Fundamentals of Sustainable and Resilient Buried Structures

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Paper prepared for presentation
at the *Climate - How is Your Jurisdiction/Organization Responding* Session
of the 2017 Conference of the
Transportation Association of Canada
St. John's, NL

Abstract

This paper's objective is to introduce a design approach which improves the performance and value of buried structures. This approach involves widening the design lens to more systematically consider sustainable and resilience aspects.

Owners desire sustainable transportation networks which regenerate the environment, support society, and minimize financial cost. For a transportation network to be sustainable it needs to meet the needs of current and future generations in terms economic vitality, social equity, and a healthy environment (Transportation Research Board, 2017). A sustainable transportation network is resilient and can adapt or accommodate unexpected events with minimal disruption to society (Transportation Research Board, 2017). Transportation networks lacking resilience experience disruptions, resulting in large repair costs, negative costs to the economy from disrupted travel, and expose the public to safety hazards. Agencies need resiliency to address climate change impacts on transportation systems within the context of their available resources

Buried structures, commonly referred to as buried bridges, culverts, or soil-metal structures, are structures which derive their support from composite interaction between the structure and surrounding soil. Buried structures have spans up to 40 m and are found across Canada. Buried structures have several accelerated bridge construction benefits such as an ability to be rapidly constructed, and installed costs which are typically 33% to 67% lower than traditional beam bridges (AFS40, 2013).

This paper will provide insight into where buried structures provide value compared to traditional beam bridges, and practical approaches which increase the likelihood of a buried structure design that:

- Is better able to withstand the test of time and unexpected events;
- Minimizes financial resources;
- Minimizes disruption and in some instances, regenerate society and the natural environment.

Keywords: Buried structures, buried bridges, resilience, climate change, extreme hydraulic events, scour, piping, washout, CHBDC.

Introduction

Sustainability and Resilience Bridges

Today's bridge industry has a problem: bridges do not sustain society's needs, and many bridges are unable to adapt to changing conditions. 'Current bridge design, construction and operation of our infrastructure has a substantial negative impact on our natural resources and ecological systems. One which treats materials, energy and fresh water supplies as if they were inexhaustible and the environment as if it were infinitely regenerative' (Transportation Association of Canada, 2015). Some in-service bridges are not able to meet or easily adapt to current functionality, social, or environmental requirements. More specifically, some bridges are damaging ecosystems or disrupting traffic, leading to owners spending funds on rehabilitation and replacement.

Sustainability is defined by Merriam-Webster's online dictionary (Merriam-Webster, 2017) as the ability to sustain such as:

1. of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged sustainable techniques sustainable agriculture;
2. of or relating to a lifestyle involving the use of sustainable methods sustainable society.

Resilience is the ability to bounce back after a disaster and involves anticipating disaster and developing systems to mitigate them (John Hopkins University, 2014). Sustainable practices contribute to resilience, and both are the ultimate goals of a healthy society (John Hopkins University, 2014).

To frame sustainability and resilience from a bridge perspective, visualize a bridge which is life cycle efficient, minimizes traffic disruption, and not only mitigates negative environmental impacts, but can also regenerate. This paper outlines a design approach for buried structures which produces buried structure crossings more likely to achieve this.

Buried Structures

Soil-metal structures are comprising shells of corrugated plates and surrounded with well-compacted soil, were first used in the United States at the beginning of the 20th Century (Bahkt, 2007). Buried structures, commonly referred to as soil-metal structures, culverts, or buried bridges, are constructed as open bottom structures (structure is supported on a footing system) and closed bottom (structure itself forms the footing).

Buried structures are used as hydraulic, wildlife and traffic crossings and are a viable option for most small to medium span bridge crossing sites. Buried structures are suitable when a single span less than 40 m is required, and when the vertical distance between the top of footing and overpass elevation is greater than 0.2 * span. Multiple barrel crossings may be used to cross larger spans as illustrated in Figure 1.

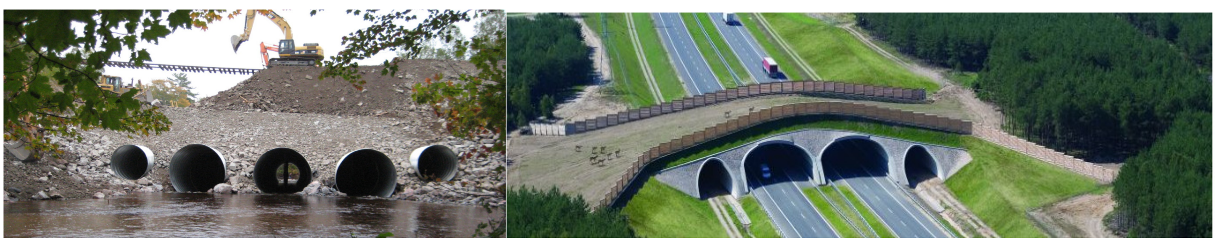

Figure 1 - Multiple Conduit Crossings

Buried structure design involves geotechnical design of the foundation and surrounding backfill, structural design of the structure and footing (if applicable), and hydrotechnical design (including scour) when the structure serves as a hydraulic conduit. Buried structure design guidelines are found in the Canadian Highway Bridge Design Code (CHBDC).

