How Resilient are Buried Bridges in Extreme Hydraulic Events?

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Abstract

Transportation agencies across the country are facing more frequent extreme hydraulic events which negatively impact and damage transportation networks. Transportation networks disrupted from more extreme hydraulic events could result in large repair costs, negative costs to the economy from disrupted travel, and expose the public to safety hazards. Agencies desire infrastructure which accommodate an agency's limited financial and environmental resources, minimize disruption to the public, and can accommodate changes such as climate change impacts.

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

The paper's objective is to evaluate a buried bridge's resilience to extreme hydraulic events and inform practitioners of best practices for designing and constructing buried bridges more resilient to extreme hydraulic events. Resilience is defined by the Federal Highway Administration as 'the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions' (Federal Highway Administration, January 2017). Climate change is increasing the frequency and severity of extreme hydraulic events. This increases the risk of public disruption from a buried bridge's surrounding backfill being compromised through piping, washout, or scour.

The 2014 CHBDC outlines buried structure hydraulic design criteria and requires designers to prevent structure and embankment failure during predicted floods. The draft 2019 CHBDC enhances this criteria by requiring designers to consider resilience and minimize damage from unforeseen events. In other words, the CHBDC requires designers to prevent public disruption under predicted conditions and minimize public disruption from unforeseen events.

This paper will present best practices to design and evaluate a buried structure's hydraulic design criteria such that it better satisfies the CHBDC's current and future design requirements. A design approach which increases buried structure's resilience against extreme hydraulic events is introduced. Findings of a desktop study evaluating how resilient various buried bridges are when their surrounding soil is piped, washed out, or scoured away are presented.

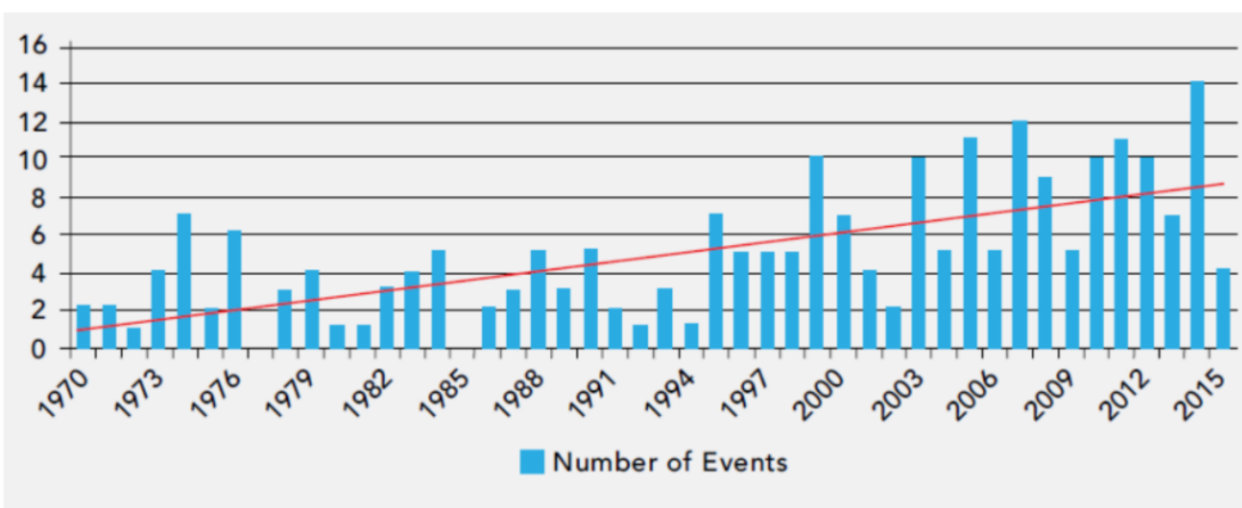
Keywords: Buried structures, buried bridges, resilience, climate change, extreme hydraulic events, scour, piping, washout, CHBDC.

