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Steel Buried Structures: Condition of Ontario Structures and Review of Deterioration Mechanisms and Rehabilitation Approaches

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Abstract

Buried steel structures, commonly referred to as buried bridges, culverts, or soil-steel structures are a valuable bridge crossing solution. Owners manage their bridge assets by evaluating their condition and rehabilitating as required. Ontario's resources for managing and rehabilitating buried steel bridge structures are limited, and an investigation into the maintenance and rehabilitation practice of Ontario's assets demonstrates a lag in their maintenance and rehabilitation. Knowledge regarding rehabilitation of these structures is dispersed and unconcise, leaving owners challenged to understanding how to best manage and rehabilitate their assets. This paper investigates the age, condition, and rehabilitation of steel buried bridges in Ontario and reviews the commonly encountered deterioration and distress mechanisms along with the state-of-the-art rehabilitation practices. With an understanding of structural behavior, deterioration, and rehabilitation opportunities for structures nearing the end of their service lives, owners will be better equipped to effectively manage their inventory and leverage the economic, social, and environmental value of buried structures.

Keywords: Steel Buried Bridges, Rehabilitation, Deterioration, Asset Management, Condition Analysis

1.1 Introduction to Research

To achieve the design service life and make reasonable management decisions, practitioners need to be knowledgeable on the durability as well as maintenance and rehabilitation opportunities for their structures. The first part of the study will investigate the management, age, condition, and rehabilitation of buried steel bridges managed by the Ministry of Transportation of Ontario (MTO). Further, the second and third part of the research will review the literature discussing the common deterioration and distress mechanisms encountered and the state-of-the art rehabilitation practices available. Furthermore, charts are presented to summarize the processes of deterioration and the possibilities for rehabilitation. At present, Ontario is the only province publicly presenting their bridge conditions and it is likely that similar patterns of deterioration and options for rehabilitation are present at many other locations across Canada.

1.2 Steel Buried Structures

1.2.1 Ministry of Transportation of Ontario's Highway Bridges

For Ontario's bridge transportation infrastructure, the MTO bridge management department is responsible for structural crossings (> 3 m span) while the highway group is responsible for non-structural crossings (< 3 m span). The Ontario Structural Manual (OSM) refers to steel buried structures as corrugated metal culverts and requires all structures spanning over 3 metres be designed according the Canadian Highway Bridge Design Code (CHBDC) guidelines (MTO 2016). Projects using steel buried structures have grown in size and variety of use in recent years. The CHBDC has made an effort to consistency and refers to soil-steel conduits with spans > 3 m as buried structures. Emphasis is placed on the word structure throughout the standard to emphasize these are structures in the same context as other bridge types; commonly used terms such as culverts or pipes are not used. As the technologies advance in industry, the CHBDC advances to keep pace with ongoing innovation and make steel buried structures a viable option for most bridge sites (Pettersson, Wadi, and Williams 2017), (Newhook 2017).

1.2.2 Ontario Bridge Management System (OBMS)

The MTO has been a leader in bridge management as they developed a unique bridge management system which inventories structures and catalogues their condition by element as described by the Ontario Structure Inspection Manual (OSIM) (MTO 2008). This enables the MTO to better determine project estimates, and make asset management decisions (Thompson et al. 1999). The OBMS was completed in the late 90's and various elements of the system have been adopted by most of the provinces across Canada.

OBMS offers a library where the condition of each primary bridge element is rated on a scale from 1 to 4 (poor, fair, good, and excellent, respectively) based on element inspection data. For each bridge type, Table 2.2 of the OSIM provides an element list for the components of the structure that needs to be inspected (MTO 2008). For buried bridge structures, a "Culvert" bridge type as well as a "Culvert" element group, which recognizes the barrel and inlet and outlet components, is defined and "Soil-Steel Structures" fall under these categories. The element inspection data is mainly sourced from visual condition state inspection and other field testing programs that are outlined in the OSIM (MTO 2008). A steel buried structure or "Soil-Steel Structures", as described in Table 4.14 in the OSIM, receives a condition rating primarily based on corrosion, deformations and bolt cracking:

- **Excellent Condition** – No observed material defects.
- **Good Condition** – Light corrosion (surface rust).
- **Fair Condition** – Medium cusping or crimping of corrugations (less than 10 mm in height); medium global deformation (less than 10% of culvert diameter); bolt tilting; medium Corrosion (shallow pitting and corrosion scale over surface – less than 10% section loss).
- **Poor Condition** – Severe cusping or crimping of corrugations (greater than 10 mm in height); severe global deformation (greater than 10% of culvert diameter or with reverse curvature); bolt cracks; severe corrosion (deep pitting and corrosion scale over surface; greater than 10% section loss).

During inspection, the amount of element in each of the four different condition states is recorded. When rating condition, the system determines an overall measure of bridge condition using the bridge condition index metric (BCI) (MTO 2009). The BCI is calculated based on the original and remaining value of a structure after deterioration. The value of a structure is calculated by summing the values of each structure element. The value of an element is calculated by multiplying the number of elements by the size of each element and element value per size. The original intact value of the asset is then the sum of all the total element type values. The remaining structure value is calculated by summing the values of each element as well, but the value multiplier is reduced by a weight factor determined by the condition state assessed in the inspection (1, 0.75, 0.5, 0.25, for excellent, good, fair, poor respectively). Finally, the BCI of the structure is calculated by dividing the remaining value of the structure over the original value.

1.2.3 Condition of MTO's Steel Buried Bridges

Using Ontario's 2017 Bridge Condition Inventory (MTO 2018), the state of in-service steel buried bridges in Ontario is examined by investigating the BCI, which is determined bi-annually, and the age of these structures. The MTO services over 4800 bridges of which 280 bridges are steel buried structures referred to as "Corrugated Steel Culverts". The BCI distribution of the 280 bridges in Ontario is plotted against the year built in Figure 1 and out of these 280 structures, 204 have never been rehabilitated, 21 have undergone minor rehabilitation, and 58 have undergone major rehabilitation. If the structure has undergone rehabilitation, the year built is listed as the year of rehabilitation in some cases. Further, if the age of the structure is unknown, the year built is recorded as 1899 (to represent that the age is unknown and not that the structure is over 100 years old). The average BCI of "Corrugated Steel Culvert" category is 70 and the majority of un-rehabilitated structures have a BCI under 70. According to the MTO, bridges with a BCI between 70 and 60 are marked for rehabilitation to be performed within the next 5 years. If the BCI < 60 rehabilitations should be undertaken within the year, and if the BCI > 70, bridges are not marked for rehabilitation at all.

1.2.4 Comparison of BCI for Common Bridge Materials in Ontario

In order to compare the BCI of the seven most common bridge materials in Ontario, steel buried structures being the 7th most common, cumulative distributions are calculated for each bridge type across their BCI, year built, and year rehabilitated. The population considered in the analysis includes all non-rehabilitated and rehabilitated bridges built after 1920. Investigating the age of the population of these structures, Figure 2 depicts the proportion of the population of different bridge types built by a certain year. For corrugated steel structures, out of the 194 bridges in-service with known construction dates, 18 % of the bridges are known to be over 50 years old and 70 % are known to be over 30 years old. With regards to age, corrugated steel structures lie in the middle of the distribution, while reinforced pre-cast concrete structures are generally newer installations and cast-in-place concrete as well as steel are the oldest structures. In Figure 3, for the different bridge types, the cumulative proportion of the population at a specific BCI and below is depicted. From the analysis, Corrugated Steel Bridges have the highest proportion of bridges with the lowest BCI as 40 % of the population has a BCI of 70 or lower, and 18 % of the population has a BCI of 60 or lower. From the BCI and age distribution data, Table 1 compares the condition of these bridge materials and their age. Corrugated Steel bridges have:

- the lowest proportion of bridges (60 %) with BCI above 70,
- the highest proportion of bridges (23 %) with a BCI between 70 and 60,
- the highest proportion of bridges (17%) with a BCI below 60.