CHBDC Design Standard

Standards help to ensure better, safer and more efficient methods and products, and are an essential element of technology, innovation and trade (Standards Council of Canada, 2017). Design standards help owners realize more value from their investment. Buried structure design standards have been continually evolving over time with the intent of realizing better, safer and more efficient methods and products. However, there are instances where an in-service buried structure experiences a performance failure such as a blocked fish passage, a durability issue, or a washout. These failures have led to significant rehabilitation or replacement costs. Challenges are generally caused by:

1. Original design/construction was insufficient for the original design conditions.
2. Current conditions differ from original design conditions (e.g. a gravel road is paved and has high road salt application);
3. Current performance requirements differ from original design requirements (e.g. a species wanting to use the structure becomes at risk);

Design codes outline structural, geotechnical and hydrotechnical design requirements and considerations based on the current knowledge and lessons from past failures. Despite these efforts, crossings which satisfied the design standard at time of construction may not satisfy current design requirements for their entire design service life. Owners are looking for structures which are better able to absorb, recover from, or more successfully adapt to these unplanned or unforeseen conditions. In other words, owners are looking for structures which are more resilient.

In some instances, designers have attempted to account for resilience concerns by applying engineering judgement and/or design experience to develop design criteria beyond standard requirements. However, these are typically based on the designer's knowledge and experience, and are difficult to apply consistently.

To better account for sustainability and resilience related concerns, CHBDC Technical Subcommittee 2 (TSC 2) is developing requirements for the 2019 CHBDC which define sustainability and resilience considerations (2, 2017). Section 2 will outline general sustainability and resilience definitions along with a sustainability design concept. These changes are intended to improve the sustainability and resilience of bridges, increasing the likelihood of crossings realizing their maximum value.

This paper will outline the most relevant considerations for applying sustainability and resilience design criteria to buried structures. The goal of more formally incorporating sustainable and resilient considerations is to improve performance for the life of the structure and consequently, maximize value. As project parameters vary greatly, it is not possible to define a one size fits all approach. Instead, this paper will attempt to present a fundamental understanding of how to best apply sustainable and resilient buried structure design considerations. The expectation is doing so will maximize a crossings value and evolve a design closer to designing to what matters.

Buried Structure Challenges

While most in-service buried structures satisfy design requirements, there are instances where a buried structure has experienced a performance challenge. Performance challenges are defined as a component failure which result in the structure not meeting functional, environmental or societal requirements. As a result, remedial action is required to bring the crossing's performance in line with what matters. This remedial work involves additional financial cost, disrupts traffic and society, and has potential negative environmental impacts such as sediment contamination.

The following is an overview of the most common buried structure performance challenges, based on the author's experience.

Wildlife Barriers

Buried structures may serve as wildlife overpass or underpass crossings. Buried structures conveying water commonly require wildlife passage such as fish and ungulates. Figure 2 illustrates a closed bottom buried structure which blocks fish passage, commonly referred as a 'perched culvert'. Perched culverts have potentially devastating impacts on streams as they either restrict or prevent fish passage. Only one perched culvert along a stream is needed to prevent fish migration. Perched culverts are a huge financial risk to owners. For instance, in Washington State, a Federal court injunction is requiring the state to replace approximately 1000 fish barrier buried structures by 2030 (Washington State Department of Transportation, 2017), at an estimated cost of $2.4 billion USD (LE, 2015). Rehabilitation with fish ladders (Wilcock, 2016) or structure replacement is usually required when buried structures no longer satisfy current wildlife passage requirements. It is noted fish passage is not the only wildlife passage concern. Other species such as herpetofauna and mammals are of concern, as is the impact of the crossing on the local ecosystem.

Figure 2 - Impeded Fish Passage (Warren, 2015)

Insufficient Hydraulic Capacity

Buried structures may be insufficiently sized to convey current or future water volume demands. Buried structures may have silted in over time (Figure 3), have inlets blocked by debris such as tree branches (Cafferata, Spittler, Wopat, Bundros, & Flanagan, 2004), undergone very large settlements relative to the stream elevation, or be inadequately sized to an increased water volumes from climate change and/or a green field reduction in the watershed. The impact is that sites with undersized conduits are at risk of road washouts. Sites with multiple barrel conduits are more prone to debris blockages. Cleanout maintenance or structure replacement is often required.