1.0 Introduction

The Extreme Hydraulic Event Challenge

Today’s bridge industry has a problem: unpredicted extreme hydraulic events are increasing in frequency and in some instances, are causing unexpected bridge failures and public disruption.

Figure 1 - Bridge Failure During an Extreme Hydraulic Event (Duhatschek, 2018)



Source: Public Safety Canada. 2016-2017 Evaluation of the Disaster Financial Assistance Arrangements.

Figure 2: Number of Natural Disasters in Canada Requiring Disaster Financial Assistance Arrangements for Provinces and Territories (Moudrak, 2017)

Resilience is the ability to bounce back after a disaster and involves anticipating disaster and developing systems to mitigate them (John Hopkins University, 2014). Owners are looking to increase the resilience of their transportation networks and reduce their transportation network vulnerability and societal disruptions from these extreme events. Every component of transportation system, including buried infrastructure, needs to be considered to make the whole system resilient. Approximately 22% of the U.S. bridge inventory consists of buried structures. Additionally, smaller culverts are commonly found every 1/4 to 1/8 of a mile on most roads in the U.S. Buried structures are a crucial part of our transportation system, where the transportation integrity is a critical lifeline to communities in the wake of natural disasters.

The CHBDC has historically outlined design requirements which produce safe structures under predicted exposures. However, there are instances where a buried structure satisfying CHBDC design requirements has experienced a performance failure due to an unexpected event. The resulting societal disruption is a function of how important the crossing is and how long the crossing is closed.

Currently, very little in the way of standard guidelines for designing and evaluating a buried structure's resilience to unpredicted hydraulic events exist. This paper's objective is to provide owners best practices for increasing a buried structure resilience during extreme hydraulic events. The paper will provide guidance on how to meet the current 2014 CHBDC and 2019 new resilient design requirements for buried structures exposed to extreme hydraulic events.

Metal Buried Structure Introduction

Soil-metal structures are comprising shells of corrugated metal and surrounded with well-compacted soil, were first used in the United States at the beginning of the 20th Century (Bahkt, 2007). Soil-metal structures, commonly referred to as buried structures, culverts, or buried bridges, are constructed as open bottom structures (structure is supported on a footing system) or 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 3.

Figure 3 - 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 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.

Design codes outline structural, geotechnical and hydrotechnical design requirements and considerations based on the current knowledge and lessons from past failures. Despite this, there are instances where an in-service buried structure experiences a performance failure such as a washout. These failures have led to significant rehabilitation or replacement costs. Performance challenges are more likely to happen when exposed conditions exceed conditions assumed during the original design. Examples of hydraulic changes include:

1. Changes in high-water level during the life of a structure from various factors including urbanization, deforestation, channel diking, and the construction of flood control structures (2014 CHBDC C1.9.1.6)
2. Climate change impacts increasing design storm events
3. Debris accumulation at the opening, reducing hydraulic conveyance (Chichak, 2012)

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.

Buried Bridge Design Criteria

Buried bridges rely on both the structure and its surrounding soil to resist load. The CHBDC's Section 7 outlines buried structure design requirements. CHBDC's Section 7 outlines specific limit state in Table 7.2. All CHBDC buried structure limit state requirements focus on evaluating structure performance based on stress predictions which incorporate a level of soil support.

Hydraulic buried structure design requirements are outlined in CHBDC Section 1.9 and are summarized as follows:

1. Bridges and culverts shall be designed to accommodate the normal design flood without damage to the structure or the approaches.
2. Bridges and culverts shall be designed to withstand a check flood (a flood greater than the normal design flood) without endangering the integrity of the structure and without approach embankment failure.

The current 2019 CHBDC draft includes a definition of sustainability and resilience and indicates these aspects shall be considered in designs. The draft defines resilience as the ability of a structure or a component to withstand unexpected events (e.g. earthquake, traffic overload, natural or man-made hazards) and minimize loss of functionality and recovery time without being damaged to an extent that is disproportionate to the intensity of the events. The 2019 CHBDC's sustainability design criteria enhances the design approach from 'prevent failure under predictable design conditions' by expecting designers to 'minimize damage in unpredicted situations'. For instance, a flood greater than the normal or check flood causing embankment failure but not damaging structure integrity.

