 100$



Steps for Risk Assessment of PT Tendons

- A risk matrix can also be used for estimating the risk level
  - Scoring is completed for an individual tendon based on its design and project qualities
  - The resulting score from likelihood attributes is an Occurrence Factor (OF) ranging from 0 to 1
  - The resulting score from the consequence attributes is a Consequence factor, again a value between 0 and 1
  - Multiply by 4 and apply to a risk matrix



Risk Reduction / Mitigation technologies

– Moderate or High Risk Profile
- Implement risk mitigation strategy
  - Electrically Isolated Tendons (EIT)
  - Stainless steel strand
  - Carbon fiber strand
  - Galvanized strand
  - Corrosion-Inhibitor tendon impregnation
- Implement risk reduction
  - Replaceable tendons
  - Increase number of tendons
  - Full adoption of: PTI/ASBI M50.3-19 [1], PTI M55-1.19 [2]
  - Enhanced QC/QA
  - Vacuum-assisted grouting
  - Include additional layers of protection
  - Structural Health Monitoring

Risk Reduction Strategies

- Risk reduction strategies can be used to reduce the risk profile score (reduced value of attribute scores)
- Table lists attributes for which scores would be affected by different risk reduction strategies

Technology	Related Attributes
Increase number of tendons	C1
Replaceable tendons	C2
Full adoption of: PTI/ASBI M50.3-19 PTI M55-1.19	A10, A11, A12, A13, A15, A17
Enhanced QC/QA	A16
Vacuum-assisted grouting	A1, A2, A11, A13, A14 A17
Include additional layers of protection	A8, A9, A10,
Structural Health Monitoring	-

Risk Mitigation Strategies

- Eliminate or reduce significantly the likelihood of corrosion damage in the tendon
  - –Mitigate the risk
    - Electrically Isolated Tendons (EIT)
    - Stainless steel strand
    - Carbon fiber strand
    - Galvanized strand
    - Corrosion-Inhibitor tendon impregnation

Post Tensioning Technology Selection for Durability Guidance

ATTRIBUTES FOR PT TENDONS
DESCRIPTIONS OF INDIVIDUAL ATTRIBUTES

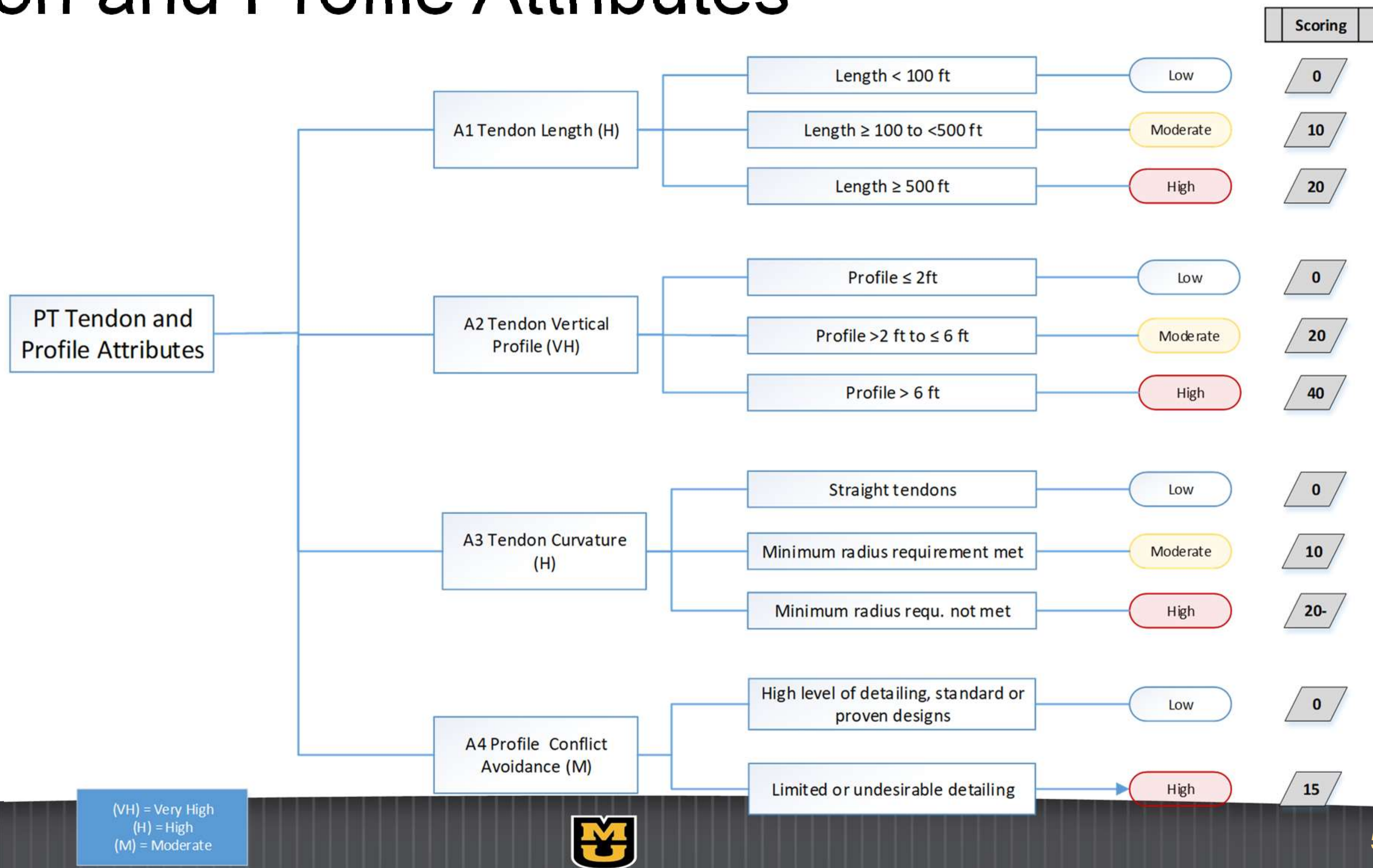
Attributes for PT Tendons

- Learning Objectives
  - Understand each of the attributes used to score the OF (likelihood) for risk assessment
  - Evaluate attribute criteria to assign the appropriate score
  - Analyze a tendon to determine the OF