Figure 3: Blocked Culvert (photo courtesy of Sean Wong, BCMOTI)

Scouring and Washouts

Scour/washouts involves the erosion of foundation and/or the surrounding, supportive engineering backfill material. Roads may be closed as a result. In some instances, structural collapse may follow, leading to an extended road closure. Structures which have either scoured out or washed out are either rehabilitated or replaced.

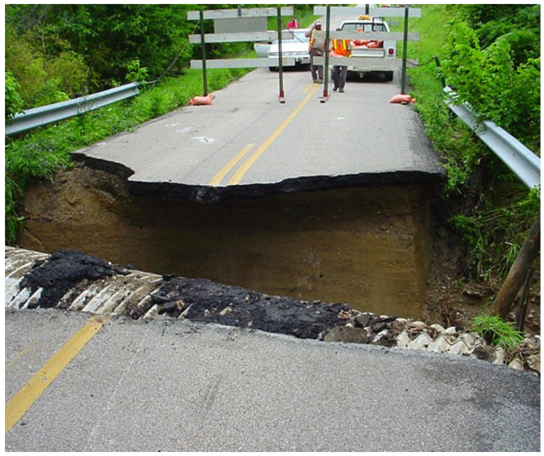

Figure 4: Scouring Washout Leading to Road Closure (Butler County Engineer's Office, 2001)

Durability

CHBDC clause 2.3.1 indicates 'The designer shall consider the environmental conditions that exist at the site or are likely to exist during the design life of the structure and shall assess their significance in relation to the possible mechanisms of deterioration in the structure.'. While this clause has good intentions, its application is not always done well. For example, unexpected environmental changes such an increased use in road salt, or utilizing products in environment conditions which the product was not designed for are major factors in structures not realizing their design service life. When invert corrosion is experienced, there is an increased risk of scouring and washout occurring, increasing society's risk. Buried structures with durability issues are either rehabilitated or replaced.

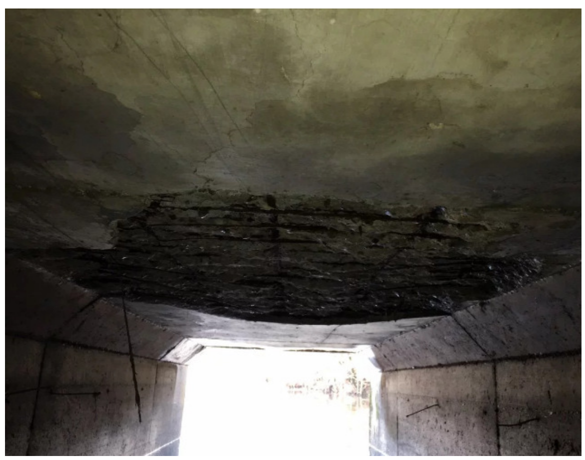

Figure 5: Spalling Resulting in Four Month Closure (Cline, 2015)

Resources Demand and Waste Generation

Buried structures consist of the structure, foundation system, and supporting backfill. Each of these components requires material resources to fabricate and construct the buried structure from. Wastes are generated during the entire life cycle ranging from material extraction to fabrication to transportation, construction, operation, and decommissioning. Considering the current sustainability bridge infrastructure challenges, reducing virgin material use along with energy and waste creation is needed to move towards more sustainable bridges.

Sustainable and Resilient Design Approach

Buried Structures: Sustainability and Resilience Fundamentals

The goal of designing with a more sustainable and resilient design lens is to add value. To maximize design value, one must first understand what sustainability and resilience related aspects are most relevant for buried structures. Table 1 presents an assessment of both the significance and relevance of the twelve sustainability themes outlined in TAC's Sustainability Considerations for Bridges Guide (Transportation Association of Canada, 2015). Resilience has been added in Table 1.

Table 1: TAC Sustainability Considerations for Bridge Guide Relevance

Item	TAC Objective	Significance for a Buried Structures	Current Relevance in Practice
1	Reduce Virgin Material Use	Moderate for structural and backfill material.	Low.
2	Optimize Waste Stream	Moderate relevance.	Low.
3	Reduce Energy Use	Moderate relevance for buried structures with structural components being of significant size.	Low.
4	Reduce Emissions to Air	Low.	Low.
5	Maintain or Improve Hydrologic Regime Characteristics	High relevance when aquatic wildlife is present.	Moderate. Open bottom conduits are used in some instances as required by regulation.
6	Maintain Biodiversity	High relevance when aquatic wildlife or fractured and stronger ecosystems present.	Moderate. Primarily a concern as required by regulation.
7	Engage Community Values and Sense of Place	Moderate when relevant.	Moderate when relevant.
8	Improve Safety	Moderate. Buried structures crossings do not require expansion joints and road surfaces are less likely to prematurely freeze.	Low. Primary decision based on economics.
9	Improve Access and Mobility	Low.	Low.
10	Improve Local Economy	Moderate. Buried structures facilitate more local bids.	Moderate. Relevance increases for remote sites.
11	Increase Lifecycle Efficiency	High.	Low. Installed cost rather than life cycle cost usually considered.
12	Promote Innovation	High. Required to address challenge.	Low. Realized through performance based specifications. Sustainability or resilience performance criteria is rare
13	*Resilience	High. Many of the challenges relate to resilience.	Not accounted for in a systematic way.