This paper will provide owners and practitioners guidance on how to satisfy the CHBDC's enhanced hydraulic design criteria through outlining:

1. Best practices for enhancing embankment resilience.
2. Means to prevent structure damage after embankment failure.

2.0 Buried Structure Resilience

A goal of designing for resilience is to minimize public disruption. The level of public disruption is highly dependent upon how long the buried structure is unable to perform its intended design function. The buried structure's ability to perform its functionality is contingent upon both the structure and the surrounding.

Damage to a buried structure is taken as the structure's inability to satisfy CHBDC ultimate limit state criteria in Table 7.2 under the required loading conditions when soil is supporting the structure. CHBDC buried structure service limit states (SLS) or fatigue limit states (FLS) are not considered relevant to potential damage caused from an extreme hydraulic event and as a result are not considered. Soil damage is defined as a loss in the backfill's ability to adequately support the structure in a manner to satisfy CHBDC limit states. In an extreme hydraulic event, soil damage is expected to be related to a loss of material through piping or washing.

Recovery time is considered as the time the structure is unable to perform its functionality; the time between the damage and the rehabilitation. Buried structures will respond to an extreme hydraulic event in one of four ways:

1) Undamaged: No recovery required.

2) Soil damage: Recovery time is expected to be days or weeks.

3) Structure damage: Recovery time is expected to be weeks or months.

4) Structure and soil damage: Recovery time is expected to be weeks or months.

Figure 4 - Structure and Soil Damage

Scenario one is the most desirable followed by scenario two. Scenario three and four are undesirable due to the potential length of public disruption time. Best practices to better realize scenarios one and two are as follows.

3.0 Undamaged Buried Structures

Having a structure survive an extreme hydraulic event is idealistic and with intentional design, easily achieved. There are three primary considerations for designing a buried structure which is highly resilient to extreme hydraulic events. Note that foundation and scour design are additional important considerations but are outside the scope of this paper.

Structure Sizing

The primary concern with structure sizing as it relates to resilience is to keep the water flowing through the conduit rather than through or over the embankments. Risk of embankment failure is low when unless the volume of water exceeds the capacity of the structure. Embankments acting like a damn have a higher failure probability.

Traditionally, buried structures are primarily sized based on the area required to convey water. Figure 5 presents an investigation into how buried structures with spans less than 6 m failed during a twelve-year storm event and an extreme event.