Post Tensioning Technology Selection for Durability Guidance

PT TENDON AND PROFILE ATTRIBUTES

PT Tendon and Profile Attributes



PT Tendon and Profile Attributes

- A1 Tendon Length (H):
  - Increased tendon length creates an increased likelihood that grout voids may be formed, particularly at intermediate high points.

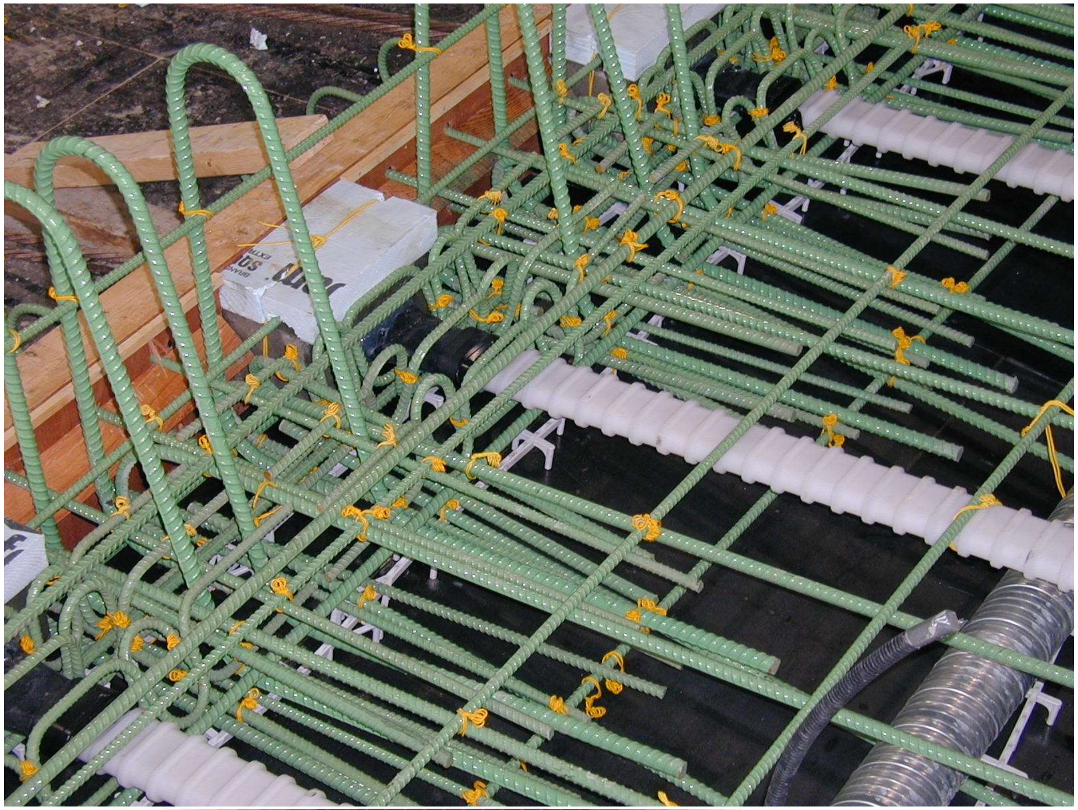
- A2 Vertical Profile (VH)
  - Tendons with a straight or nearly straight profile typically have a reduced risk of the voids forming as compared with tendons with a high profile.

PT Tendon and Profile Attributes (cont.)