*Not a specific TAC Guideline objective.

The following is a distilled list of themes most likely to yield value for typical buried structures. Each category will be discussed in more detail below.

- Material Use (item 1)
- Waste and Energy Footprint (item 2, 3, 4)
- Accommodating Nature (item 6, 13)
- Resilience (item 13)
- Innovation (item 12)

The ideal way to attain maximum value is to seek out features which have mutually reinforcing benefits. Mutually reinforcing benefits offer enhancements in more than one category and have limited to no negative aspects. Innovative fosters mutually reinforcing benefits. When mutually reinforcing benefits are not possible, solutions which balance functional, economic, social and environmental aspects are sought.

Material Use

The intent of this objective is to reduce the use of virgin materials and resources to preserve finite resources (Transportation Association of Canada, 2015). For material use, the 3R hierarchy is recommended: first reduce, then reuse, then recycle. Buried structures have three material primary material sources: the footing, structure, and engineered backfill. All assessments require a balance between economics, the environment, and safety.

- Reduce: When possible, reduce the amount of imported material (e.g. – backfill) while still satisfying all functional requirements.
- Reuse: All engineering backfill is reusable. When practical, prefer structural materials which are not only recyclable, but also in demand.
- Recycle:. When practical, prefer backfill and structural materials with a higher recycled content. An example would be putting a decision weight in the tender specifications relating to the recycled material content.

Figure 6 illustrates a buried bridge which was constructed using structural steel with a 75% minimum recycled content, and 100% recycled concrete aggregate backfill.

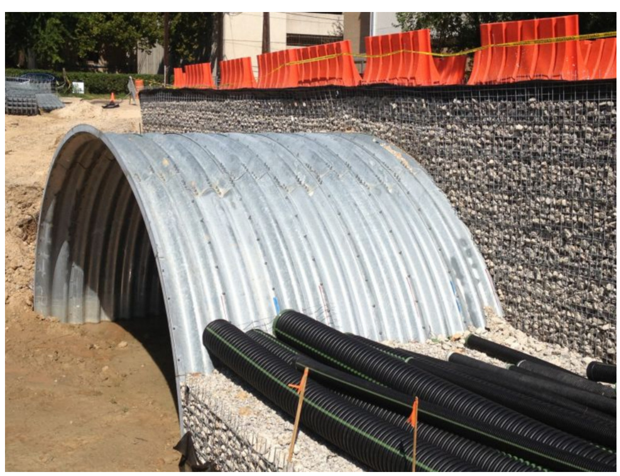

Figure 6: Buried Bridge Constructed with High Recycled Content

Waste and Energy Footprint

The intent of this objective is to reduce waste generated, energy consumed, and air emissions through all stages of the process from material extraction to transportation to decommissioning (Transportation Association of Canada, 2015). Life cycle assessments provide valuable information for evaluating the waste and energy footprint of one solution vs. another by accounting for all impacts from material extraction through to fabrication, transportation, construction and decommissioning. For example, a life cycle assessment of concrete box culverts vs. steel buried structures indicates that when the recycled content of steel is 37%, a steel buried structure will for variety of case studies, produce on average half the global warming potential emission of a concrete box culvert (Du, Pettersson, & Raid, 2015). When practical, prefer backfill and structural materials with a higher recycled content. An example would be putting a decision weight in the tender specifications relating to the waste and energy footprint.

Accommodate Nature

The intent of this objective is to maintain and/or regenerate the size and diversity of plant and wildlife populations in the surrounding ecosystem, in support of the natural systems and the services upon which we depend for daily life (Transportation Association of Canada, 2015). Buried structures are commonly used for water and/or wildlife passage. The negative impacts of not properly accommodating aquatic species has impacted ecosystems and resulted in unplanned rehabilitation or replacement of in-service structures.

As negative impacts of wildlife-vehicle collisions on both driver safety and species health increase, the need for safe wildlife passage with structures such as buried structures increases. Designing buried structures to serve as effective wildlife passage structures increases the probability the structures will meet service requirements for its entire design life.

