TechBrief

Advance Concrete Bridge Technology to Improve Infrastructure Performance Program's purpose is to advance the current state of practice for design and construction of post-tensioned bridge structures in the U.S.

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Methodology for Risk Assessment of Post-Tensioning Tendons

Introduction

The objective of this document is to provide a rationale for conducting risk assessment of Post-Tensioning (PT) tendons to aid designers in the selection of appropriate corrosion protection strategies for PT systems in bridges. The risk assessment is intended to prioritize the need for protective technologies and processes considering the likelihood and consequences of corrosion damage (i.e., the risk) based on the attributes of specific PT system designs.

PT system attributes that affect the likelihood of corrosion damage during the service life of a bridge are considered, such as tendon profile, alignment and protection, the surrounding environment, and quality processes used during construction. The consequences of corrosion damage resulting in tendon failure are considered in terms of structural reliability, ease of tendon replacement, and the overall importance of a bridge.

Scope

The methodology presented herein is applicable for assessing the risk of corrosion damage for PT tendons in bridge superstructures for the purpose of identifying appropriate corrosion protection strategies. The analysis is focused on electrolytic corrosion that commonly manifests as localized damage. The analysis is intended to assist designers in selecting appropriate corrosion protection strategies when designing new PT bridges. The methodology is appropriately implemented for the analysis of individual tendons in a bridge.

Background

The PT risk methodology was developed using the procedures described in NCHRP Report 782, *Proposed Guideline for Reliability-Based Bridge Inspection Practices* [1] [2]. The risk assessment process consists of estimating the likelihood of damage occurring, described by an Occurrence Factor (OF), and the consequences of that damage, described by a Consequence Factor (CF). The OF is analogous to a probability of failure or likelihood of an adverse event. The CF describes the potential impact of corrosion damage on safety, the cost of replacing a damaged tendon, and bridge importance.

Each of these factors are estimated by analyzing key attributes of the bridge and tendon design that affect the likelihood of damage occurring and its consequences. Risk is estimated from these two factors as follows:

$$Risk = OF \times CF \qquad \text{Equation 1}$$

The risk calculated from Equation 1 provides a relative measure of the risk associated with a given set of attributes for a tendon. This measure of risk can be used to assess the need for action to reduce the likelihood of corrosion damage during the service life of a bridge.

To identify the key attributes of bridge and tendon design that affect the risk of corrosion damage in PT tendons, a Reliability Assessment Panel (RAP) was formed of bridge experts with expertise in the design, inspection, construction, and maintenance of PT bridges. An expert elicitation process was used to identify key attributes that impact the likelihood of corrosion damage developing in a PT tendon and its consequences. The attributes were ranked and used to form a risk model consisting of a quantitative scoring process, as described below, in order to provide an estimate of the OF and the CF.

The OF attributes identified were ranked qualitatively according to their impact on the likelihood of corrosion damage developing during the service life of a bridge. An attribute was ranked "high" if it is expected to have a significant impact on the likelihood of the corrosion damage, "moderate" for a relatively smaller impact, and "low" if it is expected to have minor or no impact. The attribute scoring was initially weighted according to its rank of High, Moderate, or Low as 20, 15, or 10 pts, respectively. Those attributes ranked as "low" impact on the likelihood of corrosion damage occurring in tendons were neglected due to the relatively small influence these attributes would have on the likelihood of corrosion damage. Once the attributes were ranked, criteria were developed to differentiate the scoring of a given attribute based on the engineering judgment of the RAP. Again, a High, Moderate, and Low scales were used to rank these criteria, with "High" indicating a criteria or requirement that most increases the likelihood of damage to be assigned the maximum score (20 or 15 pts), and a rank of "low" indicating a criteria or requirement least likely to increase the likelihood of corrosion damage and receiving a minimum score, typically 0. Criteria ranked as "moderate" are typically assigned 50% of the maximum score given the ranking of the attribute. For example, for the attribute of grout quality, a lower quality grout (e.g., Class A grout) is ranked as "High," and better-quality grout (e.g., Class C grout) was ranked as "low." In this way, higher scores indicate increased likelihood of damage occurring, based on the identified attributes and the rankings. Specific values for individual attributes were subsequently adjusted based on a sensitivity study and engineering judgement to yield suitable results from the risk model overall.

The values for each relevant attribute are assigned by rating the attribute according to the criteria developed, and results from each attribute are then summed and normalized to estimate the likelihood of damage, described by the OF:

$$OF = {\sum S_i}/{\sum S_0} \qquad \text{Equation 2}$$

where S_i is the score recorded for each attribute and S0 is the maximum score for each attribute, such that the ratio is a value between 0 and 1. The CF is estimated in a similar manner, with attributes identified by the RAP being ranked and criteria developed to rate the attribute and provide a measure of the potential consequence of corrosion damage causing failure of a tendon.

The resulting OF and CF factors can be used in two ways to characterize the risk of corrosion damage in a tendon. The values can be used to place a particular tendon in the appropriate bin on a risk matrix such as that shown in Figure 1, or the product of the OF and the CF can be used to estimate a quantitative risk value on a scale from 1 to 100.

The OF and CF ratios can be used to locate the analyzed tendon on a risk matrix such as shown in Figure 1 by categorizing the likelihood (OF) and the consequence (CF). For the OF, categories of remote, low, moderate or high are used to characterize the likelihood, while categories of low, moderate, high, and severe are used to characterize the consequence for the CF. The factor for appropriate categories is determined by multiplying Equation 2 by 4, resulting in values on a scale from 0 to 4. For the OF, values between 0 and 1 are identified as "Remote," meaning the likelihood of damage is estimated to be remote, given the attributes and criteria. Values 1 or greater but less than 2 are ranked as "Low," and so on. The CFs are categorized in a similar manner based on the CF attributes. This provides a simple methodology for categorizing the likelihood of corrosion damage and its consequences by locating a given tendon in a particular bin on the risk matrix. Decisions regarding suitable actions are then based on the location on the risk matrix, with bins tending toward the upper right indicating higher risk and bins tending toward the lower left are lower risk.

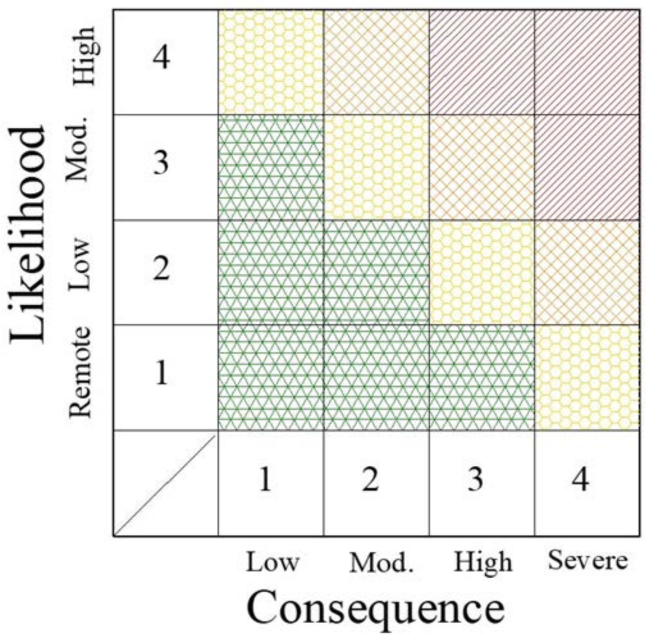


Figure 1 Illustration. Example risk matrix showing likelihood and consequence levels.

The ratios can also be applied directly to provide a risk estimate on a continuous scale using the equation:

$$R = OF \times CF \times 100 \qquad \text{Equation 3}$$

where R is a relative risk value, or risk factor, on a scale from 1 to 100.

In either case, decisions based on the risk analysis are subjective and based on engineering judgement, and threshold values or ranges must be selected to support decision making. When using the risk matrix, individual bins are identified as different levels of risk as suggested by the different colors shown in Figure 1. When using a continuous scale from 1 to 100, threshold values must be selected to characterize the level of risk. Specific recommendations for characterizing the risk for tendons are described in this TechBrief.