In the meantime, other bridge materials have a higher proportion of bridges with higher BCI ratings, but while also generally having a higher proportion of bridges that have undergone rehabilitation. At least 27% of Corrugated Steel bridges have undergone major rehabilitation and 10 % have undergone minor rehabilitation while 45 % to 84 % of other bridge materials have undergone major rehabilitations and 7 % to 33 % have undergone minor rehabilitation.

The proportions of the different bridge types that have been rehabilitated is depicted in Figure 4. The plot extends from 1950 to 2020 as the bridge populations before 1950 are of meager proportion. For each bridge type, the proportion of structures that have been rehabilitated for a specific age and before is depicted. Corrugated steel bridges have the lowest population of rehabilitated structures across all ages. Out of the structures that are over 50 years old, only 30% of the population has been rehabilitated. In contrast, 72 % to 100 % of other structures have had some sort of rehabilitation performed. A similar situation is also seen for structures that are at least 30 years old and with all present in-service structures. Of the corrugated steel population that is 30 years and older only 30 % has had any rehabilitation. Further, at present only 37 % of the total in-service population has had any rehabilitation, while other structures have had between 48 % to 88 % of their structures rehabilitated.

1.2.5 Discussion of MTO's Buried Steel Structures

All bridges deteriorate over time and the more systematic and educated owners are of their bridge assets, the better positioned they are to manage them effectively. While the population of buried steel bridges has the highest proportion of bridges with a BCI under 70, it also has one of the highest proportions of unmaintained and longest standing bridges. As many of the other bridge populations have high proportions of their bridges above a BCI of 70, they also have higher proportions of rehabilitated and more recently installed structures. The high proportion of unmaintained bridges suggests that there are issues associated with the maintenance and management of these structures. With the present BCI of these structures, according to the MTO, many of Ontario's steel buried bridges are going to require either rehabilitation or replacement within the next 5 years.

Ontario's tools for managing bridge assets, OSM, OSIM, and Ontario's Structural Rehabilitation Manual (OSRM) (MTO 2007) have significantly less insights on buried steel structures. The OSM refers to these structures as corrugated metal culverts and requires their design to follow the CHBDC guidance. Updates to the CHBDC emphasize that steel culverts with spans > 3 m are buried structures and the importance of durability and maintenance design for bridges applies to buried structures as well. Previously, the CHBDC has lagged behind recent industry knowledge on the deterioration mechanisms, protective coating options/requirements, and when applicable, metal loss estimation. As a result, there are several historical instances where a lack of adequate design standards and knowledge resulted in poor steel buried structure durability designs. For example, incorrect coatings or inadequate solutions such as a closed bottom structure being used in lieu of an open bottom structure have resulted in durability related performance issues (West, Williams, and Carroll 2013).

To effectively manage and utilize buried structure assets, asset managers and industry partners need to effectively work together and ensure the most current knowledge is available in bridge management aspects. Employing a consistent naming convention across Ontario's bridge management assets will help eliminate confusion when referring to buried structures. Within two of the tables of the OSIM, *Table 5.1 Suspected Performance Deficiencies* and *Table 6.1 Maintenance Needs*, guidance on possible maintenance and rehabilitation actions need to be developed based on observed deterioration mechanisms. Further, guidance on rehabilitation opportunities should also be written into the OSRM.

The remainder of the paper focuses on addressing these issues by summarizing observed deterioration mechanisms in these structures and the possible rehabilitation practices for them.

Deterioration and Distress of Buried Steel Structures

2.1 Introduction

Applying the CHBDC requires that durability, maintenance, and construction guidelines are followed, where environmental conditions and their possible relations to deterioration are considered (CSA 2014). To achieve the design service life of steel buried bridges and to facilitate reasonable management decisions, practitioners need to be knowledgeable in the construction and durability of steel buried bridge materials. In Ontario (MTO 2008), when applying a condition rating to the structural plate of steel buried bridges, the OSIM's primary concerns are:

1. Corrosion – pitting, rust deposits, and section loss
2. Global deformations – ovaling of the conduit greater than 10%
3. Local deformations – crimping and cusping of the conduit wall, rising of the invert, and flattening of the crown
4. Joints – seams opening, pulling apart, and bolt hole cracking.

When considering deterioration and management of these structures a number of resources are available to help in condition inspection and assessment of deterioration (Abdel-Sayed et al. 1994; Hunt et al. 2010; Caltrans 2014; Beaver and Richie 2016).

An outline on how buried steel structural walls may deteriorate due to corrosion and abrasion and how the engineering fill may be affected by soil erosion is presented in Figure 5 (the authors' synthesis of the literature is discussed in more detail through the remainder of this section). Deterioration of the structural plate wall thickness is driven by the structure's surrounding environment. Corrosion may apply to both watercourse and grade separation structures. Abrasion is a concern solely in watercourse structures where the water is flowing against the wall of the structure. Both processes may result in perforations, damaged joints, section loss, diminished structural properties and cross-sectional distortions under surface loading. These signs of distress are further discussed in Table 2. Diminished support from engineering fill may lead to cross-sectional distortions under applied surface loads and may be due to water-soil erosion mechanics and improper construction. As piping and infiltration are water-soil erosion mechanisms that result in the formation of voids around these structures, they may also lead to barrel misalignments and surface settlements and sinkholes as discussed in the Table 3. Scour, another water-soil erosion mechanism, also compromises the soil foundation of bridges which may lead to the collapse of the structure.

Diminished structural properties of the conduit wall and soil properties of the engineered fill may result in shape distortions under gravity and vehicle loads. Shape distortions may develop as ovaling, invert rising, crown flattening, result in the formation of plastic hinges and local buckling which all can lead to the collapse of the structure (Mai et al. 2014; Kunecki et al. 2017; Regier et al. 2018; Moore and Peter 2019). Further, outside of Figure 4, distress in the structure may develop when the structure has seams with an incorrect bolting assembly or when differential foundation settlements occur.

2.2 Corrosion and Abrasion

Corrosion is an electrochemical reaction that results in the loss of wall thickness and may occur on the inner, outer, or both surfaces of the structure. When uncoated steel is exposed to a corrosive environment, the oxidation reaction reduces the thickness of uncoated steel by releasing iron atoms into a polar solvent (such as water) and enabling electron flow to a cathodic site. At the cathodic site, aqueous iron atoms are free to react with oxygen, water, and regain their electrons to form hydrated ferric oxide, better known as rust (Volkan 2014). As corrosion of steel is a naturally occurring process, metal buried structures have historically been designed with zinc protective coatings and steel sacrificial thickness (AGA 2010), and more recently, advanced corrosion resistant polymer coatings (CSPI 2012a). Polymer coatings provide a moisture and oxygen barrier between the steel and its surrounding environment which prohibits the iron atoms from releasing into the polar solvent. Hot-dip galvanizing prevents corrosion of steel by forming zinc oxide and subsequently zinc carbonate (a dull gray color) which acts as a sacrificial anode since zinc is anodic to iron. Zinc carbonate corrodes very slowly and protects the zinc metal and steel underneath. In watercourse applications, the erosion of zinc may be stable or accelerated depending on the water corrosivity and abrasion conditions (Hansing and Cederqvist 2017). However, further concerns for protective zinc coatings arise in soft waters. In soft waters, the absence of dissolved salts of calcium carbonate in the water inhibits the formation of the tougher zinc carbonate protective coating. Without the formation of zinc carbonate, zinc oxide is left exposed and corrodes more rapidly than the intended byproduct of zinc carbonate. Generally, the extreme absence of calcium carbonate correlates to a site with a resistivity higher then 10 000 ohms-cm and alternative coatings or materials may be applied (NCSPA 2010). Depending on the environment, all structural components may be subject to corrosion.