An understanding of ecological impacts of transportation systems is still being developed. For example, in floodplain structures, the life requirements of a wide variety of species are strongly related to the health of a gravel-bed river's ecology (Haur, et al., 2016), which is related the impacts of structures crossing the river. When possible, it is recommended nature be accommodated as a structure which best accommodates nature is expected to have a higher probability of realizing its design service life. Figure 7 illustrates an example of a buried structure which better accommodates nature. The structure does not encroach upon the creek, leaves room adjacent to the creek for wildlife passage, maximizes light exposure, and is an open bottom structure, leaving the streambed intact.

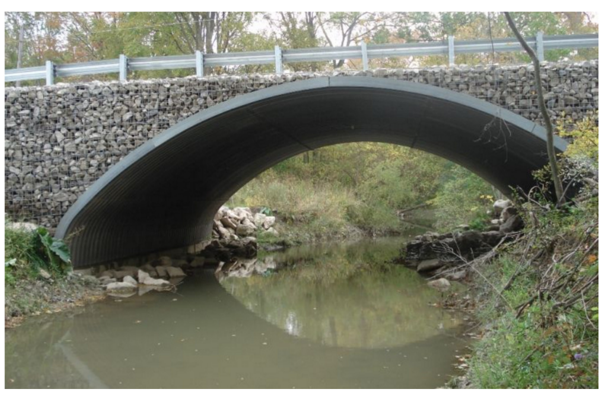

Figure 7: Open Bottom Structure Accommodating Nature

Resilience

Buried structures can satisfy resilience concerns when intentionally designed for them. When resilience is not intentionally considered, buried structures may or may not meet resilience criteria. It is desirable to move to a more systematic design approach which involves assessing a crossing's resilience as a function of the crossing's exposure (likelihood of being exposed to unexpected conditions), failure probability (potential of a system component failing when exposed to an unexpected condition), and consequence (impact if a component fails, for example, is traffic disrupted for days or weeks). A crossing's resilience may be evaluated using a tool such as the Resilience Evaluation Matrix presented in Table 2.

A buried structure's resilience is a function of site parameters and design. When desired, features may be added to buried structures to increase resilience. To facilitate effective increased resilience design, owners must first define which exposure conditions additional resilience is needed for. Designers may then balance economics and resilience requirements to attain maximum value.

Table 2: Resilience Evaluation Matrix

Concern	Exposure	Failure Probability	Consequence	Risk Score
Hydraulic blockage				
Higher foundation settlement				
Future wildlife crossing need				
Backfill washout				
Scour				
Higher than designed water flow				

Rating: 1 = low, 2 = moderate, 3 = high

Figure 8 illustrates an example of a buried structure intentionally designed for a greater resilience to higher water flows (left), and the consequences of a structure with a high risk score (right). Resilience of the design on the left was increased by selecting a structure with a span greater than the stream width, use of metal headwalls to reduce backfill water infiltration, and use of a deep corrugated metal box culvert which is likely able to remain structurally undamaged should the engineered backfill fail. A structure which remains undamaged even though engineered backfill fails is likely to result in a short road closure to replace backfill compared to a long road closure if both the backfill and structure were to fail.

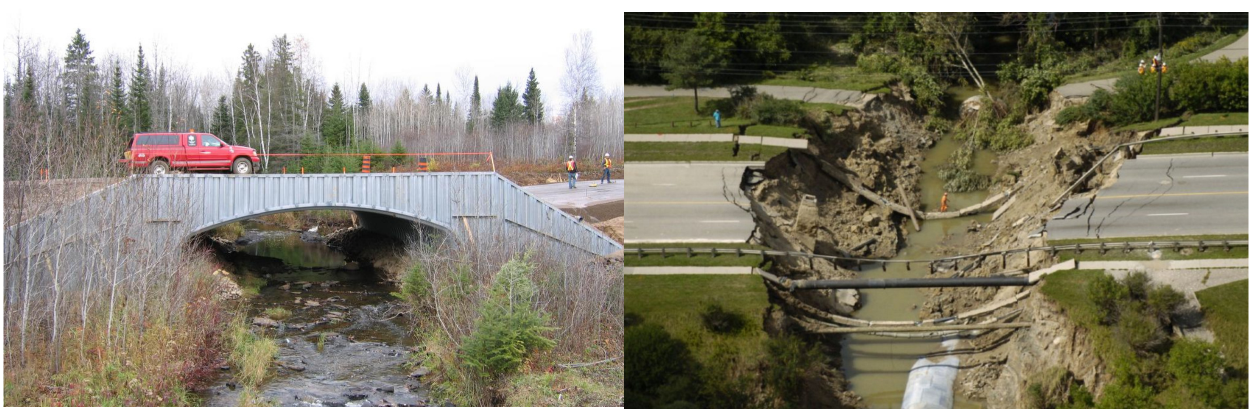

Figure 8: Adding Resilience to Avoid Backfill Washout

Table 3: Resilience Evaluation of Figure 8

Concern	Exposure	Failure Probability	Consequence	Risk Score
Higher than designed water flow: left structure	1 (low due to large end area).	1 (soil: metal headwalls protect. Structure: deep corrugated box	2 (major throughway, long detour. If soil fails, short	2