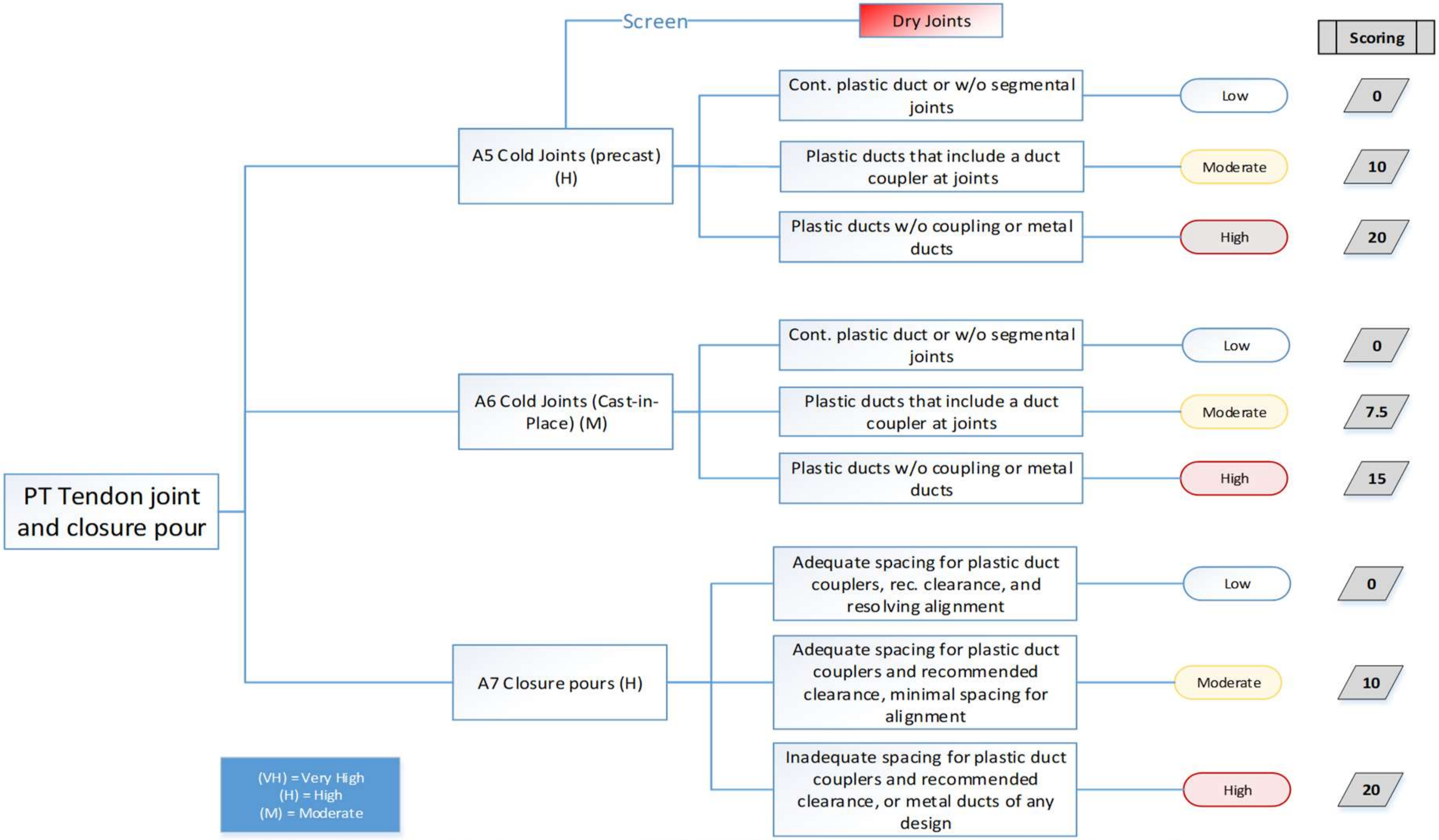
- A3 Tendon Curvature (H)
  - Tendon curvature increases the likelihood of incomplete grouting or breaching of the duct due to construction errors, damage such as abrasion, or kinking of the duct.

- A4 Profile Conflict Avoidance (M)
  - This attribute is intended to capture the increased risk of duct and anchorage breach when there are conflicts in the location of ducts and reinforcement during the construction of PT bridges.

PT Tendon Joint and Closure Attributes



PT Tendon Joint and Closure Attributes



PT Tendon Joint and Closure Attributes

- A5, A6 Cold Joints
  - Describes the resistance of the joint treatment to the entry of corrosive materials
  - This attribute depends on the use of duct couplers to ensure water tightness of the duct at joints, and/or the inherent risks of leakage associated with metal ducts.
  - Includes the increased potential impact for pre-cast sections as compared with cast-in-place
    - Increased risk with precast construction
  - Screens out any dry pre-cast joints

PT Tendon Joint and Closure Attributes

- Cold Joints (cont.)
  - A5 – Precast construction (H)
    - Screening out dry joints from risk assessment
      - Not currently an accepted practice
      - Likelihood of corrosion damage is always “High”
    - Scored on a 20 pt scale
  - A6 – Cast-in-Place construction (M)
    - Scored on a 15 pt scale

PT Tendon Joint and Closure Attributes

- A7 Closure Pours (H)
  - The likelihood of water ingress into a duct can be increased by the construction joints introduced at closure pours
    - Clearance provided for installing couplers and sealers
    - Providing adjustments to alignment
    - Metal ducts are susceptible to breach
- Additional points are assigned if there are 3 or more closer pours
  - Each closure pour presents independent likelihood of breaching, therefore more pours = increased likelihood

PT Materials and Components Attributes

PT Materials and Components Attributes

- Seven attributes associated with PT materials and components
  - A8 Anchorage Protection, Interior (H)
  - A9 Anchorage Protection, Exposed (H)
  - A10 Venting Protection (H)
  - A11 Grout Material Performance (H)
  - A12 Materials Specification (M)
  - A13 Venting (H)
  - A14 Use of Diabolos (H)