During the development of this methodology, the expert elicitation procedures from Report 782 were used to identify key attributes of PT bridges that affect the likelihood of corrosion damage in tendons and its consequences. The mechanisms or means by which corrosion damage might be initiated were identified by the RAP and described as *damage mechanisms*. One purpose of defining the damage mechanisms is to support the expert elicitation process overall by illustrating areas requiring focus, and for which different characteristics (i.e., attributes) have an impact on the likelihood of the corrosion damage. In this way, the key attributes that affect the likelihood of corrosion damage were identified and described with appropriate criteria. The RAP also considered the impact, i.e., the consequences, associated with corrosion damage that results in a tendon failure. The following section describes the damage mechanisms identified by the RAP and criteria for key attributes related to both the OF and the CF.

PT RAP Processes

The risk assessment conducted by the RAP identified damage mechanisms that affect the likelihood of corrosion damage in PT tendons. The identified damage mechanisms are vulnerabilities of the design or construction process that have a significant impact on the likelihood of corrosion damage. The damage mechanisms identified by the RAP are shown in Table 1. The identified damage mechanisms included breaching of a duct or anchorage that would allow the ingress of water and corrosive agents into the duct. The quality of the construction and workmanship was also identified as affecting the likelihood of developing corrosion damage. The aggressiveness of the environment, the adequacy of the specification and detailing, the quality of materials used, and the potential for grout voids to form in the duct were each identified by the RAP, as shown in Table 1.

Table 1. Damage mechanisms identified by the RAP.

ID	Damage Mechanism
1	Breached duct or anchorage
2	Construction and workmanship quality
3	Environment
4	Inadequate specifications and detailing
5	Poor or improper materials
6	Grout voids

Attributes were identified that correspond to one or more of these damage mechanisms. These attributes are characteristics of the design, loading, materials, and construction processes planned for a given PT system. *Design* attributes are typically characteristic of the design, such as the tendon profile or anchorage protection strategy. *Loading* attributes included externally applied loads such as the anticipated macro-environment in which the bridge will be constructed or the micro-environment surrounding a particular detail, such as an anchorage positioned near a joint that may be directly exposed to deicing chemicals. *Material* attributes were generally related to the grout used to protects strands from corrosion in the ducts, and *construction processes* included procedures and specifications to be applied during construction and the level of quality assurance. Attributes related to the procedures and specifications are generally related to the non-regulatory specifications produced by the Post-Tensioning Institute (PTI) and the American Segmental Bridge Institute (ASBI):

- PTI/ASBI M50.3–19, "Specification for Multistrand and Grouted Post-Tensioning" [2]
- PTI M55.1–19, "Specification for Grouting of Post-Tensioned Structures" [3]

The attributes identified were ranked according to the impact of each attribute on the likelihood of corrosion damage as a result of the identified damage mechanism. Criteria were developed to differentiate the scoring of a given attribute based on the engineering judgment of the RAP. Certain criteria were identified as *screening* criteria that identify characteristics that make the likelihood of corrosion damage occurring unusually high, such that the application of the developed risk model is inappropriate. In the analysis, two screening criteria were identified; the use of dry joints in segmental construction and duct vents located in the bridge deck without PTI/ASBI M50 or PTI M55-specified sealing procedures. In both cases, it was considered that these attributes made the likelihood of corrosion damage occurring unusually high such that application of the risk model was unnecessary. Attributes that describe the likely consequence of a tendon failure due to corrosion damage were also identified and ranked through the RAP process.

The following sections describe the purpose of each attribute, its relative ranking, and the criteria identified by the RAP for each attribute.

Risk Model Attributes

The risk assessment process was used to identify and prioritize attributes that contribute to the risk of corrosion damage in tendons. The document includes the attributes identified and ranked by the RAP for both the likelihood and consequences of damage.

The risk model considers 19 separate attributes that are numbered A1 thru A19 as shown in Table 2.

Table 2. Attributes and associated ranks identified by the RAP.

Attribute	No.	Attributes	Rank
PT Tendon and Profile	A1	Tendon Length	High
	A2	Tendon Vertical Profile	Very High
	A3	Tendon Curvature	High
	A4	Profile Conflict Avoidance	Moderate
PT Tendon Joint and Closure	A5	Cold Joints, Precast Segments	High
	A6	Cold Joint, Cast-in-Place (CIP) Segments	Moderate
	A7	Closure Pours	High
PT System Materials and Components	A8	Anchorage Protection, Interior	Moderate
	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	A15	Construction Quality	High
	A16	Quality Assurance	Moderate
	A17	Grouting Procedures	High
Environmental	A18	Macro Environment	Very High
	A19	Micro or Local Environment	High

The attributes are organized into five categories for convenience, including PT Tendon and Profile Attributes that describe design characteristics of the tendon being analyzed. PT Joint and Closure Attributes describe the attributes associated with joints between segments and the characteristics and number of closure pours traversed by the tendon. PT System Materials and Components Attributes describe the levels of protection provided at anchorages and vents, grout materials used, handling and storage of grout materials, location of vents relative to high points along a tendon, and the use of diabolos for external PT applications. PT Installation Quality Attributes describe the certification and specifications planned for construction and the procedures used to install grout. Environmental Attributes describe the ambient environment in which a bridge is to be constructed (macro-environment) and localized exposures to aggressive environmental conditions (micro- or local environment) such as may occur when a tendon anchorage is directly below and expansion joint or otherwise experiences localized exposure to water and corrosive agents.

The priority rank (i.e., High, Moderate) of each attribute is also shown in the table. Attributes ranked "Low" were not included in the model due to their relatively smaller impact on the likelihood of corrosion damage. Each attribute was assigned an alpha-numeric code (e.g., A1, A2, etc.) for organizational purposes.

There are three attributes used to characterize the consequences of corrosion damaged tendons in post-tensioned bridges as shown in Table 3. Of the three consequence attributes, one describes the importance of tendons in terms of structural reliability, one describes the ease of replacement (i.e., potential cost), and one refers to the importance of the bridge itself in terms of the transportation network. The latter was characterized as "optional," indicating that bridge owners/designers may choose not to consider this in the analysis.

Table 3. Consequence attributes identified by the RAP.

No.	Attribute	Rank
C1	Tendon Importance, System Level	High
C2	Ease of Tendon Replacement	High
C3	Bridge Importance	Optional

Adoption of Current Specifications

The risk model considers the partial or total adoption of two key voluntary specifications that describe current state-of-the-practice for construction of durable post-tensioned bridges.

- PTI/ASBI M50.3-19, "Specification for Multistrand and Grouted Post-Tensioning," [2]
- PTI M55.1-19, "Specification for Grouting of Post-Tensioned Structures." [3]

The adoption of some or all portions of these specifications is known to vary among different bridge owners, with some owners adopting these specifications in full, while others may adopt only portions of the specifications or utilize owner-specified requirements that may differ. Users should consider the extent to which the PTI/ASBI specifications are implemented or required within the design process. A number of attributes that contribute to the risk of corrosion damage in post-tensioned bridge construction are mitigated through implementation of these specifications.

Attributes Descriptions

The following section describes the attributes in the risk model for corrosion damage in PT tendons. Criteria for differentiating attribute scoring are also shown, along with the values determined for each of the criteria. Commentary related to the risk analysis and attribute descriptions are provided where appropriate. The attributes are grouped in five categories as shown in Table 2.

Commentary – Grout Voids: *Attributes related to the formation of grout voids are located in different general categories of attributes. Increased likelihood of voids in the installed grout increases the likelihood of corrosion damage occurring at the location of the void. Grout voids provide areas for water and corrosive agents to collect and/or the tendons materials to be exposed to atmospheric corrosion. In addition, the grout / tendon interface at the void can be affected by localized corrosion due to the presence of moisture and oxygen, which may be accelerated due to shifts in the pH content of segregated grout at the interface. The attributes associated with the likelihood of grout voids forming include characteristics of the tendon geometry, methods materials, and procedures used for grout installation, and the use of proper venting to prevent void formation. As a result, attributes related to grout voids are distributed into different general attribute categories.*

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. 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 4).

Table 4. Criteria for A1, Tendon Length.

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

A2 Vertical Profile (VH): High and low points along a continuous tendon create a more challenging grouting process and increase the likelihood that voids could form in the high point areas and near anchorages. Tendons with a straight or nearly straight profile have a reduced risk of the voids forming compared with tendons with a high profile. A rank of "low" is assigned for a tendon with 24 inches or less of vertical profile and a rank of "High" is assigned for tendons with more than 6 ft of vertical profile, based on engineering judgement characteristics per PTI M55 4.4.8.2 – Schupack pressure bleed test. As a result of the known challenges for preventing grout voids in tendons with large vertical profile variations, the scoring values assigned for "moderate" and "high" are set at 20 and 40 pts, respectively (Table 5).