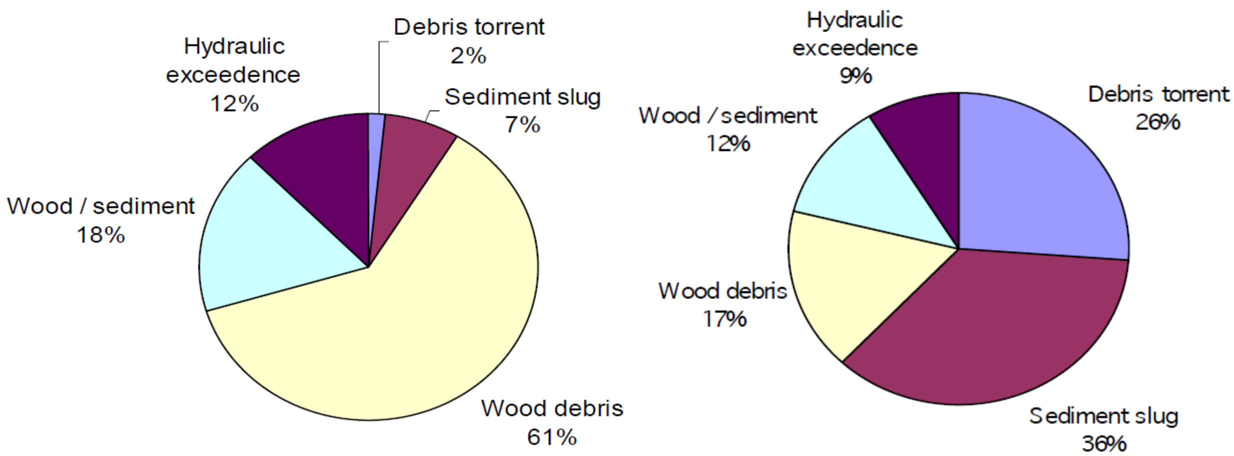


Figure 5: How Culverts Fail in Hydraulic Events: 12 year storm (left) and Extreme Event (Right) (Flanagan, 2018)

The study observed that only a small percentage of structures failed due to improper hydraulic sizing, which suggests designers are doing a good job at sizing buried structures for hydraulic conveyance. Unfortunately, the investigation suggests designers are not considering other key elements such as debris. A challenge with smaller diameter conduits is they are vulnerable to debris accumulation activities such as beaver damming. Debris and sediment accumulation reduces end area, thereby increasing water pressure against the embankment, producing more embankment failures.

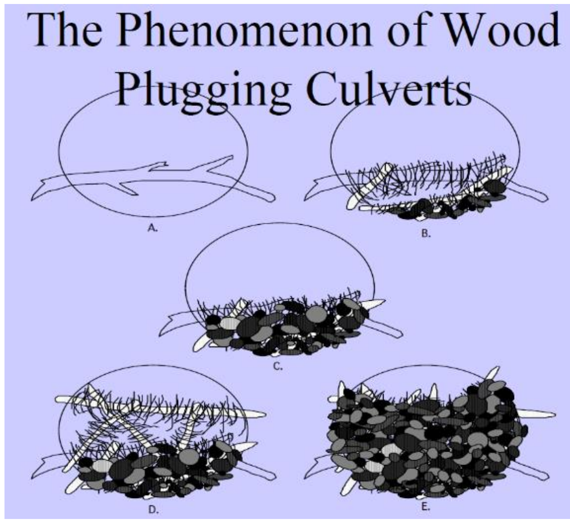


Figure 6 - How Debris Restricts Hydraulic Conveyance (Flanagan, 2018)

A best practice to reduce the risk of debris accumulation and other failure mechanisms is to size buried structures such that their span exceeds the bank width, rather than purely sizing on hydraulic conveyance requirements. A standard bank width sizing rule for hydraulic buried structures is to size their span such that their span is 20% greater than the bank width. It is also advisable to consider conditions upstream and historic flood events as an indicator of what debris could

From an economical perspective, increasing the span has a relatively minor impact on the installed cost of the project and it is often worthwhile for owners to invest slightly more in the initial solution and reduce future maintenance and increase resilience.

End Treatments

Water flowing through soil tends to move particles. The idea behind end treatments is to reduce water infiltration to reduce risk of piping/washing of backfill. The CHBDC indicates end treatment shall be provided where there would otherwise be a possibility of uplift, piping, undermining, or damage due to ice or debris. Clay seal, closed face such as sheetpiling, concrete. Headwalls which are rigidly connected to the structure and add stiffness offer potentially beneficial additional structure support.

Figure 7 - End Treatment During and After High Water Event

Backfill – Gradation and GRS

Erosion and piping are natural processes of a hydraulic channel. Water wants to move particles to create a wider, deeper channel. Designers need to incorporate features to restrict particle movement and prevent loss of backfill support. This can be achieved through various means.
The backfill gradation can be modified. A well graded backfill reduces the risk of particle movement through increased particle interlock and reduced voids. This limits the ability of the water to move the smaller particles. A clear stone backfill adds resilience by eliminating the small particles that are easiest for water to move. Water can travel through the clear stone, which may create the requirement for a filter layer or other means of preventing infiltration of fine material.