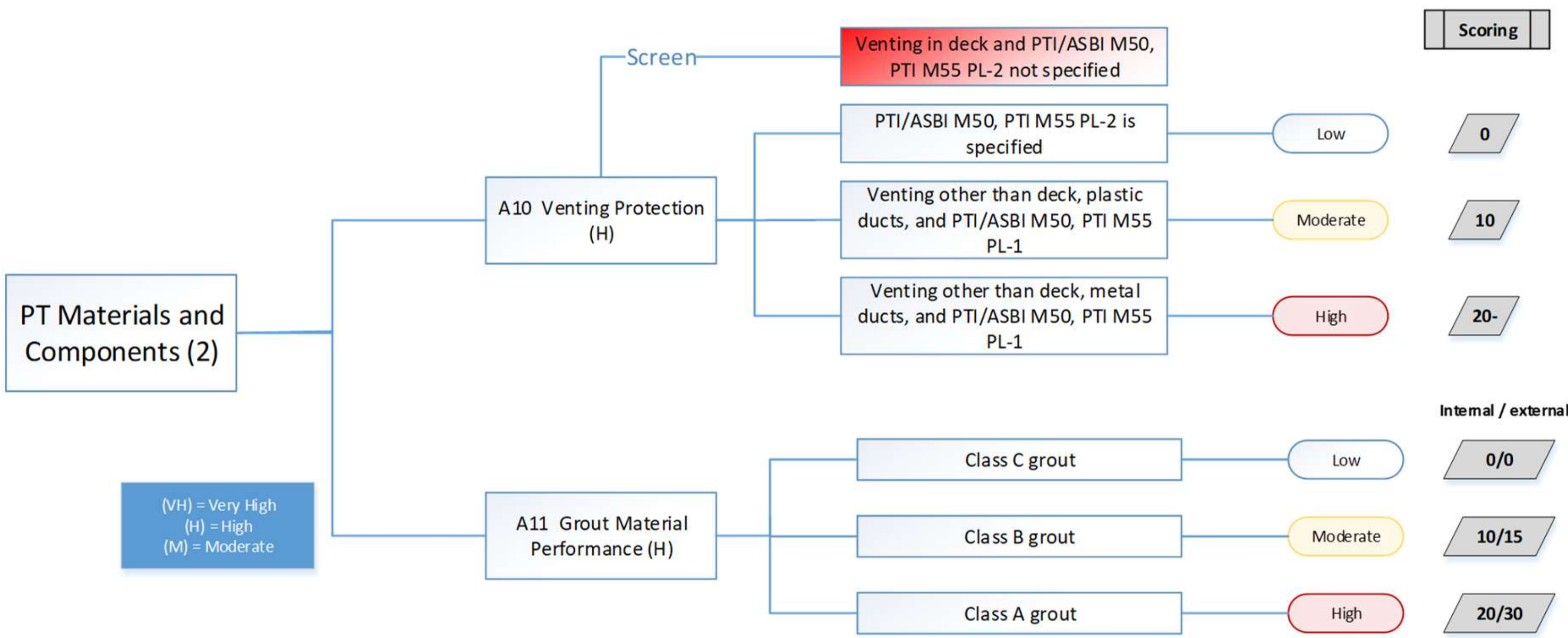
PT Materials and Components Attributes

- Anchorage Protection
  - A8 Anchorage Protection, Interior (H)
    - For interior anchorages
      - Additional layers of protection could include grout, permanent heavy-duty sealed grout cap, an applied coating, and a pourback (PL-2)
      - (See PTI/ASBI M50 Section 3.0, Appendix A)
  - A9 Anchorage Protection, Exposed (H)
    - For anchorages not fully enclosed by the structure
      - Expansion joints or exterior faces
      - Four possible layers of protection include grout, permanent heavy-duty sealed grout cap, an applied coating, and a pourback. (See PTI/ASBI M50 Section 3.0, Appendix A)

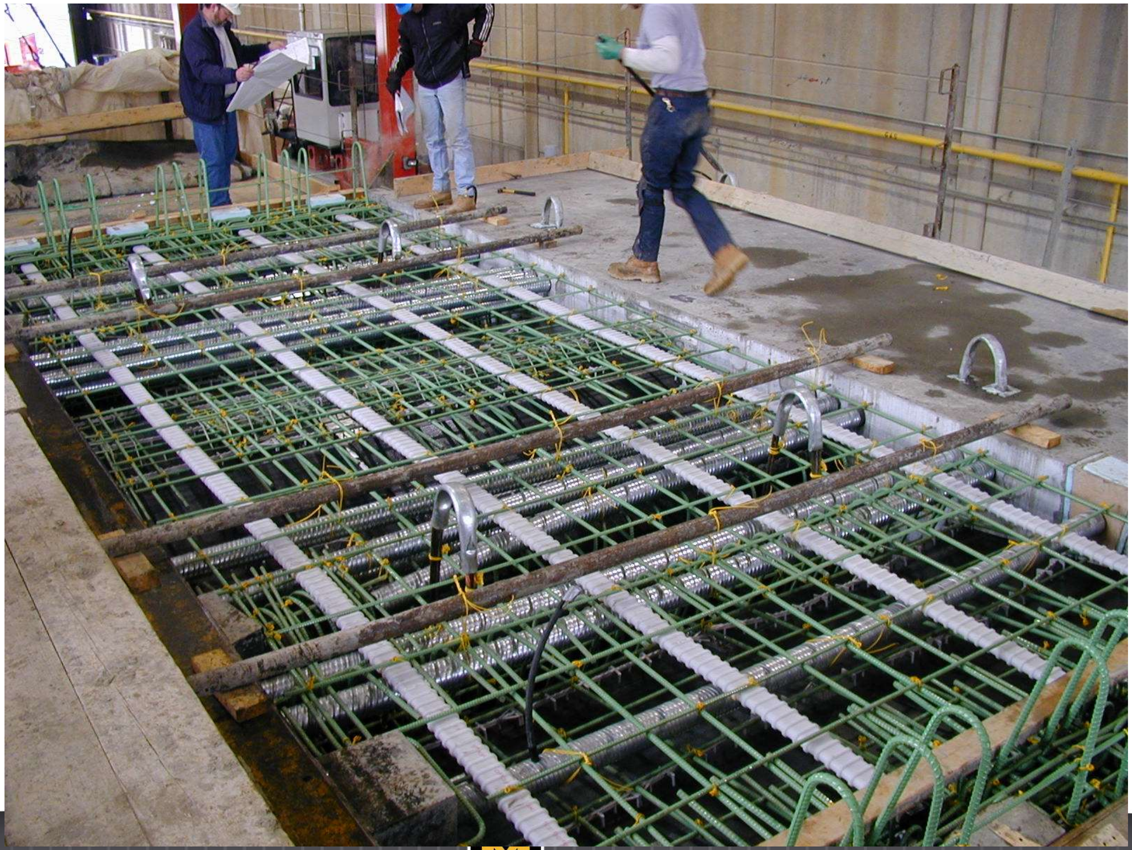
PT Materials and Components Attributes

- Venting protection and Grout
  - A10 Venting Protection (H)
    - This attribute considers the sealing of grout inlet/outlet locations along the duct
    - The criteria reflect the generally increased likelihood of metal ducts being breached as compared with a plastic duct.
    - Screening criteria when venting in deck and appropriate specifications not applied.
  - A11 Grout Material Performance (H)
    - Reflects the increased likelihood of corrosion damage due to poor quality grout.