		culvert has low reliance on soil support).	road closure as structure is likely undamaged).	
Higher than designed water flow: right structure	3 (small end area and no end treatments)	2 (soil: high as no end treatments, and high reliance on soil support as embankment is high)	3 (major throughway. If soil failure occurs, long road closure as structure will fail.)	18

Innovation

Bridge crossings currently have sustainability and resilience related challenges. To address these challenges, the bridge community needs to change and innovate. The intent of this objective is to encourage innovation and develop benchmarks for continuous improvement towards the overarching goal of attaining maximum value by having more sustainable and resilient buried structures (Transportation Association of Canada, 2015). Innovations at all project stages including design, procurement, construction, operation and rehabilitation. Examples include utilizing buried structures where they offer more value compared to traditional solutions, considering life cycle costing, and implementing procurement criteria to promote more sustainable and resilient buried structures. Innovation, particularly procurement which promotes innovation, has the greatest potential impact.

Buried vs. Beam Structure Crossings

The primary difference between a buried structure and a beam structure (Figure 9) is a buried structure relies on support from the structure and soil, whereas a beam bridge relies on support from the structural components alone. Therefore, assessing the sustainability and resilience of these two bridge types is primarily a function of the soil. Table 4 includes a general assessment on the impact of soil, and concludes that provided the soil remains in place, buried structures are likely to be more sustainable and resilient crossing than a beam crossing. In some instances, buried structures may be designed to survive partial or complete backfill loss. As backfill loss risk is primarily associated with water, buried structures are expected to be a preferred solution for non-hydraulic crossings.

Figure 9: Buried (left) and Beam (right) Structure Crossings

Table 4: Buried vs. Beam Crossings

Category	Soil Impact	Preferred Bridge Type
Installation Cost	Buried structures 33 to 67% lower cost on average (Transportation Research Board, 2017).	Buried
Material Use & Waste	A significant portion of the crossing's load carrying resistance is sourced from locally available material and is easily reusable.	Buried
Resilience: Backfill Loss	Structure at higher risk of failure when backfill is lost.	Beam
Resilience: Road Salt	Protects structural elements from exposure.	Buried.
Resilience: Heavier Live Load	Provides high load carrying and load path redundancy.	Buried
Foundation Settlement	Variable impact. Flexible buried structures are typically more tolerant of settlement than rigid beam structures.	Buried
Road Surface	Insulates road surface reducing deck freeze risk. No expansion joints needed, reducing maintenance.	Buried

Case Study: Roy Creek Crossing

The following case study outlines a project specific approach, and evaluates the sustainability and resilience aspects of an innovative project owned by BCMOTI. Figure 10 illustrates the existing structure, which had reached its service life. This structure is on Vancouver Island, and is in an area where multiple partners are collaborating to rehabilitate this salmon and trout stream, an initiative which began in 1981 by local community members.

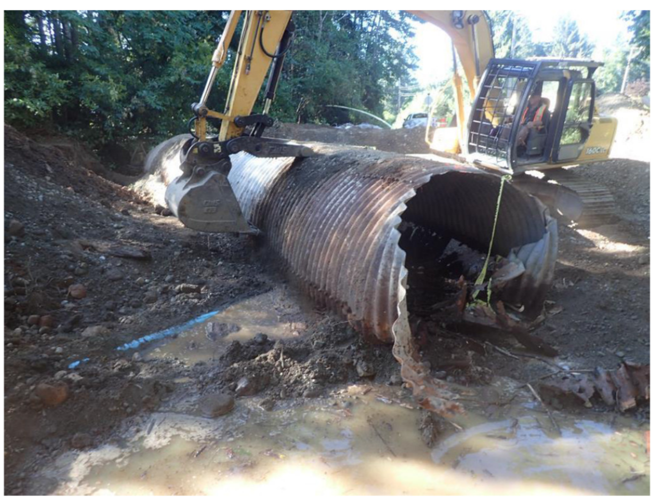

Figure 10: Structure at End of Service Life (photo courtesy of Sean Wong, BCMOTI)

Sustainable and Resilient Design: Use Table 5 to assess whether buried structure relevant sustainable and resilience considerations can be incorporated into the project. When the design is complete, use Table 2 to evaluate the design's resilience and modify the design if a more resilient solution is required.