Abrasion is an erosive process that results in the loss of conduit wall thickness of buried structures on their water side. Conduit wall loss occurs due to physical damage or removal of metal from the exposed conduit surface by the sediment conveyed in flowing water. The sediments carried by the flow of water (bed load) may impact and deteriorate the structure if they are rolling, sliding, or skipping along the structure (DeCou and Davies 2007). The most severe environments for abrasion typically occur around large elevation gradients that promote rapid and large flows of water with sand, and gravel rocks present in the stream bed (Molinas et al. 2009). Further, non-abrasive environments include the presence of silt, clay, and heavy vegetation (ODOT 2018). If the flow is not in contact with the structure's wall, as in some open bottom structures, or protected by either rip rap or another barrier, the structure is also not subject to an abrasive environment.

In order to estimate the rate of wall thickness loss and the durability of a structure in a given environment, CSPI and Caltrans both provide guidance on how different material types perform in different environmental conditions when considering corrosion and abrasion (Caltrans 2017). In general deterioration is estimated in terms of the water acidity, soil resistivity, and bed load. The CSPI method employs a uniform thickness loss method which is believed to be a conservative simplification. The method is outlined in CSPI Technical Bulletin 13 (CSPI 2012a), explained in a white paper (CSPI 2012b), and will be referenced in the 2019 CHBDC. Further, the Caltrans method provides an estimation of thickness loss to first perforation which is outlined in the state of California's Highway Design Manual (Caltrans 2017). Common signs of corrosion and abrasion are presented and discussed in Table 2. In steel structures, signs of corrosion appear as patchy discolorations and concentrated nodules of rust deposits. Signs of abrasion are also accompanied by corrosion and discolorations. Abrasive action will result in the loss of protective coating and wall thickness, the exposed steel will become discolored as it naturally corrodes and develops a passivation coating. As corrosion and or abrasion continue to remove the wearing surface, perforations will occur and may lead to joint issues, section loss, and soil erosion. This process continues until the invert is completely eroded and possible instability may lead to further damage.

2.3 Piping, Infiltration and Scour

Piping is an erosive mechanism that occurs with the progressive dislodgement of soil particles through tractive forces. Tractive forces are produced by inter-granular seepage flow and the mobilizing tractive forces are greatest where flow concentrates at an exit point. As fine particles are washed away, empty spaces develop in the form of voids (Richards and Reddy 2007). In steel buried structures, water saturating soil embankments will develop hydraulic gradients along the path of least resistance. Soil-structure boundaries are more hydraulically conductive than the adjacent soil and offer a path of less resistance for flow to concentrate at.

Infiltration is a soil erosion mechanism where water flow exits the soil into the structure. In steel buried structures, common observed infiltration points are joint openings and perforated sections. To gain insight into the erosion mechanism, small scale experimental testing has been performed (Qin and Moore 2019). From the experiments, for a soil erosion event in sand around a rigid pipe, three distinct stages were identified: 1) initial leakage into the conduit 2) the affected soil undergoes erosion and void formation 3) the void reaches a stable state due to capillary pressure and arching effect.

Scour has resulted in the catastrophic failure of many different bridge types. Scour is the erosive mechanisms which excavates and carries away materials from the bed and banks of streams around bridge abutments, piers, and foundations (Deng and Cai 2010). Generally, the potential for scour to occur is affected by contraction zones (i.e. the channel of a bridge span) as they accelerate water to a higher velocity.

Common signs of soil erosion are presented and discussed in Table 3. In steel buried structures, soil erosion may propagate large movements of the structure. If soil erosion were to advance, signs of distress start to present themselves in the form of voids, structure settlement, surface settlements, foundation scour and soil raveling through joints. Guidance to mitigate piping and calculate the depth of scour is provided in the CHBDC (CSA 2014). To estimate the development of erosion voids, a preliminary prediction method for the maximum extent of the erosion void has been proposed (Qin and Moore 2019). The prediction method accounts for the effect of hydraulic variations and interactions between sand particles and groundwater.

2.4 Bolt Hole Tears and Differential Foundation Settlements

Cracks along longitudinal seams, often referred to as bolt hole tears, generally propagate due to incorrect bolting sequence (Abdel-Sayed et al. 1994). Bolt hole tears are often horizontal and originate from the bolted part of the corrugation subjected to tension forces. As the conduit wall is also subjected to compressive forces, the cracks rarely extend over the entire section. When bolted incorrectly, the cracks propagate from local damage such as sharp dents made in the plate by either a bolt head or nut.

Differential foundation settlement is a performance requirement for buried steel structures being written into the 2019 edition of the CHBDC. Prior to the foundation failing due to shear failure of the supporting soil, a foundation may sufficiently settle to cause damage to the supported structure. Rather than being a result of deterioration, differential settlement occurs due to elastic and consolidation settlement of the underlying soil layers (Das 1999). In buried steel bridges, if one side of the footing settles more than the other there is a differential settlement stress introduced into the conduit walls. If the structure differentially settles across the length, twisting will occur. Open bottom structures are at the greatest risk of differential settlement and visual signs of its occurrence may include local buckling of the structure or formation of a plastic hinge.

Rehabilitation

3.1 Solutions to Distressed Buried Structures

Several rehabilitation methods are available to extend the service life of buried steel structures (Ballinger and Drake, 1995; Moore, 2005; NCHRP 14-19, 2010). To provide guidance on asset management and rehabilitation decisions, general guides have been developed by federal and state level organizations (Cooper et al. 2005; Hunt et al. 2010; Matthews et al. 2012; Caltrans 2014). From the authors' synthesis of the review, a flow chart presents rehabilitation opportunities based on root problems, deterioration mechanisms, and signs of distress in Figure 6. A colour is assigned to each root problem and possible deterioration mechanisms along with the likely areas affected are connected to possible signs of distress. Further, signs of distress are then linked to different rehabilitation options. In some cases, the colour of the root problem may directly extend to a solution, but in other cases, different deterioration mechanisms may lead to the same signs of distress and require similar rehabilitations. When the signs of distress may be due to one or more mechanisms, a black line extends to the possible rehabilitation opportunities. The purpose of the chart is to present options for managing steel buried bridges for different types of distress and making sure the root of the problem is also addressed. In general, depending on the nature of the deterioration, only parts of the structure need to be either rehabilitated, stiffened, or protected. In other cases, with large deformations in all parts of the structure or when worker access is restricted, entire conduit relines may be performed to add protection and even stiffness. With this method, the structure may be transformed into a semi-rigid or even rigid structure. Further, if deformations are occurring due to inadequate engineering fill support, soil stabilization techniques should also be applied.

3.2 Spot Repair Methods

In large diameter structures, where worker access is possible, spot repair techniques provide options for restoring structural and hydraulic integrity of joints and plate sections (Matthews et al. 2012). If compromised joints and plate sections (joint openings, bolt hole tearing, loss of wall thickness, section loss, excessive deformation, and crimping of the wall section) are not rehabilitated, they can facilitate further deterioration which can critically compromise the structure. A variety of spot repair techniques that address these issues are introduced throughout this section.

3.2.1 Temporary Props

Temporary props, either timber columns (200 x 200 mm) or steel struts of hollow circular section, may be employed in order to prevent further excessive inward deformations and collapse as a last resort measure. Props may prevent the catastrophic failure of the structure, but also constrict worker access in the conduit and are generally used if the pipe is to be replaced. When applying props to resist vertical deformation, they are typically spaced at 1000 – 1500 mm apart and designed to carry the weight of the volume of soil which is statically apportioned to them (Abdel-Sayed 1994).

3.2.2 Plate Re-bolting

Longitudinal cracking of seams may occur from excessive displacement, incorrect assembly of the plates, and differential soil pressures. Repairs are made by splicing, re-bolting or welding with reinforcing steel to the inside corrugation valleys at the location of seam distress (Caltrans 2014).

3.2.3 Sleeve Section Repair

When structurally compromised or missing sections require sealing against leakage, specialty stainless steel or polyvinyl chloride repair sleeves may be used. When the sleeves are folded, they’re positioned within the conduit and snapped into place. When leaking is the sole concern, internal joint sealing with flexible rubber seals may be applied (Matthews et al. 2012).