PT Materials and Components Attributes

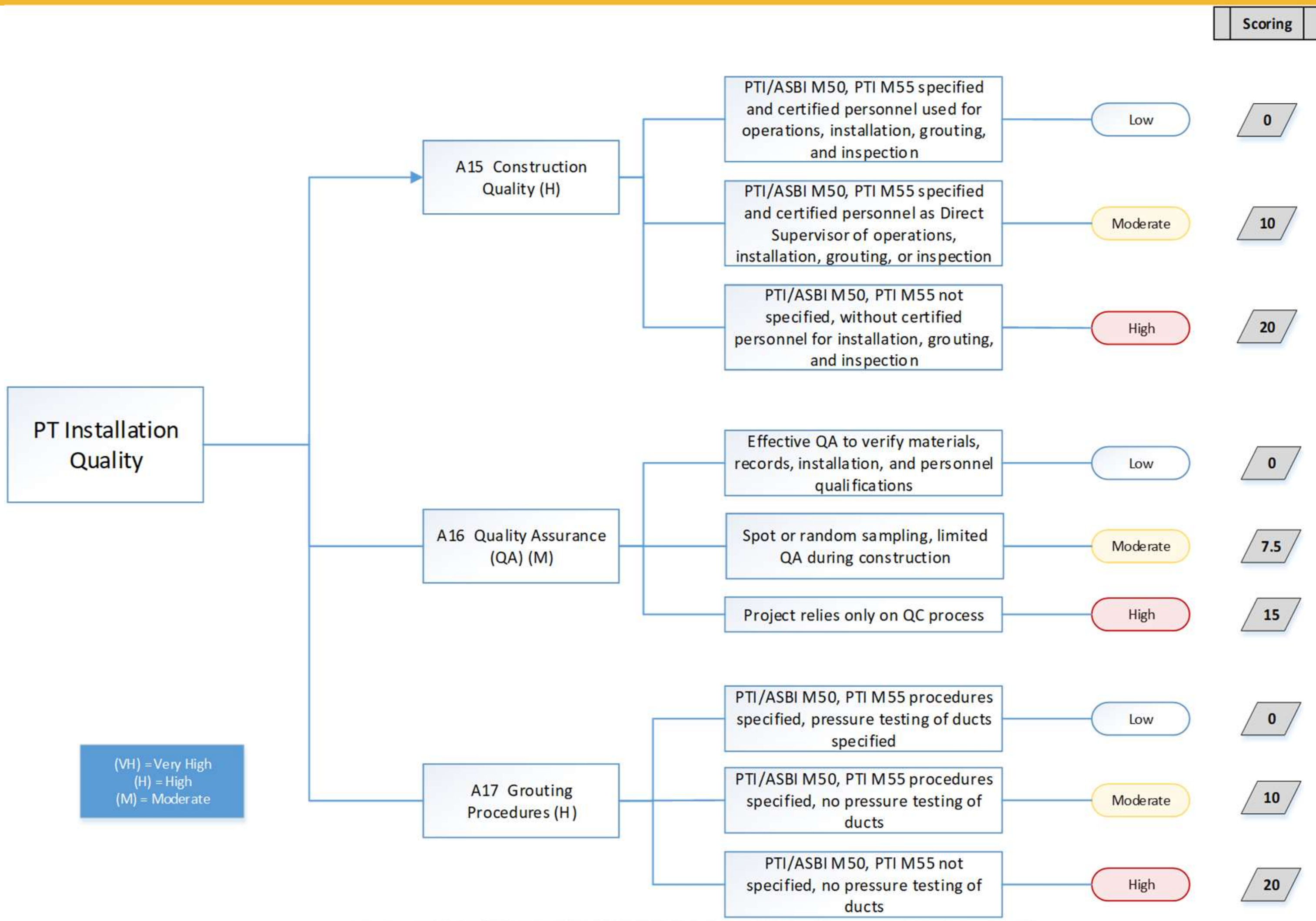


PT Installation Quality Attributes



PT Installation Quality Attributes

- Venting protection and Grout
  - A15 Construction Quality (H)
    - This attribute describes the quality of the construction process in terms of corrosion prevention of the PT system. Generally, this attribute identifies if the recommended practices of PTI/ASBI 50/ PTI 55 are followed and if certified personnel are used during the grouting process.
  - A16 Quality Assurance (QA) (M)
    - This attribute is intended to capture the improved reliability of corrosion prevention when effective quality assurance measures are used during the construction process.
  - A17 Grouting Procedures (H)
    - Proper grouting procedures reduce the likelihood of grout voids forming during the installation process in PT tendon ducts.