For this site, an innovative geosynthetic reinforced soil (GRS) buried structure was used, the first of its kind for BCMOTI. A GRS open bottom buried structure consists of reconstructing the stream and placing the structure directly on a natural boulder footing. Horizontal deadman anchors and geosynthetic fabric is placed in the backfill to provide load carrying resistance and increase resilience by effectively sandbagging the backfill against movement from water piping through the backfill. Steel with a polymer coating was used to provide an estimated material service life of 100 years. An alternative to galvanized coating was required as the existing structure clearly demonstrated the water environment was not suitable for galvanized steel.

Table 5: Buried Structure Sustainable and Resilience Considerations Checklist

Item
Material Use ☐ Local backfill reused when possible. ☐ Recycled or reclaimed backfill materials considered. ☐ Use of recycled materials in the structure considered.
Waste and Energy Footprint ☐ More efficient transportation considered (e.g. rail vs. truck or nesting pipes). ☐ Incorporate energy-efficient practices for installation. ☐ Minimize installation time through measures such as using quality backfill materials. ☐ Use a design and materials which minimize footprint (e.g. use life cycle assessments)
Accommodate Nature ☐ Structure and footings dos not encroach into stream. ☐ Wildlife passage permitted for all aquatic and terrestrial species present. ☐ Streambed impacts eliminated. ☐ Materials which adversely affect water quality avoided.
Resilience ☐ Long service life considered. ☐ Accommodate nature/stream widths (if applicable). ☐ Consider less permeable end treatments and/or backfill reinforcement. ☐ Consider structure shapes less susceptible to backfill loss (e.g. box culvert vs. arch).
Innovation ☐ Value of buried structures leveraged. ☐ Innovative designs which maximize resilience and sustainability value considered. ☐ Resilience design criteria assessed and defined. ☐ Procurement considers life cycle efficiencies rather than lowest installed cost. ☐ Procurement based on performance specification. ☐ A sustainability evaluation system is utilized.

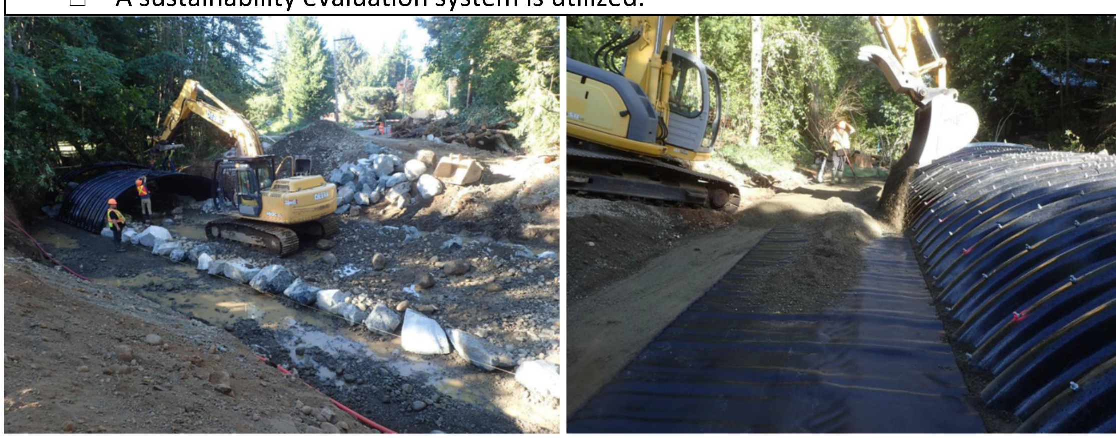

Figure 11: GRS Buried Structure During Construction (photo courtesy of Sean Wong, BCMOTI)

Figure 12 illustrates the vegetated headwall end treatment, which promotes vegetation and insect growth (i.e. – fish food) at this crossing. "At Roy Creek Royston Road a closed-bottom culvert that was past its service life was replaced with an open-bottom fish-stream crossing with vegetated retaining walls, was cost-effective and straightforward to install with conventional construction equipment, sufficiently robust to withstand climate change impacts and provide over 75 years of service life. Related habitat restoration was done as part of this project and throughout the watershed by multi-partner collaborations as part of the rehabilitation of this salmon and trout stream, that began in 1981 by local community members. The new fish-friendly stream crossing is an important component to ensure BC's wild fisheries are sustained and restored." (Wong, 2016). Table 6 evaluates the sustainability and resilience enhancements attained with the GRS buried structure solution.