3.2.4 Partial Concreting

Conduit wall sections may be reinforced using partial concreting and shear connectors. When damage to the invert from corrosion and abrasion is the primary concern, invert paving with reinforced concrete along with other materials is one of the most effective rehabilitation solutions (Caltrans 2014). Partial concreting may be applied to prevent further excessive deformations due to loss of stiffness from either loose adjacent fill or loss of wall thickness as well as to transmit shear forces over missing sections or sections with bolt hole tears (Abdel-Sayed 1994).

Typically, 90 to 180 degrees of the invert is paved with Portland cement based conventional or high strength concretes. When extending invert paving over the haunches, the concrete can be cast in two lifts. The first lift extends up to the haunches and the second lift can be cast nearly vertical from the first. Alternatively, concrete may be applied in the haunch areas and in any partial sections of the pipe with the use of shotcrete.

When performing any partial concrete installation, effective contact, stiffening of the section, and transmission of loads is achieved through the application of shears studs. Shear studs are generally machine welded to the buried steel structure after exposing the steel by grinding off any coating. Generally, small diameter welded wire mesh is also included as light reinforcement. Reinforcement should be applied closer to the face subjected to tensile flexural forces. The depth of the reinforcement within the concrete or shotcrete depends on the bending moments the repaired section is subjected to. For example, for a pipe arch section, when applying shotcrete to the crown, reinforcement should be away from the conduit wall and closer to the exposed surface and vice versa when applying reinforcement and concrete around the spring lines.

From experimental investigations on corrugated steel structures, it has been observed that the system is significantly stiffened by the rehabilitation. In shallow burial conditions, the strength of the rehabilitated pipe may still be governed by bending plastic hinge formation in the shoulders before the rehabilitation fails (Tetreault 2016). Further, moments may develop on each side of the corrugated steel directly above the termination of the concrete paving.

3.2.5 Partial Relining

Partial relining provides a quick solution to restore the structural and hydraulic integrity of a steel buried structure with damage below the springline due to corrosion, (Lundstr et al. 2012). A new lower portion of the structure is assembled and inserted into the deteriorating structure. The new assembly material should be designed with adequate corrosion and abrasion considerations. Further, the connection between the old structure and the lower structure is designed to transfer the normal and flexural forces between the new assembly and the existing structure. The connections are welded to the old structure, bolted to the new lower portion, and are subsequently completely encased in concrete during the concrete pour. When pouring concrete between the old and new structure, lifting forces (due to buoyancy and any applied pressure) must be calculated in order to determine the necessary spacing of props to prevent lifting of the new lower portion.

When passage for aquatic species also becomes a critical concern along with invert corrosion, a polymer coated river fish baffle may be applied as a partial re-line in a similar manner as previously described. The river baffle restricts the flow of water with polymer coated plates to build up the volume of water within the conduit. Small passages are shaped into the plate where the water flows over, and fish are then able to pass (Duguay et al. 2015; Wilcock 2016).

3.2.6 Concrete Rock Slope Protection, and Steel Armor Plating

When the invert of a large diameter steel buried structure is suffering due to highly abrasive conditions, concreted rock slope protection and steel armour plating can provide increased resistance to abrasion and impact damage (Caltrans 2014). With concreted rock slope protection, the barrel roughness is increased and thus the flow velocity is also decreased within the barrel. In structures that can accommodate a reduction in the waterway area, steel armor plating may be applied.

3.3 Conduit Reline

Loss of wall thickness, perforated sections, joint pull-apart, and circumferential distortions are all reasons why a buried pipe conduit may no longer be considered stable and serviceable. Provided there are no major shape distortions threatening collapse and severe misalignments or distortions are not compromising the hydraulics of the structure, a variety of innovative trenchless repair techniques exist in order to extend the service life of these deteriorating structures.

3.3.1 Cured-in-Place Pipe Liner

Cured-in-Place Pipe (CIPP) lining is a technique where a soft sock is cured to become a flexible liner after being inserted within the pipe (ASTM 2016). A workable felt (non-reinforced) or fibre-glass (reinforced) woven sock is impregnated with a thermosetting resin prior to installation. When on site, the resin filled sock is either pulled through or inverted into the deteriorated host pipe. Once in place, the sock is then inflated using air pressure against the inner walls of the old pipe for curing. In order to set the resin, steam, hot water, or UV-light may be used depending on the type of product being used. Once curing is complete, the liner is transformed into either a conventional CIPP or high-strength fibre-reinforced CIPP. As these liners have been around for over 40 years, a retrospective investigation has been performed. Liners up to 25 years old have been assessed and determined to show minimal signs of distress indicating that they will deliver on their full service life (Allouche et al. 2014).

3.3.2 Spiral-Wound Liner

Spiral-wound lining employs a continuous plastic strip that is wound into the deteriorating pipe and the installation method generally does not require a water bypass. The strip is fabricated with male and female joint edges that can be chemically, mechanically, or thermally joined to the previous strip width to form a continuous pipe when lining the conduit. Under some circumstances, this winding process can be undertaken using a machine placed within the host pipe allowing the new pipe to be formed as it is slipped into place. Grouting between the liner and the host pipe generally follows unless a tight-fitting installation process is used. In general, an annular space between the host pipe and the liner is created and normally grouted. The strip can be made of different non-composite or reinforcing-composite materials of different cross sections to offer a variety of different deterioration resistant and stiffening solutions (Thornton 2005; Matthews et al. 2012).

3.3.3 Sprayed on Liners

Sprayed lining is a technique where a liquid material is jetted out a nozzle to form a continuous lining within the host pipe. The liner material may be formed from either cementitious or non-cementitious materials such as cement mortar, concrete, epoxy, urethane, polyurethane, polyurea. The lining is typically performed by hand with the use of jet nozzle or machine cast with centrifugal (i.e. spin) casting equipment.

Cement mortar lining involves the application of a shotcrete mix that can be reinforced with wire mesh. Typically, in reinforced applications, a first thickness of cementitious material is applied, followed by placement of the wire mesh, and then a final application of cementitious material. From experimental results, corrugated steel pipes rehabilitated with cementitious liners behave as rigid or semi-rigid structures (Becerril García and Moore 2015).

3.4 Grouted Liners

Grouted lining is a rehabilitation technique that may be employed to rehabilitate open bottom and closed conduit structures of various geometries over 3-metre span lengths. Depending on the configuration, either continuous sections of liner are pushed into the old deteriorated pipe or liner segments are brought into the deteriorated pipe and assembled from within. With open bottom spans exceeding 6 metres, sliding footing solutions which involve construction of new footings within the old structure, which then allow for full span segments of structural liner to be assembled outside of the host pipe, be pulled in segment by segment, and fastened together. When installed, the liner has a smaller diameter than the existing pipe and leaves a gap between the new and old pipe. The gap left between the liner and the deteriorated pipe is grouted with either a low, high strength, or expanding polymer grout. For grouted slip-lining, almost any type of pipe (e.g. thermoplastic, reinforced concrete, centrifugally cast pipe, fibre reinforced polymer, corrugated steel (CSPI 2010), fiberglass, steel reinforced polyethylene, tunnel liner plate etc…) may be used as the lining material.

From full scale experimental investigations on structures with a span < 3 m employing HDPE liners (Simpson et al. 2015), it has been observed that the system is significantly stiffened by the rehabilitation and most of the strength is associated with the annulus of grout if using high-strength grout. Further experimentation has presented the differences between performance of high and low strength grouts, and has examined the composite behaviors of the system (Tetreault 2016). It was observed that with low strength grout, the system was non-composite under all loading while with high strength grout the system demonstrated composite behavior at service loads, and only began to exhibit slip across the grout-liner and/or grout-host pipe interfaces at higher loads.

Corroded steel buried pipe structures with an adjacent soil void have also been tested before and after being slip lined with steel reinforced HDPE pipe and low strength grout (Moore and Peter 2019). The installation was grouted using low density foam-based grout in two stages, filling the annulus between the pipes and the void. Testing revealed that the installation had reduced deformations by an order of magnitude under service loads. Further, the ultimate limit state of the rehabilitated system, even though the grout had cracked, was controlled by plastic hinges forming at the crown, invert, and springlines of the liner system.