Table 5. Criteria for A2, Vertical Profile.

Criteria	Rank	Score
Tendons with ≤ 24 in. profile	Low	0
Tendons with > 24 in. and ≤ 6 ft profile	Moderate	20
Tendons with > 6 ft profile	High	40

Commentary – Tendon Geometry: *Attributes A1 and A2 address tendon geometric characteristics of vertical profile and length. Generally, the likelihood of grout voids forming is increased for long tendons with large vertical profile as compared with short tendons with large vertical profile. The likelihood of a grout void forming is lowest for short, straight tendons.*

A3 Tendon Curvature (H): The tendon curvature attribute describes the risk associated with excessive tendon curvature. 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. Specified minimum radius of bending requirements of the specific PT system in use must be met to consider this attribute. If the minimum radius requirements are not met, the risk of duct breaching is assumed to be high (Table 6).

Table 6. Criteria for A3, Tendon Curvature.

Criteria	Rank	Score
Straight tendons	Low	0
Minimum radius of bending requirements met	Moderate	15
Minimum radius of bending requirements not met	High	20

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. The use of integrated (i.e., three-dimensional) drawings and careful conflict reviews during the design phase can help reduce the risk of geometric conflicts in construction. The use of proven, constructible details, proper spacing and careful local zone detailing near anchorages can reduce the likelihood of conflicts and improve constructability. Geometric conflicts can lead to misplaced ducts, unexpected stresses acting on ducts, unanticipated alignment issues, etc. that may increase the likelihood of a breach (Table 7).

Table 7. Criteria for A4, Profile Conflict.

Criteria	Rank	Score
High level of detailing to avoid geometric conflicts, use of standard or proven designs	Low	0
Limited or undesirable detailing	High	15

PT Tendon Joint and Closure Attributes

A5 Cold Joints (Precast) (H): If a bridge is constructed using precast components with untreated, dry joints, the risk associated with moisture breaching the duct is high, because the level of protection offered by sealing the joint to preclude the entry of water and corrosive agents is not present. Therefore, if dry joints were planned, which is not accepted practice currently, the likelihood of corrosion damage would be assumed to be high and the OF value placed at 1.0. For sealed joints traversed by duct, this attribute depends on the use of duct couplers to ensure water tightness of the duct at the joint. Plastic ducts without suitable couplers at the joint and metal ducts with or without couplers both rated as high (Table 8).

Table 8. Criteria for A5, Cold Joints (precast).

Criteria	Rank	Score
Continuous plastic duct or bridge without segmental joints	Low	0
Plastic ducts that include a duct coupler at joints	Moderate	10
Plastic ducts without duct coupling or metal ducts	High	20
Dry joints[1]	Screen	

[1] Not accepted practice

A6 Cold Joints (Cast-in-Place) (M): For cast-in-place (CIP) construction, where construction practices typically include casting fresh concrete against previously cast concrete, the likelihood of duct breach is increased for metal ducts as compare with plastic ducts. This is due to the potential for duct breach associated with the seam in a metal duct and loss of duct section due to corrosion that may provide a pathway for water and corrosive agents to penetrate the duct. Plastic ducts that are continuous across the construction joints provide increased protection as compared with plastic ducts with coupling at the joint (Table 9).

Table 9. Criteria for A6, Cold Joints (CIP).

Criteria	Rank	Score
Continuous plastic ducts or bridge without joints	Low	0
Plastic ducts that include a duct coupler at joint	Moderate	7.5
Plastic ducts without duct coupling or metal ducts	High	15

A7 Closure Pours (H): The likelihood of water ingress into a duct can be increased by the construction joints introduced at closure pours, especially when there is inadequate clearance provided at the closure pour. Adequate clearance is necessary to allow for the installation of duct couplers. Recommended or required additional clearance allows for the installation of heat shrink to ensure the connection is water-tight. Adequate clearance is also needed to ensure alignment of tendon ducts and make alignment adjustments if needed. For metal ducts, the seam in the duct provides a pathway for ingress of water and corrosive agents regardless of the adequacy of the spacing at the closure pour (Table 10).

Table 10. Criteria for A7, Closure Pours.

Criteria	Rank	Score
Adequate spacing for plastic duct couplers, recommended clearance, and resolving alignment	Low	0
Adequate spacing for plastic duct couplers and recommended clearance, minimal spacing for alignment	Moderate	10
Inadequate spacing for plastic duct couplers and recommended clearance, or metal ducts of any design	High	20

If a given tendon traverses multiple closure pours, the likelihood of a duct being breached will be increased. To reflect the increased likelihood, additional points are assigned if there are more than 2 closure pours along the length of the tendon being analyzed. The number of points assigned depends on the value of A7; 50% of the value of A7 should be added if there are three or four closure pouts, and 100% added if there are more than four closure pours along the length of the tendons, as shown in Table 11.

Commentary – Cold Joints: *The attribute of cold joints describes the resistance of the joint treatment to the entry of corrosive materials. This attribute has been divided to differentiate precast construction from cast-in-place (CIP) construction. For precast construction, joint treatments would typically include the application of a sealing material on the joint between precast surfaces and may include couplers to join ducts between adjacent segments. For CIP construction the joint consists of casting fresh concrete against previously cast concrete, and duct may extend across this interface or may be joined by couplers. The likelihood of duct breaching was generally considered greater for a joint in precast construction as compared with CIP construction. For this reason, attribute A5 Cold Joints (Precast) is assigned a maximum score of 20 pts while attribute A6 Cold Joints (CIP) is assigned a maximum value of 15 pts. A risk model for a tendon should include either A5 or A6, but not both. If construction includes both precast sections and CIP sections, A5 should be used.*

Table 11.Additional points assigned to express increased likelihood from traversing multiple closure pours.

Number of Closure pours	Added points	
	A7 Moderate	A7 High
1-2	0	0
3-4	5	10
4+	10	20

PT Materials and Components Attributes

A8 Anchorage Protection, Interior (H): This attribute is assigned for anchorages that are enclosed within the structure (Table 12). Interior anchorages are located inside a box girder where the enclosure provides the first layer of protection from the intrusion of the water and corrosive agents. Adequate drainage is required. If adequate drainage is not provided, attribute A9 should be used. The likelihood of corrosion damage during the service life of the bridge may increase, making inadequate drainage a screening criterion. 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) .

Table 12. Criteria for A8, Anchorage Protection, Interior.

Criteria	Rank	Score
Four or more layers of protection	Low	0
Three layers of protection	Moderate	10
Two layers of protection	High	20
Inadequate drainage provided	Screen	

A9 Anchorage Protection, Exposed (H): This attribute is assigned for anchorages that are not fully enclosed within the structure, such as at an expansion joint, between segments , or at the exterior face of a post-tensioned element (Table 13). 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). For anchorages located between segments, layers of protections could include grout, permanent heavy-duty sealed grout cap, a pourback, and sealer or coating applied to the surface of the segment and covering any outlets (PL-2).

Table 13. Criteria for A9, Anchorage Protection, Exterior.

Criteria	Rank	Score
Four layers of protection	Low	0
Three layers of protection	Moderate	10
Less than three layers of protection	High	20

Commentary –Anchorages: *Attributes A8 and A9 describe the layers of protection for anchorages at either end of the tendon. If both ends of the tendon are inside the enclosure of the structure, attribute A8 should be used. If either or both of the anchorages is not enclosed within the structure, A9 should be used. Anchorage located on the faces between segments should be rated using A9.*

A10 Venting Protection (H): This attribute considers the sealing of grout inlet/outlet locations along the duct (Table 14). The venting protection system should be according to the PTI/ASBI M50 / PTI M55 specification PL-2 to ensure a permanent leak-tight barrier. If this specification is not used in design and constructing the PT venting system or the design is according to PL-1 then a leak-tight barrier is not ensured and the likelihood of breaching of the duct is increased. The criteria reflect the generally increased likelihood of metal ducts being breached as compared with a plastic ducts. If the venting protection system follows the recommendation of the PTI/ASBI M50/ PTI M55 PL-2 specifications, the risk of breach due to the venting protection system is considered low regardless of the duct material.