Scoring
PT Installation Quality
A15 Construction Quality (H)
PTI/ASBI M50, PTI M55 specified and certified personnel used for operations, installation, grouting, and inspection
Low
0
PTI/ASBI M50, PTI M55 specified and certified personnel as Direct Supervisor of operations, installation, grouting, or inspection
Moderate
10
PTI/ASBI M50, PTI M55 not specified, without certified personnel for installation, grouting, and inspection
High
20
A16 Quality Assurance (QA) (M)
Effective QA to verify materials, records, installation, and personnel qualifications
Low
0
Spot or random sampling, limited QA during construction
Moderate
7.5
Project relies only on QC process
High
15
A17 Grouting Procedures (H)
PTI/ASBI M50, PTI M55 procedures specified, pressure testing of ducts specified
Low
0
PTI/ASBI M50, PTI M55 procedures specified, no pressure testing of ducts
Moderate
10
PTI/ASBI M50, PTI M55 not specified, no pressure testing of ducts
High
20
(VH) = Very High
(H) = High
(M) = Moderate

Environmental Attributes

Environmental Attributes

- A18 Macro Environment (VH):
  - This attribute is being described by the environmental classification included in the AASHTO Guide Specification for Service Life Design Construction Quality (H).

Criteria	Rank	Score
C-NA2 Other exterior exposure C-NA1 Interior exposure C-B Buried	Low	0
C-D1 Atmospheric in deicing salt environment C-D2 Indirect deicing salts C-M2 Marine submerged C-M1 Marine atmospheric	Moderate	20
C-D4 Direct deicing salt (High) C-D3 Direct deicing (low) C-M3 Marine tidal/splash zone	High	40

Environmental Attributes

- A19 Micro or Local Environment (H)
  - This attribute is intended to capture the increased environmental exposure for tendons with direct exposure to water and deicing chemicals such as those located at or near expansion joints, ¼ pt hinges, or positioned in the deck of a box girder.
  - The attribute is scored based on attribute A18, Macro Environment.
    - If the macro environment is rated as low, the micro environment is scored as 0 points.
    - If the Macro Environment is moderate or high, the value of the microenvironment is 50% or 75% of the value of A18, respectively.

Post Tensioning Technology Selection for Durability Guidance

EXAMPLE
APPLICATION OF THE METHODOLOGY TO A SAMPLE BRIDGE

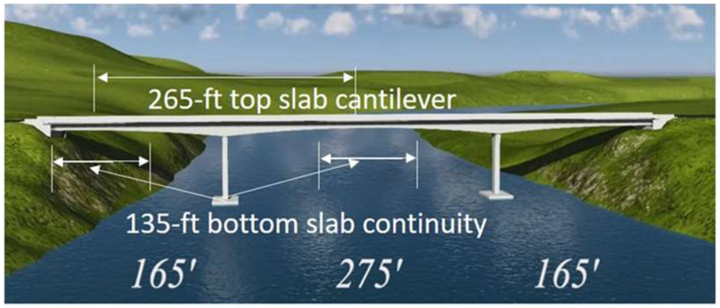
Example Bridge

- Learning Objectives
  - Synthesize the elements of the risk assessment
  - Apply the risk assessment to an example bridge
  - Understand the implementation of the guidelines

Example Bridge

- Precast segmental bridge
- Consider two cases
  - Case 1: Current best-practices are used, PL2 with plastic ducts
  - Case 2: Current best-practices not used, PL1 with plastic ducts
- Compare the risk values from the two cases

A



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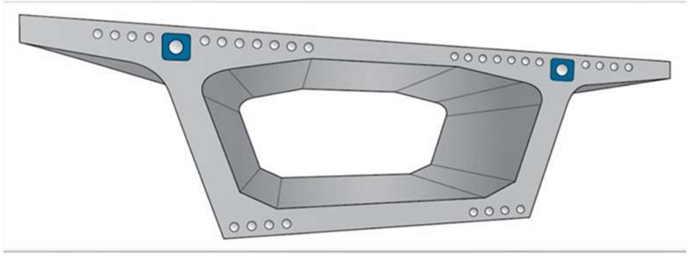

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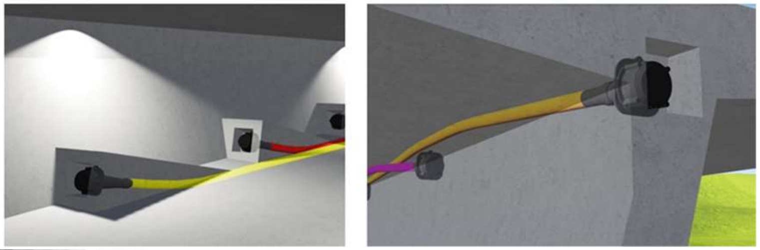


Example Bridge – Precast Segmental Bridge

Tendon Attributes (case 1 & 2)

- Tendon Length = 135/265 ft
- Profile < 2 ft of elevation change
- 1 closure pour, mid-span
- Macroenvironment: Moderate
- Grout material: Class C grout
- Macro Environment: Moderate
- Micro Environment: Not exposed

Consequence Attributes (case 1 & 2)

- Tendon Importance: Low, 4 tendons per web
- Ease of replacement: High, bonded internal tendons
- Bridge Importance: Typical

Case 1 – High Level of corrosion protection

- PTI/ASBI M50, PTI M55 PL-2 is specified
- At least four levels of protection
- Proper venting for all ducts
- Effective QA implemented to verify records, installation, and personnel qualification
- Pressure testing of ducts completed to ensure water-tight plastic ducts

Key Attributes

Attribute	Criteria
A8, Anch. Prot., Int.	Four layers of protection
A9, Anch. Prot, Ext.	Four layers of protection
A10, Venting protection	PTI/ASBI M50, PTI M55 PL-2 is specified
A12, Materials Specification	PTI/ASBI M50, PTI M55 specified for duct materials and handling of grout
A13, Venting	Tendons with proper venting according to PTI/ASBI and all high points vented
A15, Construction Quality	PTI/ASBI M50, PTI M55 specified and certified personnel used for operations, installation, grouting, and inspection
A16, Quality Assurance	Effective QA to verify materials, records, installation, and personnel qualifications
A17, Grouting Procedures	PTI/ASBI M50, PTI M55 procedures specified, pressure testing of ducts specified