3.5 Soil Stabilization

Erosion voids adjacent to the steel buried structures and within the structural backfill can cause critical instability and generally require soil stabilization techniques to be employed. Settling foundations may also require soil stabilization if settlements are to continue beyond an acceptable threshold. Soil stabilization is generally a trenchless repair method where voids can be filled and surface profiles restored with pourable, pressure, and compaction-grouting methods. If worker access within the structure is possible, the grouting process may be carried out inside the structure. Alternatively, if accurate locations of the voids are known, the grouting process may be performed from the road surface. Further, piping and scour may also be limited by redesigning the inlet to enhance the ingress of water through the inlet to increase the flow capacity or by applying either protection barriers or filters.

3.5.1 Pourable Grout

Pourable grout is typically used to fill voids occurring below the haunches and inverts of culverts. The grout can be poured directly into the void, or alternatively through tubes. In order to ensure air isn't trapped when pouring grout, grout is poured into a tube that fills the void from the bottom and rises upwards until it escapes from another tube installed at the top of the void. For this process, Portland slurry cement-based grouts and mortars, chemical grouts, and foaming grouts can be used (Ballinger and Drake 1995).

3.5.2 Pressure Grouting

Pressure grouting is typically used to fill voids adjacent to buried CSP structures. Grout is pumped through a tube to the bottom of the void filling it in an upwards fashion. The grouting continues until grout exits the second tube located at the top of the void which is used for air to escape. For this process, Portland slurry cement-based grouts and mortars, chemical grouts, and foaming grouts can be used (Ballinger and Drake 1995).

3.5.3 Compaction Grout

Cement based and polymer-based compaction grout methods are typically used to stabilize compressible soil-systems. Cement grout is injected into the soil to form bulbs that displace and compact soil rather than permeating it (Mathews et al. 2012). Polymer compaction-grouting injects a high-density polymer into the soil system where it fills voids and pore spaces, expands from its original volume, and densifies the soil system. These processes might be used for soil stabilization, and to remediate settled roadways and sinkholes. The process has also been employed by the New Mexico Department of Transportation to stabilize a steel buried structure 4.3 m high and 6.4 m wide which experienced up to 15 cm of settlement (Jaques 2008).

3.5.4 Underpinning

In order to strengthen or rehabilitate the foundation of buried steel structures, underpinning is a technique that may improve weak underlying soils, raise settled foundations, and stabilize undesirable soil conditions. Foundation underpinning techniques bypass issues associated with the soil by adding additional structural elements to the soil to transfer loads to more competent soil layers. Many techniques may be applied for underpinning a foundation, including some of the grouting techniques previously described, to strengthen or even lift the settling foundation (Kazemian and Huat 2009; Hayward Baker 2019).

3.5.5 Inlet Modifications

Inlet modifications help promote the proper conveyance of flow through the conduit section. Under some circumstances, the flow of water may result in soil erosion around the conduit walls, uplift of the conduit ends, and scour around bridge footings, piers, and abutments. In order to avoid critical deterioration and failure, the CHBDC provides guidelines on how to mitigate these issues (CSA 2014). Generally, end treatments to mitigate soil erosion, uplift, and scour consist of:

- headwalls and cut-off walls of metal, masonry, or concrete;
- clay seals and impermeable barriers;
- embankment shaping to improve flow characteristics;
- rip rap, sheet piling, aprons, and invert paving

Adverse effects from uplift forces are successfully mitigated by installing appropriate concrete cutoff walls and headwalls. When challenged with water seepage through the embankment adjacent to the conduit, clay seals can provide an inexpensive and effective barrier. Further, when scour erodes soil, rip-rap and filter cloth are common solutions to provide protection (Loo et al. 2008); sheet piling, and flexible aprons may also be applied. Furthermore, the water flow may also be stabilized by redirecting the flow parallel to the piers and in turn improving the hydraulics of the waterway which in turn reduces the erosion. Finally, the channel bottom may also be protected with either a paved concrete invert or steel invert installation.

Conclusion

An investigation into the condition and rehabilitation of Ontario's bridge structures has been undertaken. Further, a review of the deterioration, rehabilitation, and Ontario's management of steel buried structures was performed. In particular, the processes of deterioration, potential rehabilitation opportunities, and inspection and condition rating have been discussed. From this investigation and review, it was found that:

- The population of buried steel bridges in Ontario has the highest proportion of bridges with the worst condition rating as well as the highest proportions of un-maintained and longest standing bridges. As a result, many of Ontario's steel buried bridges are going to require either rehabilitation or replacement within the next 5 years.
- The high proportion of unmaintained buried steel bridges in Figure 4 and the lack of content on the subject in Ontario's bridge management resources suggest that there are issues associated with maintenance and management of these structures in Ontario.
- Resources are available for assessing, managing, maintaining and rehabilitating steel buried structures. An overview of the deterioration and rehabilitation possibilities of steel buried structures is presented in this work, and a summary of the results is presented in Figure 6.

- Guidance on rehabilitation opportunities should be written into the OSRM.
- Accompanied by the review, flow charts have been developed to summarize the process of structural wall and soil deterioration, Figure 5, along with the rehabilitation options related to signs of distress, Figure 6.
- Deterioration is dependent on the local environment of the structure which varies significantly across Canada and within provinces. Methods to evaluate the rate of deterioration and select appropriate materials based on the in-situ conditions for a variety of site conditions have been identified in section 2.2.

With updated management practices and knowledge owners may become aware of issues in earlier stages and take more proactive action to potentially reduce rehabilitation costs, extend service life, and avoid replacement. With the improved condition information, asset management tools that assess risk and time-value of waiting, rehabilitating, and replacing may be more effectively used.

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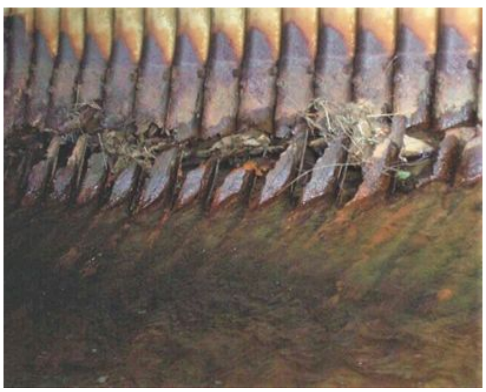
Table 1. Condition of Ontario Bridges

Bridge Material	Average Age (years)	Percent of Bridges With				
		BCI>70	70<BCI<60	BCI<60	Major Rehab	Minor Rehab
Reinforced Cast-In-Place Concrete:	50	73	22	5	51	20
Prestressed Precast Concrete:	31	94	6	0	72	17
Post-Tensioned Cast-In-Place Concrete:	41	92	8	0	84	21
Steel:	47	81	16	3	74	33
Weathering Steel:	31	96	4	0	60	17
Reinforced Precast Concrete:	16	96	4	0	45	7
Corrugated Steel:	36	60	23	17	27	10

3 Table 2. Types of Distress Due to Corrosion and Abrasion

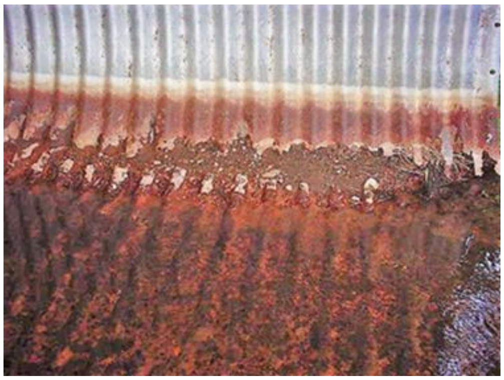
Type of Distress	**Commentary**
 Concentrated Bolt Corrosion*2.1  Joint and Seam Corrosion*2.2	Concentrated Bolt Corrosion - rust and salt deposits are forming around the bolts and seeping down the crests. As these deposits are above the waterline, a highly corrosive soil environment is likely driving the loss of conduit wall thickness from the soil-side. Salts are likely present from de-icing salt being distributed on the road surface above. Salts feature aggressive ions which also increase the rate of corrosion. As the joint leaks, rust and salt stains run down the crests and rust deposits concentrate on the outside surface of the bolts. Joint and Seam Corrosion - corrosion occurs due to external factors above the waterline as salt and rust deposits form at joints and seams. The affected section of pipe is located under a soft shoulder and the side slopes of the embankment. The parts under the pavement were not exposed to the salts.