If such grout inlet/outlets are located in the deck where exposure to water and corrosive agents is high and PTI/ASBI PL2 is not specified, then the likelihood of corrosion damage is very high regardless of other attributes of the PT system, and therefore, such circumstances are a screening criterion. In such a case, the OF should be assumed to be 1.0 (PTI/ASBI M50 sections 4.3, 9.9, App. A, PTI M55 section 5.6).

Table 14. Criteria for A10, Venting Protection.

Criteria	Rank	Score
PTI/ASBI M50, PTI M55 PL-2 is specified	Low	0
Venting other than deck, plastic ducts, and PTI/ASBI M50, PTI M55 PL-1	Moderate	10
Venting other than deck, metal ducts, and PTI/ASBI M50, PTI M55 PL-1	High	20
Venting in deck and PTI/ASBI M50, PTI M55 PL-2 not specified	Screen	

A11 Grout Material Performance (H): The grout material quality attribute is intended to reflect the increased likelihood of corrosion damage due to poor quality grout (Table 15). Grout quality issues such as excessive grout bleed, bleed pockets, segregation, or formation of soft grout are considered by this attribute. For external tendons where venting of high points is restricted, susceptibility to voids is increased. For this reason, external tendons have a higher point value when low quality grouts are used (PTI M55.1-19, section 3.3).

Table 15. Criteria for A11, Grout Material Performance.

Criteria	Rank	Score	
		Internal	External
Class C grout	Low	0	0
Class B grout	Moderate	10	15
Class A grout	High	20	30

A12 Materials Specification (M): This attribute is intended to characterize the increased risk associated with improper handling of grout materials prior to installation and/or the use of non-standard duct materials (Table 16). Proper handling of grout includes suitable storage conditions for the grout in terms of temperature, humidity, and coverage. This attribute also addresses the improved quality obtained through testing, traceability, and other requirements described in the PTI/ASBI M50, PTI M55 specifications (PTI/ASBI M50, Sections 4.0, 8.0, PTI M55, section 2.0, 5.0).

Table 16. Criteria for A12, Materials Specification.

Criteria	Rank	Score
PTI/ASBI M50, PTI M55 specified for duct materials. handling of grout	Low	0
PTI/ASBI M50, PTI M55 not specified for duct materials, handling of grout	High	15

A13 Venting (H): Proper venting of ducts is required to ensure that the ducts are full and to prevent the formation of voids during installation (Table 17). Proper venting of ducts is shown PTI/ASBI M50 section 9.9. Venting at high points reduces the likelihood of grout void formation. For external tendons, high points may not be accessible for venting. External tendons without high points vented should be scored as moderate the ducts are vented within 39 inches of the highpoint according to PTI/ASBI M50 section 9.9, locations C and E on Figure 9.1. If venting for external tendons does not meet this requirement, the attribute should be rated as high (PTI/ASBI M50 section 9.9).

Table 17. Criteria for A13, Venting.

Criteria	Rank	Score
Tendons with proper venting according to PTI/ASBI and all high points vented	Low	0
External tendons with proper venting according to PTI/ASBI but high point not vented	Moderate	10
Improper or incomplete venting	High	20

A14 Use of Diabolos (H): This attribute applies only to external tendons (Table 18). The use of diabolos to prevent misalignment and distortion (i.e., pinch points) of draped external tendons contributes to the prevention of grout voids and reduces the likelihood of breaching the protection level provided by the duct. The use of diabolos can also improve the quality of installation as compared with pipes. Welded pipe connections provide a uniform barrier to the ingress of water and corrosive agents. Booted pipe connections can provide a pathway for the ingress of water and corrosive agents, and therefore do not provide the same level of protection as a welded pipe connection. This attribute reflects the increased risk associated with not using diabolos.

Table 18. Criteria for A14, Use of Diabolos.

Criteria	Rank	Score
Diabolos with welded pipe connection	Low	0
Diabolos with booted connection	Moderate	15
Diabolos not used	High	20

PT Installation Quality Attributes

A15 Construction Quality (H): This attribute describes the quality of the construction process in terms of corrosion prevention of the PT system (Table 19). 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. Certification requirements include the Direct Supervisor of Post-Tensioning Operations, Foreman for each installation and stressing crew, and the Foremen on each grouting crew be certified as a PTI Level 2 Multistrand & Grouted PT Field Specialist. In addition, Foreman on each grouting crew should be certified according to ASBI requirements as a Certified Grouting Technician and at least 25% of each crew shall be certified in PTI Level 1 Multistrand & Grouted PT Installation (PTI/ASBI M50 section 7.0, PTI M55 section 4.5).

Table 19. Criteria for A15, Construction Quality.

Criteria	Rank	Score
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): This attribute is intended to capture the improved reliability of corrosion prevention when effective quality assurance measures are used during the construction process (Table 20). The QA processes envisioned are in addition to the typical quality control (QC) measures consistent with the procedures outlined in PTI/ASBI M50 section 6.0 and PTI M55 section 4.0, which are commonly the responsibility of contractor. Effective QA processes described herein are anticipated to include formalized and documented practices that verify materials, records, installation procedures and outcomes, post-grout visual inspections, and the appropriate certification of personnel (PTI/ASBI M50 section 6.0, PTI M55 section 4.0).

Table 20. Criteria for A16, Quality Assurance.

Criteria	Rank	Score
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): Proper grouting procedures reduce the likelihood of grout voids forming during the installation process in PT tendon ducts. In addition to voids, there is also a potential for segregation and soft grout due to improper procedures. This can be due to poor storage, over pressurizing, over-watering (batching or in-situ water), poor sequence of grouting and use of vents, or incorrect mixing. Specifying pressure testing of ducts to ensure the integrity of the ducts reduces the risk of leaks that could contribute to formation of voids (PTI/ASBI M50 section 4.0, PTI M55 section 5.0). This attribute is used to characterize the quality of the procedures (Table 21).

Table 21. Criteria for A17, Grouting Procedures.

Criteria	Rank	Score
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

Environmental Attribute Data

A18 Macro Environment (VH): This attribute is being described by the environmental classification included in the AASHTO Guide Specification for Service Life Design [4]. The environmental classifications provided within this TechBrief have been divided into three levels. The most aggressive environment is described by C-D4, Direct deicing salt (high) and C-M3, Marine tidal or splash zone. The least aggressive environment is described by C-NA2, Other exterior exposure, such as arid environments, interior exposure (such as inside a box girder) (C-NA1), or C-B, Buried (Table 22).

Table 22. Criteria for A18, Macro-Environment.

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

***Commentary – Environment:** The aggressiveness of the environment surrounding the bridge will have an effect on the risk of corrosion damage in tendons. The macro environment is intended to describe the surrounding environment in the area of the bridge and the general exposure of the bridge to aggressive environments resulting (primarily) from the application of deicing chemicals. The micro-environment is intended to describe the location-specific environmental exposure of a tendon or anchorage.*

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 (Table 23). Segmental joints that are unsealed or where deterioration of sealing between segments may be likely may also be characterized as a micro-environment. Tendons exposed to recharge (i.e., exposed to water intrusion regularly) could also be assigned a value under this attribute.

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.

Table 23. Criteria for A19, Micro or Local Environment.

Criteria	Rank	Score	
		A18 Moderate	A18 High
All other tendons	Low	0	0
Tendons in plastic ducts located in the deck of a box girder or other exposed location	Moderate	10	20
Tendons in metal ducts located in the deck of a box girder or other exposed location	High	15	30

Consequences

The following tables describe the three factors (attributes) that affect the consequences associated with corrosion damage in PT tendons, as identified by the RAP. Criteria for ranking the effect of each attribute are shown in the tables. In some cases, the input from the PT-RAP has been interpreted to provide ranking criteria. For example, the tendon importance on a system level is describe by redundancy factors as provided in the available literature. These reliability factors were then partitioned into high, medium, and low rank for the purposes of assessment.

C1 Tendon Importance, System Level (H): This attribute is based on considerations of structural redundancy described by a system factor, ϕ_s. Values for the system factor have been ranked as shown in Table 24. The factor considers the type of construction, continuity, number of webs per box, and the number of tendons per web for post-tensioned box girder bridges, as shown in Table 25.

Table 24. Criteria for C1, Tendon Importance, System Level.