Occurrence Factor Calculation

Case 1

	Attribute	Attribute Characteristic	Score
A1	Tendon Length	100-ft <= length < 500-ft	10
A2	Vertical Profile	Profile < =2-ft	0
A3	Tendon Curvature	Minimum radius of bending requirements met	15
A4	Profile Conflit Avoidance	High level of detailing to avoid geometric conflicts, use of standard or proven designs.	0
A5	Cold Joints, Precast	Plastic ducts that include a duct coupler at joints	10
A7	Closure Pours	Adequate spacing for plastic duct couplers, recommended clearance, and resolving alignment	0
A8	*Anchorage Prot., Interior*	*Four or more layers of protection*	0
A9	*Anchorage Prot., Exposed*	*Four layers of protection*	0
A10	*Venting Protection*	*PTI/ASBI M50, PTI M55 PL-2 is specified*	0
A11	Grout Materials Performance, Internal	Class C grout	0
A12	Materials Specification	*PTI/ASBI M50, PTI M55 specified for duct materials and handling of grout*	0
A13	Venting	*Tendons with proper venting according to PTI/ASBI and all high points vented*	0
A15	Construction Quality	PTI/ASBI M50, PTI M55 specified and certified personnel used for operations, installation, grouting, and inspection	0
A16	Quality Assurance	Effective QA to verify materials, records, installation, and personnel qualifications	0
A17	Grouting Procedures	PTI/ASBI M50, PTI M55 procedures specified, pressure testing of ducts specified	0
A18	Macro environment	Moderately aggressive, C-D1,2, C-M1,2	20
A19	Micro environment	Not applicable	NA
		Total	55/345
		Occurrence Factor	**0.16**

Example Bridge Case 1

- The OF factor is 0.16, remote likelihood of corrosion damage
- The consequence factor is determined to be 0.67, High
  - System factor > 1.05 (low)
  - Bonded internal tendons
    - Expensive if replacement is needed
    - High
  - Bridge importance: Typical
- Risk factor = **11 -** Low risk for corrosion damage

Example Bridge Case 2

- PL 1 is used, typical QA processess

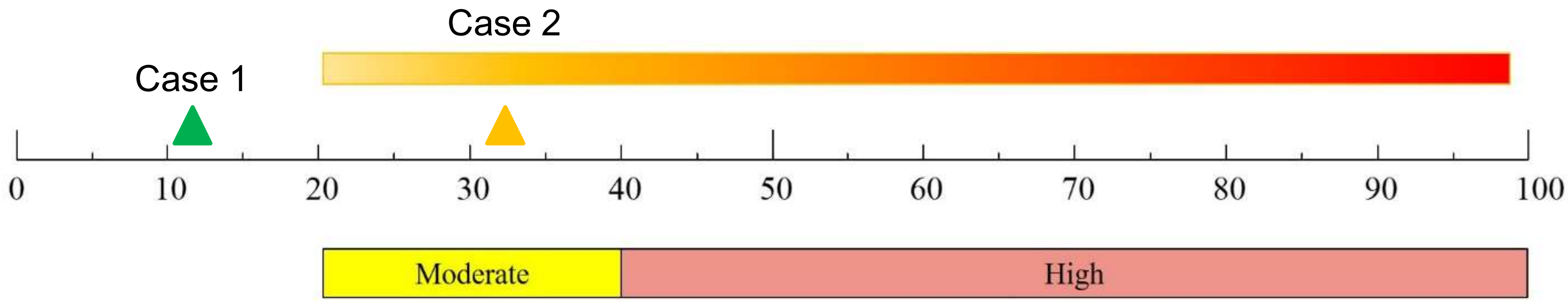
Attribute	Criteria
A8, Anch. Prot., Int.	Two layers of protection
A9, Anch. Prot, Ext.	Less than three layers of protection
A10, Venting protection	Venting other than deck, plastic ducts, and PTI/ASBI M50, PTI M55 PL-1
A12, Materials Specification	PTI/ASBI M50, PTI M55 not specified for duct materials and handling of grout
A13, Venting	Improper or incomplete venting
A15, Construction Quality	PTI/ASBI M50, PTI M55 specified and certified personnel in at least one of the following areas: Direct Supervisor of operations, installation, grouting, or inspection
A16, Quality Assurance	Spot or random sampling, limited QA during construction
A17, Grouting Procedures	PTI/ASBI M50, PTI M55 procedures specified, no pressure testing of ducts

Example Bridge Case 2

- Occurrence Factor for Case 1: 0.49
- Consequence Factor (same as Case 1): 0.67
- Risk Factor: **32**