 Invert Corrosion*2.3	Invert Corrosion - non-uniform deposits of rust are present within and around the water environment, below the springline, and concentrated between the haunches and invert. Moderate perforations on the crests around the waterline level are also visible. The development of perforations near and at the waterline suggest a corrosive water environment. At the waterline, the oxygen differential from water to air further promotes the site of the reduction reaction.
 Corrosion Section Loss*2.4	Section Loss - advanced stages of loss of wall thickness resulting in complete section loss around the haunches of the structure. The development of perforations at the tops and upstream side of the crests suggest some erosive water action. Dark, stained, wear zones suggest the galvanizing has worn away and steel is being exposed.
 Corrosion Perforation*2.2	Corrosion Perforation - corrosive water damage is present and seems to be the leading cause of barrel wall deterioration. Evidence of the corrosive water environment include: 1) irregular patchy patterns of rust 2) rust primarily located in bolt holes 3) lack of signs and possibility of abrasion.

 Abrasion & Corrosion[*2.1]	Abrasion & Corrosion - abrasive bedload deposits from peak flow events are present in the conduit. As the bed load is concentrated to the invert and lower haunches of the pipe, the relative zinc coating is uniformly worn down by abrasion. Following the event, the exposed the steel is readily oxidized when exposed to the atmosphere. As corrosion is uniformly concentrated to the area of the bedload, the loss of wall thickness is mainly driven by abrasion and accelerated by corrosion.

4 [*2.1](Hunt et al. 2010); [*2.2](Courtesy of Dr. Ian Moore); [*2.3](Moore 2008); [*2.4](El-Taher and Moore 2008);

6 Table 3. Soil Erosion Signs of Distress

Types of Distress	**Commentary**
 Loss of Haunch Section*3.1	Loss of Haunch Section – the section loss facilitates erosive action by offering sites for infiltration as water can seep from the embankment into the conduit and piping as internal water pressure during peak storm events may force water to seep into the soil.
 Crown Joint Separation*3.2	Crown Joint Separation – joint separation at the crown has occurred due to differential deformations along the crown. The separation allows for soil infiltration to occur as water can seep in from the embankment carrying soil particles with it. In buried steel bridges, the largest unbolted space is 500 mm which helps minimize joint separations.
 Piping Void at Outlet*3.3	Piping Void at Outlet - a large void has formed around the haunch and invert of the buried CSP pipe arch. The development of the void may be due to either loose bedding material underneath the pipe or excess scouring at the outlet. Peak flow events can build high water pressures, which seepage flow underneath the pipe, if the capacity of the conduit is insufficient or if the conduit becomes obstructed.

Small Piping Void[*3.3]

Small Piping Void – a small piping void has developed along the invert of a pipe. Piping may occur along the length of the pipe until the flow exists the end wall of the embankment. Typically, preventative measures include proper compaction practices and seepage collars.

Large Void at Invert[*3.2]

Large Void at Invert - a large void and stream underneath the pipe has formed as piping erosion continued to develop the void underneath the pipe. As piping progresses, water and bedload flowing over exposed sections of soil may detach and transport soil particles.

Continuous Barrel Misalignment[*3.3]

Continuous Barrel Misalignment – large soil movements likely due to soil erosion have resulted in a continuous barrel misalignment. For steel buried bridges, joints are fastened with bolts and no circumferential seams exist to form differential movement between segments. Consequently, the barrel has absorbed the movement in extreme shape distortions and misalignment.

Transverse Surface Crack[*3.2]

Surface Settlement[*3.2]

Surface Sink Hole[*3.2]

Transverse Surface crack & Surface Settlement - signs of inadequate support from soil due to either soil erosion or soil compaction issues during construction are present on the road surface over the buried soil structure. Soil erosion may extend to the surface through either infiltration or void collapse mechanisms. Signs of structural distress are seen as large surface depressions with flexible asphalt overtop and large transverse cracks with more brittle roadways. In some cases, soil erosion can leave the road surface unsupported with minimal signs of distress. With soil movements causing surface depressions, voids, and barrel settlements, joint separation and other points for infiltration are likely present.

Surface Sink Hole - soil erosion has developed to the point of road collapse. Soil infiltration has likely extended to the surface and as the void collapsed a sink hole was formed. The buried conduit beneath has likely collapsed or undergone large joint separations and barrel settlements.

[*3.1](El-Taher and Moore 2008); [*3.2](Hunt et al. 2010); [*3.3](Matthews et al. 2012);