Criteria	Rank	Score
$\phi_s > 1.05$	Low	10
$1.0 \leq \phi_s \leq 1.05$	Moderate	20
$\phi_s < 1.0$	High	30

The system factors increase as a function of the number of tendons in each web and the continuity provided by the design. Rationale for the system factors is provided in the AASHTO Manual for Bridge Evaluation, 3rd edition [5]. In the table, Type A joints refers to joints in precast segments that have an epoxy sealer applied to the surfaces, and Type B joints are dry joints. For PT beams, system factors have been described in the Florida Department of Transportation report "*New Directions for Florida Post-Tensioned Bridges*, Volume 10B, *Load Rating Post-Tensioned Concrete Beam Bridges* [6]." Table 26 shows the system factors, ϕ_s, for PT beams [6].

Table 25. System factors as described in the AASHTO Manual for Bridge Evaluation for Post-Tensioned Segmental concrete box girder bridges [5].

Bridge Type	Span Type	# of Hinges	System Factors, ϕ_s Number Tendons per web			
			1	2	3	4
Precast Balanced Cantilever Type A Joints	Interior Span	3	0.90	1.05	1.15	1.20
	End or Hinge Span	2	0.85	1.00	1.10	1.15
	Statically Determinate	1	n/a[2]	0.90	1.00	1.10
Precast Span-by-Span Type A Joints	Interior Span	3	n/a	1.00	1.10	1.20
	End or Hinge Span	2	n/a	0.95	1.05	1.15
	Statically Determinate	1	n/a	n/a	1.00	1.10
Precast Span-by-Span Type B Joints	Interior Span	3	n/a	1.00	1.10	1.20
	End or Hinge Span	2	n/a	0.95	1.05	1.15
	Statically Determinate	1	n/a	n/a	1.00	1.10
Cast-in-Place Balanced Cantilever	Interior Span	3	0.90	1.05	1.15	1.20
	End or Hinge Span	2	0.85	1.00	1.10	1.15
	Statically Determinate	1	n/a	0.90	1.00	1.10

[1] For box girder bridges with three or more webs, table values may be increased by 0.10.

[2] Not Applicable or Not Allowed, per [5].

Table 26. System Factors for Post-tensioned beam bridges [6].

Number of girders in cross section	Span type	# of Hinges for mechanism	System factors, ϕs1, 2 Number tendons per web			
			1	2	3	4
2	Interior Span	3	0.85	0.90	0.95	1.00
	End Span	2	0.85	0.85	0.90	0.95
	Simple span	1	0.85	0.85	0.85	0.90
3 or 4	Interior Span	3	1.00	1.05	1.10	1.15
	End Span	2	0.95	1.00	1.05	1.10
	Simple span	1	0.90	0.95	1.00	1.05
5 or more	Interior Span	3	1.05	1.10	1.15	1.20
	End Span	2	1.00	1.05	1.10	1.15
	Simple span	1	0.95	1.00	1.05	1.10

[1] Above values can be increased by 0.05 for spans containing more than 3 intermediate, evenly spaced diaphragms in addition to the diaphragms at the end of each span.

[2] In no case shall the System Factor exceed 1.25. The System Factor need not be less than 0.85.

C2 Ease of Replacement: This factor is associated with the cost of repair as a result of corrosion damage in tendons (Table 27). Although cost is not explicitly considered, the relative cost of replacing damaged tendons for a given structure depends on whether the original design considered replaceability of the tendons. Tendons designed for replacement may include internal tendons with flexible fillers, external tendons detailed for replacement, extruded/greased strands in grouted ducts, and design allowances for supplemental tendons.

Table 27. Criteria for C2, Ease of Replacement.

Criteria	Rank	Score
Tendons designed for replacement or supplement	Low	10
External tendons	Moderate	20
Bonded internal tendons	High	40

C3 Bridge Importance: This consequence attribute can be used at the owner's option to adjust the consequence analysis to consider the importance of a given bridge to the transportation network overall (Table 28). The operational importance of a bridge is described here according to Section 1.3.5 of the AASHTO *LRFD Bridge Design Specifications* [7] (which are mandated by reference in 23 CFR 625.4(d)(1)(v) and adopted with modifications by most state highway agencies).

"Guidelines for classifying critical or essential bridges are as follows:

- Bridges that are required to be open to all traffic once inspected after the design event and are usable by emergency vehicles and for security, defense, economic or secondary life safety purposes immediately after the design event.
- Bridges that should, at a minimum, be open to emergency vehicles and for security, defense, or economic purposes after the design event, and open to all traffic within days after that event."

Table 28. Criteria for C3, Bridge Importance.

Criteria	Rank	Score
Relatively less important bridges	Low	0
Typical Bridges	Moderate	10
Essential Bridges	High	20

Implementing the Risk Model

The risk model is implemented by selecting the relevant attributes for determining the OF and scoring each attribute according to the guidance provided herein. Analysis is conducted for a single tendon in a bridge; tendons with different attributes should be analyzed separately. Bridge design plans and specification for the subject bridge are needed to determine the relevant attributes and the appropriate rating for each attribute.

The OF is determined from Equation 2 based on the summation of the relevant attributes. Attributes that are not relevant to a particular tendon design should be omitted from the analysis. The CF is determined from the three relevant attributes related to the system redundancy, the replaceability of the tendon, and the importance of the bridge. The bridge importance attribute is optional and can be omitted from the analysis.

Based on the calculated values of the OF and the CF, the risk rating can be calculated according to equation 3 to determine the relative risk level for the tendon analyzed. Alternatively, the results may be plotted on a risk matrix, as described below. A spreadsheet format is suitable for implementing model. Examples provided in Appendix A illustrate a spreadsheet application of the attributes for determining the OF and the CF.

Risk Levels

The risk model results in a relative score for the OF and the CF. The decision-making based on this output can be implemented using a risk matrix, in which the OF and CF are each categorized as one of four possible categories, and the risk level is assessed based on the bins in the risk matrix, shown in Figure 1.

Alternatively, a continuous scale from 1 to 100 can be implemented to estimate the level of risk based on Equation 3. Using this approach, the level of risk can be assessed using Figure 2. The figure illustrates threshold values for moderate risk for scores that exceed 20, and high risk for scores exceeding 40. Scores in the 30-40 range may be considered moderate to high risk.

Risk mitigation or reduction strategies should be considered for tendons assessed to have moderate or high risk. The following section describes common risk reduction and mitigation technologies that can be implemented to reduce the level of risk.

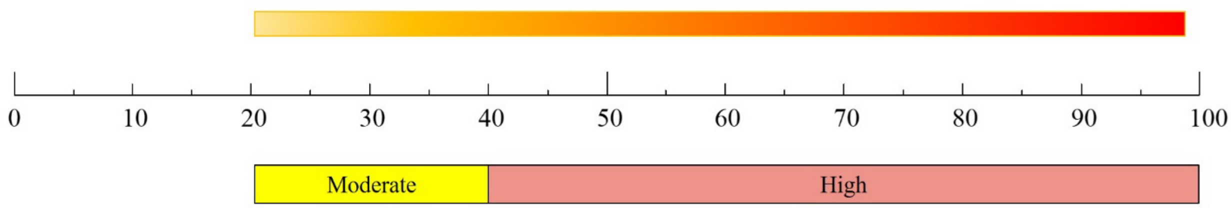


Figure 2. Chart. Risk levels based on 100-point risk scale.

Technologies for Preventing Corrosion Damage

This section describes available technologies for corrosion protection of PT tendons that could be implemented for PT tendons with elevated risk. The technologies have been divided into two groups, as shown in Table 29. This includes Mitigation Strategies that minimize the likelihood of corrosion damage in PT tendons uniformly, and Risk Reduction Strategies that can be implemented to reduce the value of certain attributes and thereby reduce the value of the OF. Relative measures of the cost and effectiveness of these technologies on a qualitative scale (Low, Medium, High) is also shown in Table 29.

The first group, Mitigation Strategies, describes technologies that could be implemented to minimize the likelihood of corrosion damage in PT tendons. These technologies should be considered when the risk level is determined to be moderate to high. This includes Electrically Isolated Tendons (EIT), selection of corrosion-resistant strands (e.g., stainless steel strands), use of corrosion-inhibitor in the tendon, or health monitoring technology to provide early warning of developed corrosion damage. The mitigation strategies include the use of tendon materials that have reduce susceptibility to corrosion, such as stainless-steel strands or electrically isolating the tendons. Implementing these technologies in the design of PT systems is assumed to reduce the OF to remote, thereby reducing the risk of tendon failure due to corrosion damage.