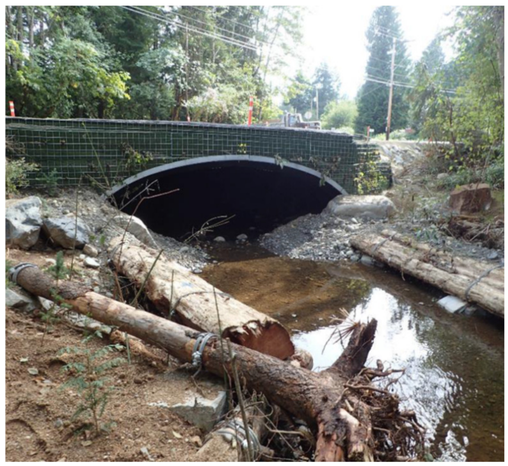

Figure 12: Constructed GRS Buried Structure (photo courtesy of Sean Wong, BCMOTI)

Table 6: Sustainability Enhancement Record

Category	Enhanced Sustainability and Resilience Attained
Functional	Enhanced durability with open bottom and polymer coated structural plate. Extreme weather resilience with geotextile reinforced backfill. Lower maintenance with open bottom, wider span structure.
Social	Fish restoration – cultural support.
Environmental	Fish restoration. Vegetated wall provides supports local ecology. Reconstructed natural streambed enhanced stream ecology. Natural footings used instead of imported material.
Economic	Accelerated construction (light weight equipment with small construction footprint) Life cycle efficiency (maintenance, durability, construction) Natural footings reduced required span (span taken from inside of structure rather than inside of footing). Natural footings eliminated the cost of imported footings.
Innovation	BCMOTI's first GRS buried structure.

Conclusions

Today's bridge industry has a problem: many bridges do not sustain society's needs and are unable to adapt to changing conditions. Widening the current design lens to more intentionally consider less-traditional, but relevant functional, social, environmental and economic aspects will bring designs closer to addressing its problems as structures designed through a sustainability and resilience lens are more likely to attain maximum value.

Buried structures are used as hydraulic, wildlife and traffic crossings and are a viable option for most small to medium span bridge crossing sites. Buried structures are suitable when a single span less than 40 m is required, and when the vertical distance between the top of footing and overpass elevation is greater than 0.2 * span. While most in-service buried structures satisfy design requirements, there are instances where a buried structure has experienced a performance challenge which requires rehabilitation or replacement. The most common buried structures challenges are wildlife barriers, insufficient hydraulic capacity, scouring, washouts, and durability. Buried structures are most likely to attain maximum value and address common buried structure challenges if design effort and procurement decisions focus on their: material use, waste and energy footprint, accommodating nature, resilience. Innovation is an essential tool to mitigate changes and attain more value.

Material Use: When evaluating material use, apply the 3R hierarchy: first reduce, then reuse, then recycle. When possible, first reduce the amount of imported material (e.g. – backfill) while still satisfying all functional requirements. Secondly, prefer backfill and structural materials with a higher recycled content and backfill with higher recycled content. Lastly, when practical, prefer structural materials which are not only recyclable, but also in demand.

Waste and Energy Footprint: When practical, prefer backfill and structural materials with a higher recycled content. Additionally, use a procurement decision weight based on the solution's waste and energy footprint.

Accommodate Nature: When possible, it is recommended nature be accommodated as a structure which best accommodates nature is expected to have a higher probability of realizing its design service life. Designing buried structures to serve as effective wildlife passage structures also increases the probability the structures will meet service requirements for its entire design life.

Resilience: Buried structures are more likely to satisfy resilience concerns if they are intentionally designed for them. To design a more resilient buried structure, owners need to define which exposure conditions additional resilience is needed for. With this information, designers are better able to balance economics and resilience requirements to attain maximum value.

Innovation: Bridge crossings currently have sustainability and resilience related challenges. To address these challenges, the bridge community needs to change and innovate. Innovations include leveraging the value of buried structures where they offer more value compared to beam crossings, considering life cycle costing, and implementing procurement criteria to promote more sustainable and resilient buried structures. Procurement which promotes innovation has the greatest potential impact.

Provided supportive backfill remains in place, buried structures are likely to be a more sustainable and resilient crossing compared to a beam crossing. In some instances, buried structures may be designed to survive partial or complete backfill loss. As soil loss risk is primarily associated with water, buried structures are expected to be a preferred solution for non-hydraulic crossings, in part due to buried structures being on average 33 to 67% more economical than beam bridges.

Crossings utilizing buried structures designed with a fundamental understanding of sustainable and resilience aspects are more likely to attain maximum value.

Recommendations

It is recommended practitioners use buried structures when they provide more value than alternative crossing solutions. The buried structure sustainable and resilience considerations checklist (Table 5), sustainability enhancement record (Table 6), and resilience evaluation matrix (Table 2) presented in this paper are practical tools which will help realize this goal.

Future research to better understand resilience related features which increase the probability of backfill remaining in place are recommended. Additionally, additional research to better understand the impacts when backfill support is compromised is recommended.

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