Results of Case 1 and Case 2

- Risk Factors

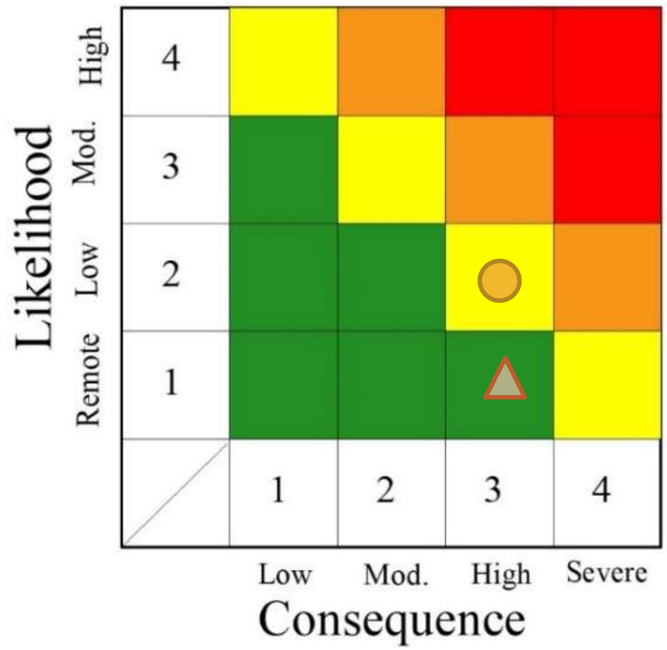


Results of Case 1 and Case 2

- Risk Matrix

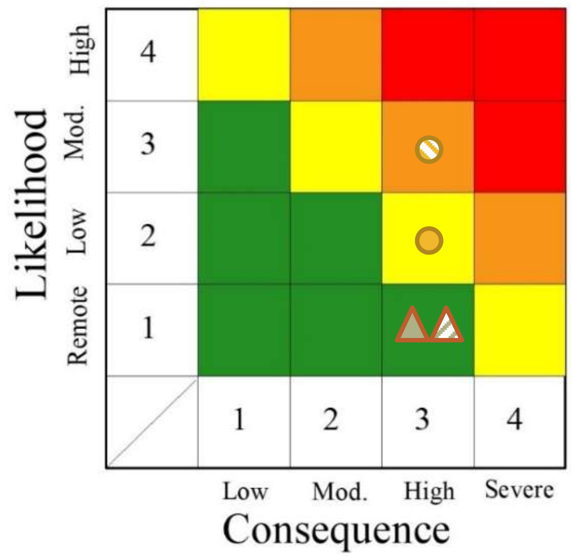
△ Case 1

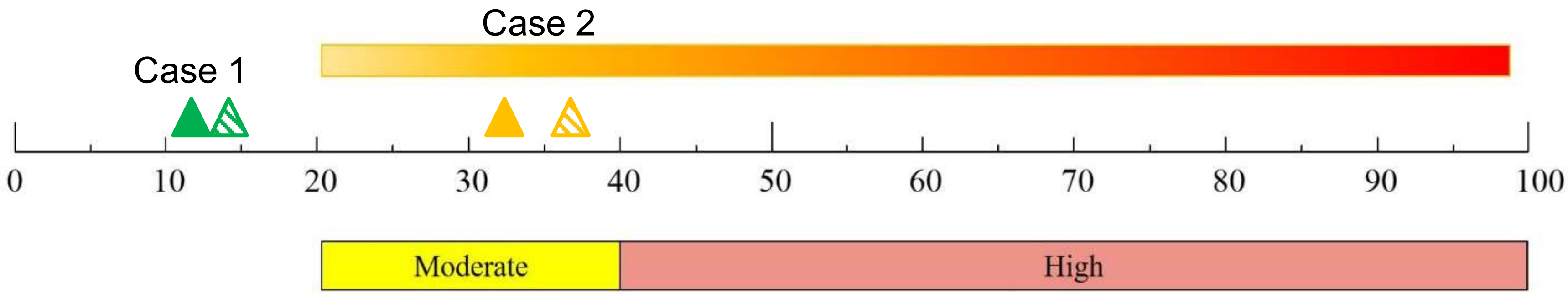
○ Case 2



Example (cont.)

- What if the bridge were located in a aggressive environment?
  - Case 1 Risk Factor = **14**
  - Case 2 Risk Factor = **36**





Examples: Conclusion

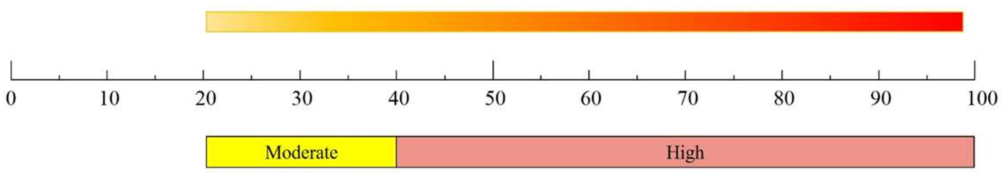
- Case 1 presents full corrosion protection to current standards (PL2)
  - Elevated quality processes
  - **Low risk** result, even with an aggressive environment
- Case 2 presents lower level of corrosion protection (PL1)
  - Typical quality processes
  - Moderate level of risk
  - *Elevated risk in an aggressive environment*

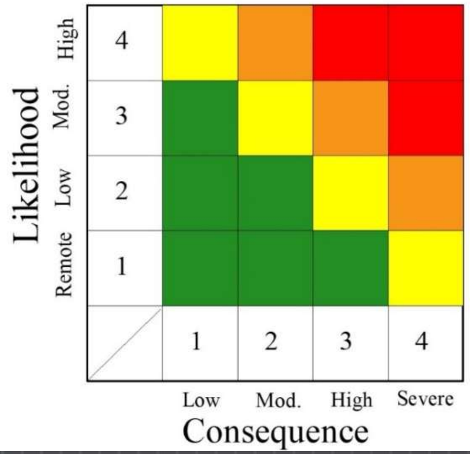
Summary and Review

- Guideline developed for risk assessment of PT tendons
  - Occurrence Factor describes the likelihood of corrosion damage developing in tendons
    - Based on attributes related to design, materials, and specifications
  - Consequence Factor describes the outcome of corrosion damage
    - Based on the importance of the tendon, cost/ease of replacement, and importance of the bridge
  - Elevated levels of risk can be addressed through
    - Risk mitigation strategies
    - Risk reduction strategies

Summary and Review

- Risk assessment can be plotted on:
  - –Risk Matrix
  - –Risk scale
- Determine if improved corrosion protection strategies are needed to ensure durable bridge design





Questions ?