The second group, Risk Reduction Strategies, describes technologies or choices that could be selected to reduce the numerical value of the OF or the CF by modifying various attribute values. These technologies should be considered to reduce the overall risk profile.

Table 30 lists the Risk Reduction Strategies and the corresponding attributes that could affected by implementing these technologies. This group includes increasing the number of tendons in the design to reduce the value of C1, "Tendon Importance, System Level" or implementing replaceable tendons to reduce the value of attribute C2, "Ease of Tendon Replacement."

Table 29. Corrosion protection technologies.

Strategy	Technology	Cost	Benefit
Mitigation Strategies	Electrically Isolated Tendons (EIT)	L	H
	Stainless steel strand	H	H
	Carbon fiber strand	VH	H
	Galvanized strand	M	M
	Corrosion-Inhibitor tendon impregnation	M	M
Risk Reduction Strategies	Replaceable tendons	M	H
	Increase number of tendons	L	M
	Full adoption of: PTI/ASBI M50.3-19 [1] PTI M55-1.19 [2]	L	H
	Enhanced QC/QA	L	H
	Vacuum-assisted grouting	L	H
	Include additional layers of protection	L	M
	Structural Health Monitoring	M	M

Table 30. Attributes affected by Risk Reduction Strategies.

Technology	Related Attributes
Increase number of tendons	C1
Replaceable tendons	C2
Full adoption of: PTI/ASBI M50.3-19 [2] PTI M55-1.19 [3]	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	-

Several of these technologies can be used to reduce the OF, such as increasing the number layers of protection at anchorages, implementing enhanced QA procedures, or implementing PTI/ASBI specifications. These technologies can directly impact the rating of criteria for the attributes listed in Table 30. Vacuum-assisted grouting can significantly reduce or eliminate the likelihood of voids occurring in the tendons; the corresponding attributes listed are those associated with the damage mechanism of grout voids. Use of this technology may justify the reduction of criteria rating for these attributes, thereby decreasing the OF and the overall risk profile.

Structural health monitoring does not directly reduce the likelihood of corrosion damage occurring but may provide early warning of damage accumulation that can be used to reduce the likelihood that damage propagates sufficiently to require tendon repair or replacement.

References

[1] G. Washer, M. Nasrollahi, C. Applebury, R. Connor, A. Ciolko, R. Kogler, P. Fish and D. Forsyth, "Proposed Guideline for Reliability-Based Bridge Inspection," National Academy of Sciences, Washington, DC, 2014.

[2] PTI/ASBI, "Specification for Multistrand and Grouted Post-Tensioning," Post-Tensioning Institute, American Segmental Bridge Institute, Farmington Hills, MI, 2019.

[3] PTI, "Specification for Grouting of Post-Tensioned Structures," Post-Tensioning Institute, Farmington Hills, MI, 2019.

[4] T. Murphy, T. Hopper, E. Wasserman, M. Lopez, J. Kulicki, F. Moon, A. Langlois and N. Samtani, "Guide Specification for Service Life Design of Highway Bridges," National Academy of Sciences, Washington, DC, 2019.

[5] AASHTO, "The Manual for Bridge Engineering," American Association of State Highway and Transportation Officials, Washington, DC, 2018.

[6] Corven Engineering, Inc., "New Directions for Florida Post-Tensioned Bridges," Florida Department of Transportation, Tallahassee, FL, 2002.

[7] AASHTO, "LRFD Bridge Design Specifications," American Association of State Highway and Transportation Officials, Washington, DC, 2020.

Appendix A – Examples

Two examples illustrate the methodology:

- Example Bridge 1 – a spliced PT girder
- Example Bridge 2 – a span-by-span box girder

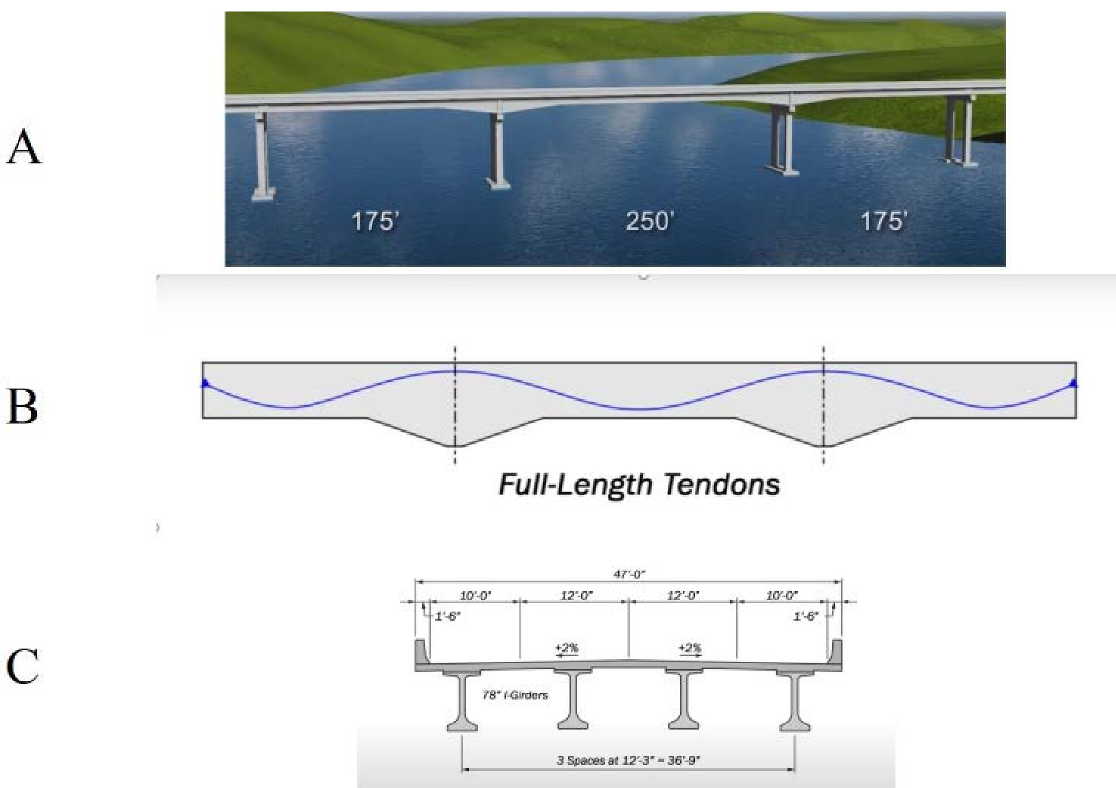
A simple spreadsheet program was used to score a tendon in each of the example bridges. The OF and the CF were calculated according to Equation 2, and the risk factor is presented for each bridge according to Equation 3.

For each bridge, a listing of each attribute is shown along with an explanation of the rating of each attribute for a tendon. Example scoring sheets are shown for each bridge. The following section describes the characteristics of each example bridge, shows the scoring sheet completed for the bridge, and indicates the results of the analysis.

Example Bridge 1: Spliced PT Girder Bridge

Example 1 was a spliced PT girder bridge with a total length of 600 ft as shown in Figure A - 1. The tendon analyzed in the example was a full-length tendon with a vertical profile of slightly less than six feet. The ambient environment surrounding the bridge was moderate. Anchorages were external and exposed under expansion joints at either end of the bridge. The system level redundancy factor is 1.1, with four primary members and four tendons in each member, as shown in Figure A - 1.

The design characteristics of the bridge are summarized in Table A - 1, which lists each of the attributes for the bridge used to determine the OF and the CF along with an explanation of the rating. It was assumed that this bridge was to be constructed using contemporary PTI/ASBI M50 and PTI M55 specifications with a protection level of PL2. As shown, certain attributes may not be applicable to a given tendon and therefore rated as NA. For example, the bridge has internal PT tendons, so the use of diabolos was NA because these devices are only relevant for external PT applications.



Source: FHWA

Figure A - 1. Illustrations. Example Bridge 1 showing overall bridge elevation (A, top), full-length tendon profile (B, middle), and four-girder cross section (C, bottom).

Table A - 1. Design characteristics of Example Bridge 1.