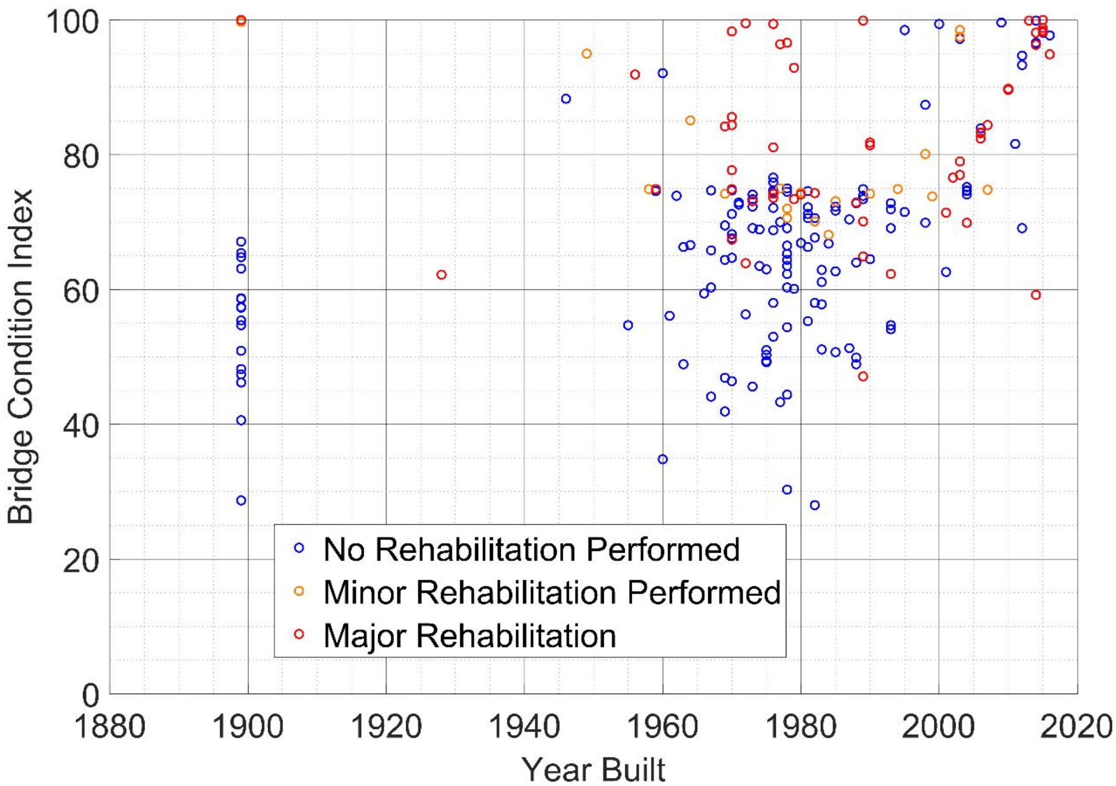


Figure 1. BCI and Age of Buried Steel Bridges in Ontario

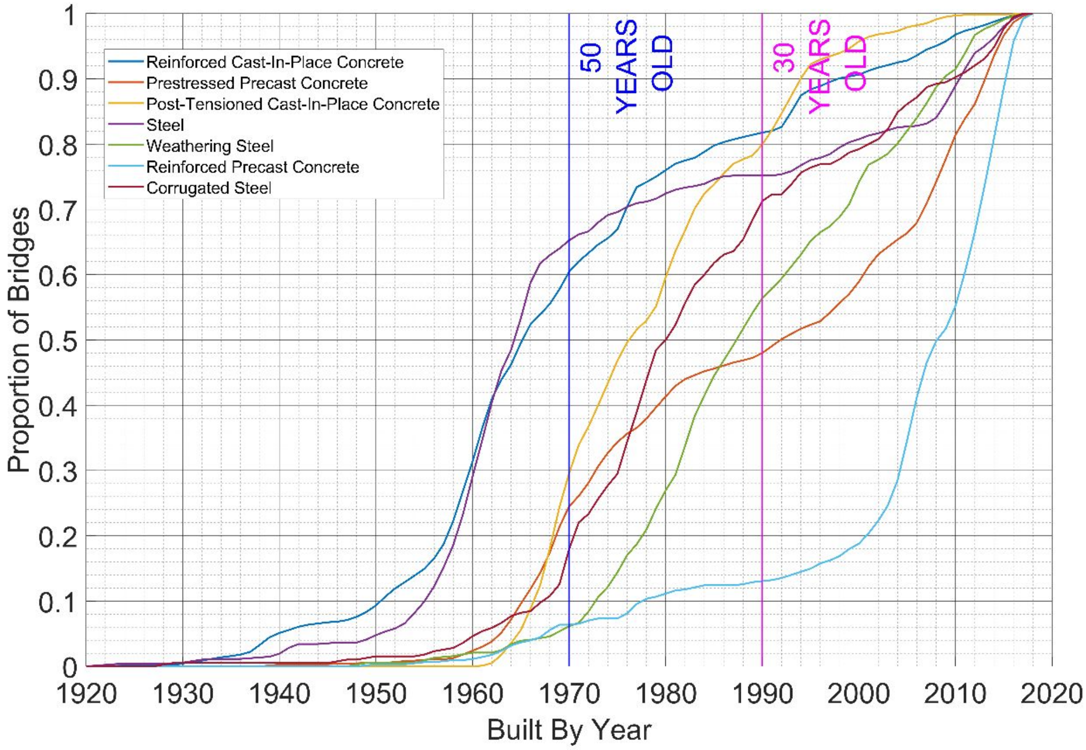


Figure 2. Proportion of In-Service Ontario Bridges Built by Year

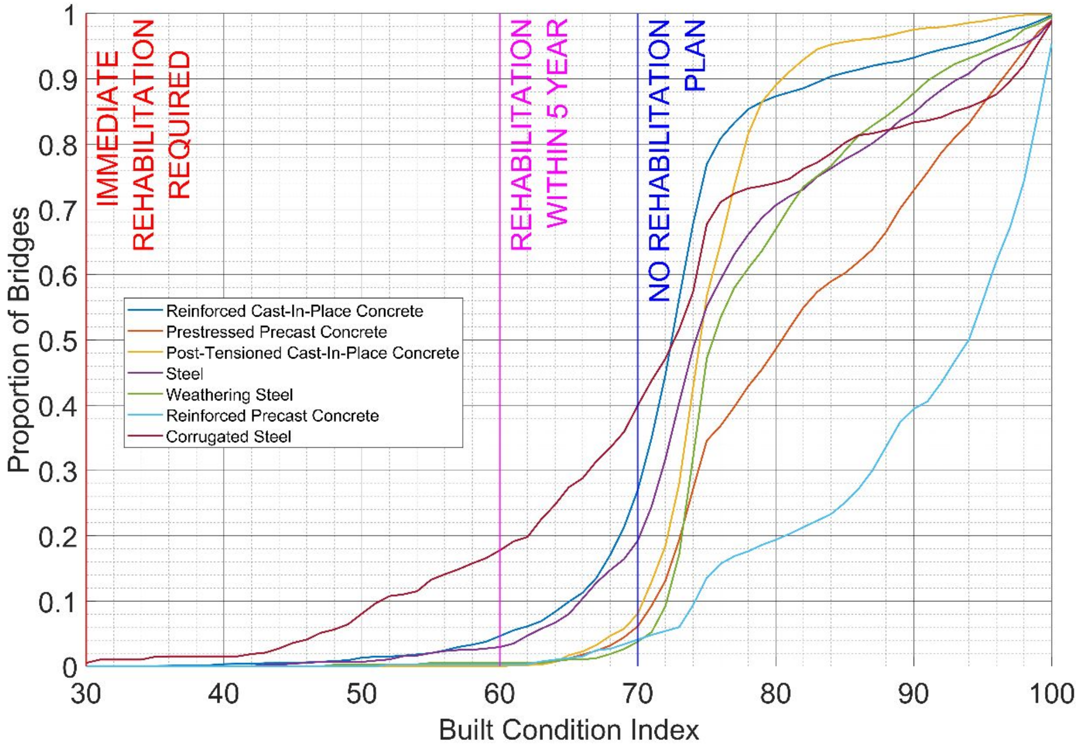


Figure 3. Proportion and Condition of All Common Bridge Materials

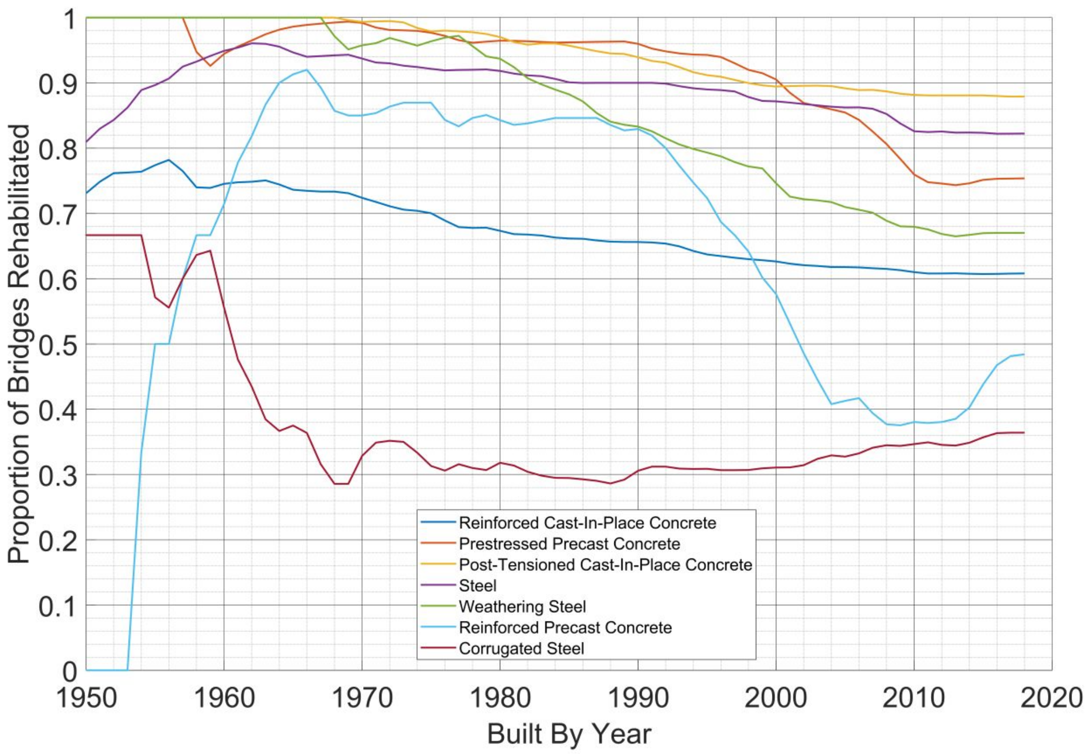