Attribute	Number	Attributes	Attribute Characteristics
PT Tendon and Profile	A1	Tendon Length	The tendon length of 600 ft. was determined from design plans.
	A2	Tendon Vertical Profile	The vertical profile of 5.7 ft. was determined from design plans.
	A3	Tendon Curvature	For this attribute it was assumed tendon curvature met bending requirements.
	A4	Profile Conflict Avoidance	Profile conflict avoidance procedures such as 3-D drawings and/or conflict design reviews was assumed.
PT Tendon Joint and Closure	A5	Cold Joints, PC Segments	For this example, use of PTI/ASBI specification was assumed, including the use of couplers at joints.
	A6	Cold Joint, CIP Segments	Not applicable for this bridge.
	A7	Closure Pours	It was determined from design plans that there were four closure pours along the length of the tendon analyzed.
PT System Materials and Components	A8	Anchorage Prot., Int.	No applicable for this bridge
	A9	Anchorage Prot., Exposed	The anchorages for the tendon analyzed are located at the girder ends and exposed at expansion joints at either end of the tendon. Four layers of protection were present.
	A10	Venting Protection	PTI/ASBI M50, PTI M55-PL2 were specified for the tendon, indicating adequate venting protection.
	A11	Grout Material Performance	PTI/ASBI Specifications with PL2 were specified for the tendon including Class C engineered grout. Ducts are internal; external grout material performance attribute was recorded as NA.
	A12	Materials Specification	PTI/ASBI M50, PTI M55-PL2 specified.
	A13	Venting	It was assumed that all high points were vented properly based on the specifications used.
	A14	Use of Diabolos	The ducts are internal and therefore the use of diabolos is NA.
PT Installation Quality	A15	Construction Quality	PTI/ASBI M50, PTI M55-PL2 specified including certified personnel for operations, installation, grouting, and inspection
	A16	Quality Assurance	It was assumed that enhanced QA procedures in excess of minimums specified in PTI/ASBI M50 section 6.0 and PTI M55 section 4.0 were implemented on the project.
	A17	Grouting Procedures	In addition to specifying PTI/ASBI M50, PTI M55-PL2, pressure testing of ducts was required for the project.
Environmental	A18	Macro Environment	The environment surrounding the bridge was identified as a moderate environment meeting the description of C-D2, Indirect deicing salts
	A19	Micro or Local Environment	The tendon anchorages are located at expansion joints at either end of the tendons, producing a potential for an aggressive micro-environment due to joint leakage.
Consequence	C1	Tendon Importance (sys.)	Design plans indicated four girder lines and four tendons per web. The continuous tendon extends between expansion joints and was treated as including the end-span. According to Table 26, the system factor is 1.1, indicating a low rank for this attribute
	C2	Ease of Replacement	The tendons are bonded internal tendons without plans for replacement, indicating a high rank for this attribute.
	C3	Bridge Importance	The bridge was assumed to be of typical importance.

The scoring sheet for this bridge is used to select appropriate criteria as shown in Table A - 2. Attribute ratings were selected from the drop-down lists as applicable, with “NA” selected for those attributes that do not apply to the tendon being analyzed. The score each attribute is shown along with the maximum possible score for that attribute.

Based on the data for this bridge, the OF was calculated at 0.34 (110/325), which corresponds to a relative likelihood of corrosion damage as “Low.” For the CF, the calculated value was 0.67 (60/90), which corresponds with a “High” consequence level. The risk factor was determined using equation 3 to be R=23.

Table A - 2. Risk model scoring sheet showing occurrence factor for Example Bridge 1 showing ratings for each attribute.

Attribute Data	Number	Attribute	Attribute Characteristic	Score	MAX
PT Tendon Geometry and Profile	A1	Tendon Length	Length > =500-ft	20	20
	A2	Vertical Profile	2-ft < profile < = 6-ft	20	40
	A3	Tendon Curvature	Minimum radius of bending requirements met	15	20
	A4	Profile Conflict Avoidance	High level of detailing to avoid geometric conflicts	0	15
PT Tendon Joint & Closure	A5	Cold Joints, Precast	Plastic ducts that include a duct coupler at joints	10	20
	A6	Cold Joints, CIP	Not applicable	NA	0
	A7	Closure Pours	Adequate spacing for plastic duct couplers and recommended clearance, minimal spacing for alignment	10	20
	Q	Number of closure pours crossed:	3-4 Closure pours	5	
PT System Materials And Components	A8	Anchorage Prot., Interior	Not applicable	NA	0
	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 C grout	0	20
	A11	Grout Materials Performance, External	Not applicable	NA	0
	A12	Materials Specification	PTI/ASBI M50, PTI M55 specified for duct materials and handling of grout	0	15
	A13	Venting	Tendons with proper venting according to PTI/ASBI and all high points vented	0	20
	A14	Use of Diabolos	Not applicable	NA	0
PT Installation Quality	A15	Construction Quality	PTI/ASBI M50, PTI M55 specified and certified personnel used for operations, installation, grouting, and inspection	0	20
	A16	Quality Assurance	Effective QA to verify materials, records, installation, and personnel qualifications	0	15
	A17	Grouting Procedures	PTI/ASBI M50, PTI M55 procedures specified, pressure testing of ducts specified	0	20
Environmental	A18	Macro-environment	Moderately aggressive, C-D1,2, C-M1,2	20	40
	A19	Micro-environment	Tendons in plastic ducts located in the deck of a box girder or other exposed location	10	0
			LIKELIHOOD OF CORROSION TOTAL SCORE	110	325
			Occurrence Factor	0.34	**Low**

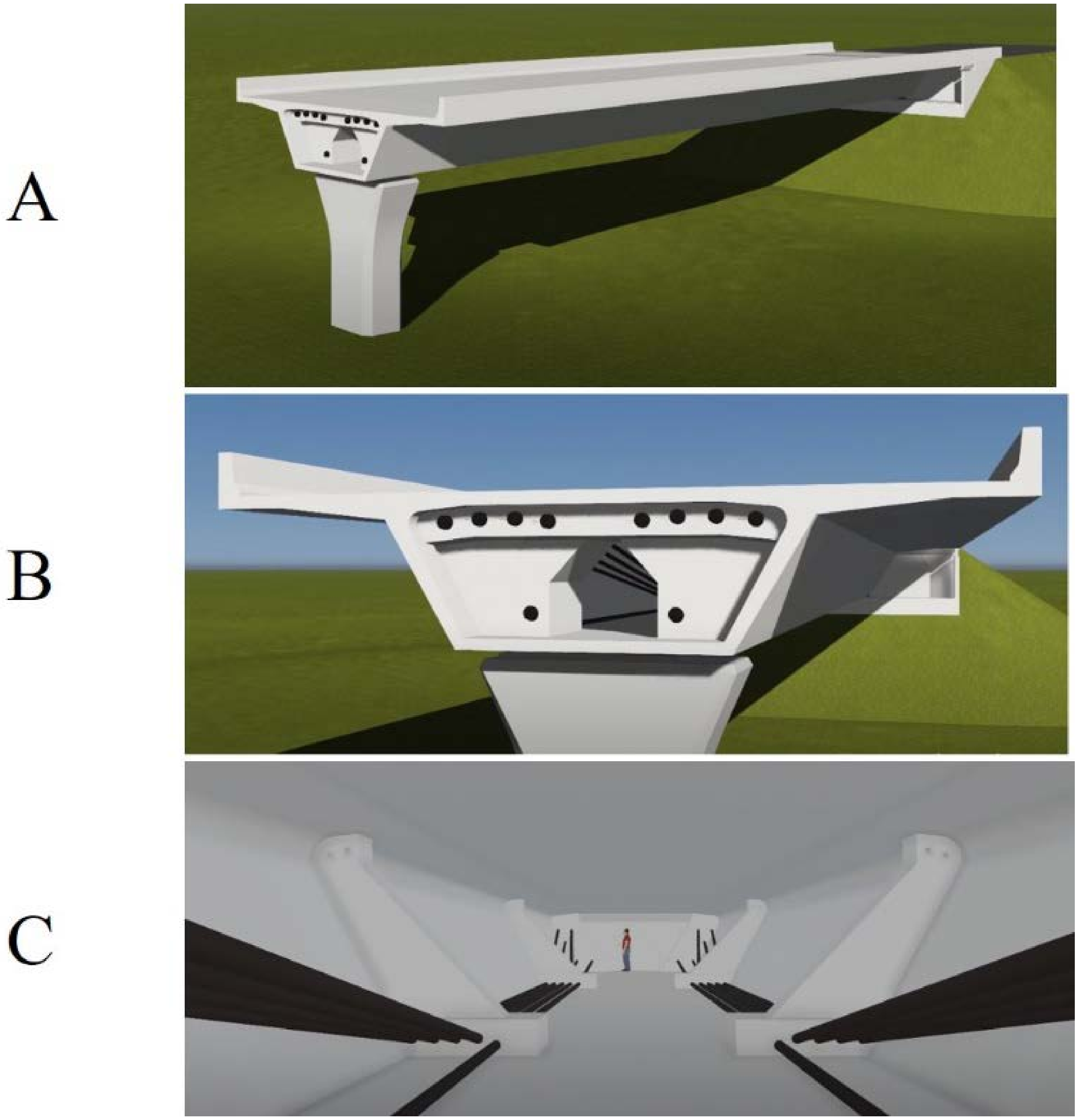
Table A - 3. Risk model scoring sheet showing consequence factor for Example Bridge 1 showing ratings for each attribute.

Number	Attribute	Attribute Characteristic	Score	MAX
C1	Tendon Importance (System)	System factor > 1.05	10	30
C2	Ease of Tendon Replacement	Bonded internal tendon	40	40
C3	Bridge Importance	Typical Bridges	10	20
		CONSEQUENCE TOTAL SCORE	60	90
		CONSEQUENCE FACTOR	0.67	High

Example Bridge 2: Span by Span Girder

Example Bridge 2 is a single span, simply-support box girder with external PT. The structure is a 9-ft deep single-cell box girder with 5 external tendons per web, as shown in Figure A - 2. The tendon analyzed was a full-length tendon with a vertical profile of 6.6 ft, as shown in Table A - 4. The ambient environment surrounding the bridge is moderate. Tendon anchorages are located within the box girder and were treated as internal anchorages. The system level redundancy factor was found to be 1.1, with five tendons per web. The design characteristics of the bridge are shown in Table A - 4.

The design characteristics of the bridge are summarized in Table A - 4 which lists each of the attributes for the bridge used to determine the OF and the CF. It was assumed that this bridge to be constructed using contemporary PTI/ASBI M50 and PTI M55 specifications with a protection level of PL2. As shown in the table, certain attributes may not be applicable to a given tendon, and therefore rated as NA.



Source: FHWA

Figure A - 2. Illustrations Example Bridge 2 showing overall elevation (A), cross section at support (B), and internal views of external PT.

Table A - 4. Design characteristics of Example Bridge 2.

Attributes	Number	Attributes	Attribute Characteristics
PT Tendon and Profile	A1	Tendon Length	The tendon length of 150 ft. was determined from design plans.
	A2	Tendon Vertical Profile	The vertical profile of 6.6 ft. was determined from design plans.
	A3	Tendon Curvature	For this attribute it was assumed tendon curvature met bending requirements.
	A4	Profile Conflict Avoidance	Profile conflict avoidance procedures such as 3-D drawings and/or conflict design reviews was assumed.
PT Tendon Joint and Closure	A5	Cold Joints, PC Segments	For the example there were two closure pours at either end of the segment and no cold joints. NA
	A6	Cold Joint, CIP Segments	Not applicable for this bridge. NA
	A7	Closure Pours	The tendon analyzed did not traverse any closure pours. NA
PT System Materials and Components	A8	Anchorage Prot., Int.	No applicable for this bridge
	A9	Anchorage Prot., Exposed	The anchorages for the tendon analyzed are located at the girder ends and exposed at expansion joints at either end of the tendon. Four layers of protection were present.
	A10	Venting Protection	PTI/ASBI M50, PTI M55-PL2 were specified for the tendon, indicating adequate venting protection.
	A11	Grout Material Performance	PTI/ASBI Specifications with PL2 were specified for the tendon including Class C engineered grout. Ducts are external; internal grout material performance attribute was recorded as NA.
	A12	Materials Specification	PTI/ASBI M50, PTI M55-PL2 specified.
	A13	Venting	The external tendons were vented according to PTI/ASBI M50 section 9.9. Rated as moderate.
	A14	Use of Diabolos	The ducts are external, but diabolos are not used.
PT Installation Quality	A15	Construction Quality	PTI/ASBI M50, PTI M55-PL2 specified including certified personnel for operations, installation, grouting, and inspection
	A16	Quality Assurance	It was assumed that enhanced QA procedures in excess of minimums specified in PTI/ASBI M50 section 6.0 and PTI M55 section 4.0 were implemented on the project.
	A17	Grouting Procedures	In addition to specifying PTI/ASBI M50, PTI M55-PL2, pressure testing of ducts was required for the project.
Environmental	A18	Macro Environment	The environment surrounding the bridge was identified as a moderate environment meeting the description of C-D2, Indirect deicing salts
	A19	Micro or Local Environment	The tendon anchorages are located within the section and no expansion joints are present in the tendon analyzed. Therefore, the microenvironment was rated as low. .
Consequence	C1	Tendon Importance (sys.)	Design plans indicated five tendons per web for the end-span section analyzed. According to Table 25, the system factor is 1.10, indicating a low rank for this attribute
	C2	Ease of Replacement	The tendons are external tendons indicating a moderate rating for this attribute.
	C3	Bridge Importance	The bridge was assumed to be of typical importance.

The scoring sheet for this bridge is used to select appropriate criteria as shown in Table A - 5. Attribute ratings were selected from the drop-down lists as applicable, with “NA” selected for those attributes that do not apply to the tendon being analyzed. The score each attribute is shown along with the maximum possible score for that attribute.

Based on the data for this bridge, the OF was calculated at 0.37 (115/325), which corresponds to a relative likelihood of corrosion damage as "Low." For the CF, the calculated value was 0.44 (40/90), which corresponds with a "Moderate" consequence level. The risk factor was determined using equation 3 to be R=16.

Table A - 5. Risk model scoring sheet showing occurrence factor for Example Bridge 2 showing ratings for each attribute.

Attribute Data	Number	Attribute	Attribute Characteristic	Score	MAX
PT Tendon Geometry and Profile	A1	Tendon Length	100-ft <= length < 500-ft	10	20
	A2	Vertical Profile	Profile > 6-ft	40	40
	A3	Tendon Curvature	Minimum radius of bending requirements met	15	20
	A4	Profile Conflict Avoidance	High level of detailing to avoid geometric conflicts	0	15
PT Tendon Joint & Closure	A5	Cold Joints, Precast	Not applicable	NA	0
	A6	Cold Joints, CIP	Not applicable	NA	0
	A7	Closure Pours	Not applicable	NA	0
	Q	Number of closure pours crossed:	3-4 Closure pours	NA	
PT System Materials and Components	A8	Anchorage Prot., Interior	Four or more layers of protection	0	20
	A9	Anchorage Prot., Exposed	Not applicable	NA	0
	A10	Venting Protection	PTI/ASBI M50, PTI M55 PL-2 is specified	0	20
	A11	Grout Materials Performance, Internal	Not applicable	NA	0
	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 Diabolos	Diabolos not used	20	20
PT Installation Quality	A15	Construction Quality	PTI/ASBI M50, PTI M55 specified and certified personnel used for operations, installation, grouting, and inspection	0	20
	A16	Quality Assurance	Effective QA to verify materials, records, installation, and personnel qualifications	0	15
	A17	Grouting Procedures	PTI/ASBI M50, PTI M55 procedures specified, pressure testing of ducts specified	0	20
Environmental	A18	Macro-environment	Moderately aggressive, C-D1,2, C-M1,2	20	40
	A19	Micro-environment	All other tendons	0	0
			LIKELIHOOD OF CORROSION TOTAL SCORE	115	315
			Occurrence Factor	0.37	**Low**

Table A - 6. Risk model scoring sheet showing consequence factor for Example Bridge 2 showing ratings for each attribute.

Number	Attribute	Attribute Characteristic	Score	MAX
C1	Tendon Importance (System)	System factor > 1.05	10	30
C2	Ease of Tendon Replacement	External tendon	20	30
C3	Bridge Importance	Typical Bridges	10	20
		CONSEQUENCE TOTAL SCORE	40	90
		CONSEQUENCE FACTOR	0.44	**Moderate**

Conclusion

The outcome of the analysis for Example Bridge 1was a risk factor of R = 23, while the outcome for Example Bridge 2 was a risk factor of R = 18. In both cases, the analyzed tendons indicate low to moderate risk.

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