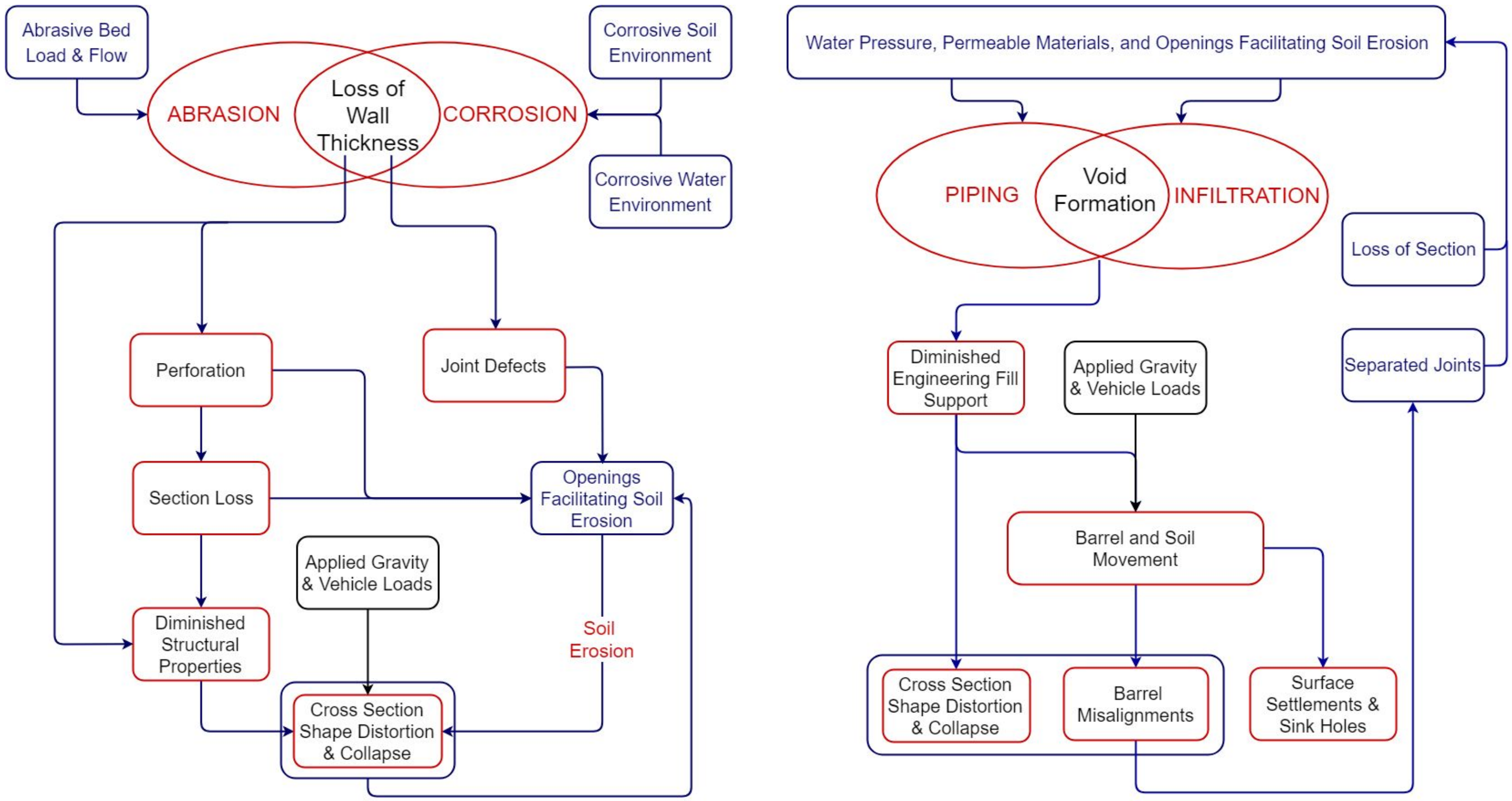


Figure 4. Proportion of Bridges Rehabilitated Built by Year "x" and Earlier



Structural Wall Deterioration

Soil Erosion

Figure 5. Deterioration of Steel Buried Bridges

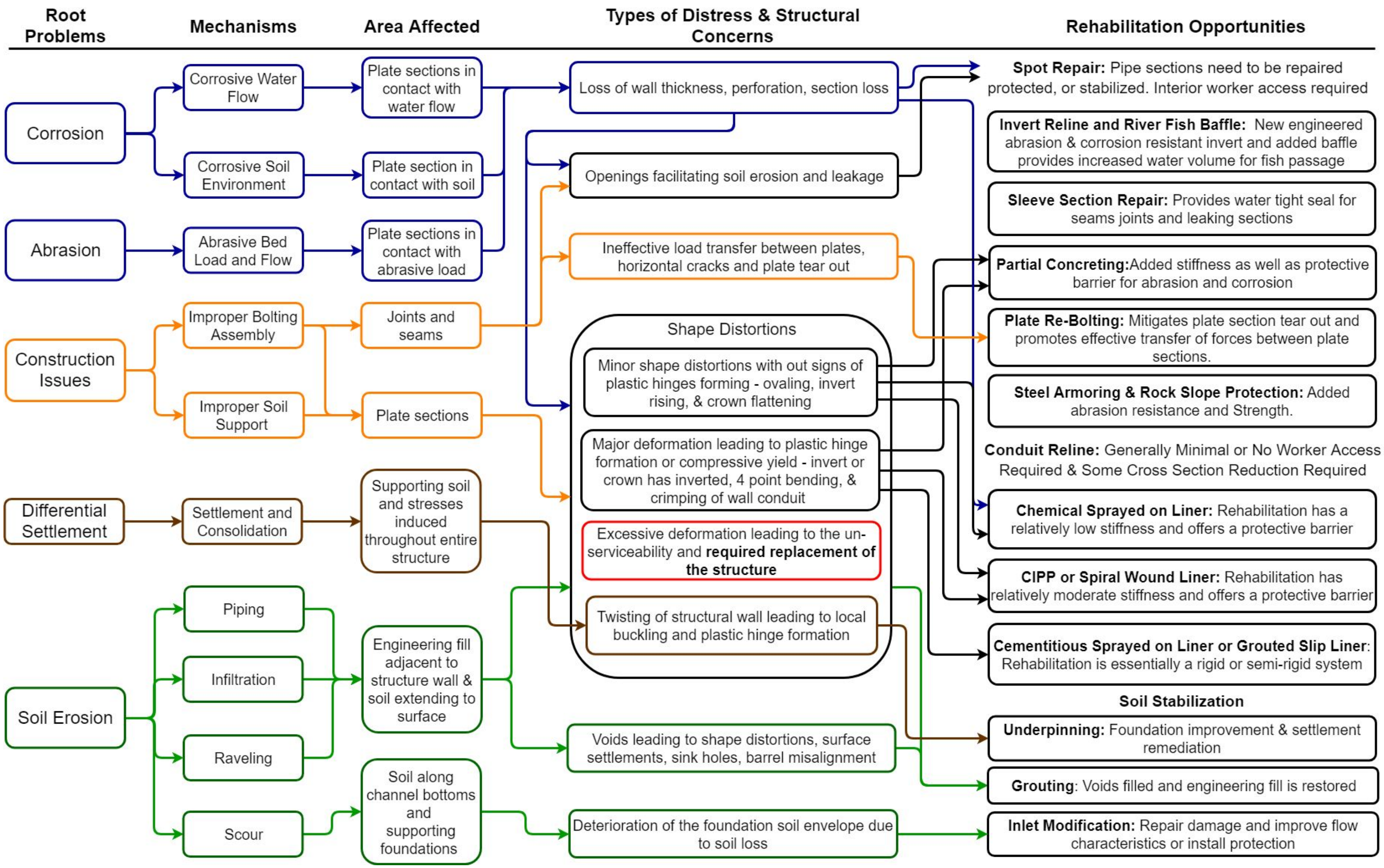


Figure 6. Rehabilitation Options for Distressed Steel Buried Bridges