Material can also be added to the backfill to add strength and restrict movement. Geotextile reinforced structures (GRS) have geotextile layers running the full length of the structure spaced vertically approximately every 275 mm. These layers restrict particle movement and keep from migrating through headwalls. Additionally, the GRS layers offer a level of load carrying redundancy to the soil which not only helps maintain soil-structure interaction but also enhances soil support.

Figure 8 - GRS being Backfilled (Wong, 2016)

4.0 Buried Structure with Soil Damage Only

In some instances, an extreme hydraulic event may result in soil damage to structure. Soil damage which does not cause structure damage fits into the CHBDC's resilient goal of minimizing impact in an extreme event. If the structure is undamaged and backfill can be rehabilitated or reconstructed in a time efficient manner, societal disruption will be relatively minor.

Currently no CHBDC guidelines for designing a structure such that it remains undamaged in the event soil is damaged exist. The following is an attempt to outline a resilient limit state (RLS) for extreme hydraulic events which results in an undamaged structure when the embankment material has been damaged/washed.

For the structure to remain undamaged, specific ultimate limit states and resilient limit states are deemed to be the same. The proposed load combination would be based on permanent loads. Transitory and extreme loads would not be considered in the RLS combination. Buried structures are traditionally designed for vehicular loading and seismic loading. Vehicular load is neglected as the probability of the structure experiencing vehicular traffic when the embankment soil is damaged is considered low as vehicles are unlikely to drive across a buried structure with damaged embankments. Seismic loading was not considered as the probability of a seismic event coinciding with an extreme hydraulic event is considered low. Best practice is to align the length of the structure with stream entrance direction to minimize stream and ice loading.

The hydraulic RLS load combination is defined as follows: RLS Combination 1: α_d

Section 14, the Evaluation Section of the CHBDC, is proposed for determining the appropriate load and resistance factors. Utilizing Section 14 to determine factors enables owners to have more flexibility in defining an acceptable level of risk for the RLS and gives owners more flexibility to balance risk and economics. While Section 14 in the 2014 CHBDC does not specifically address buried structures, it is expected the 2019 CHBDC will. Until a D category for buried structure soil loading is defined it is recommended dead load factors be based on the D2 category found in CHBDC Table 14.7 be used. It is proposed resistance factors be based on CHBDC Section 14.14.1.

Internal forces for the RLS shall be determined using a representative analysis method. Refined analysis may be used. Internal forces shall be determined based on a structure with soil damage and worst-case loading conditions. At minimum the following cases shall be considered:

1. RLS Combination 1 - Soil embankment on one side of the structure completely washed away but embankment material above the structure remains in place (Figure 9).
2. RLS Combination 2 - Soil embankment on both sides of the structure completely washed away but embankment material above the structure remains in place Figure 10).

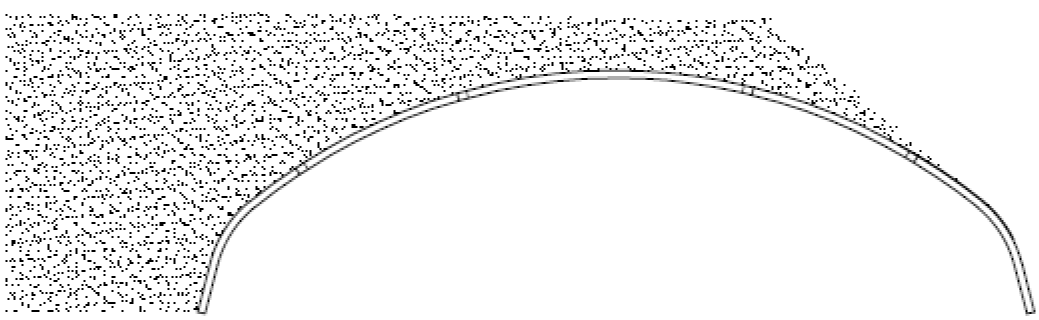


Figure 9 - RLS Combination 1

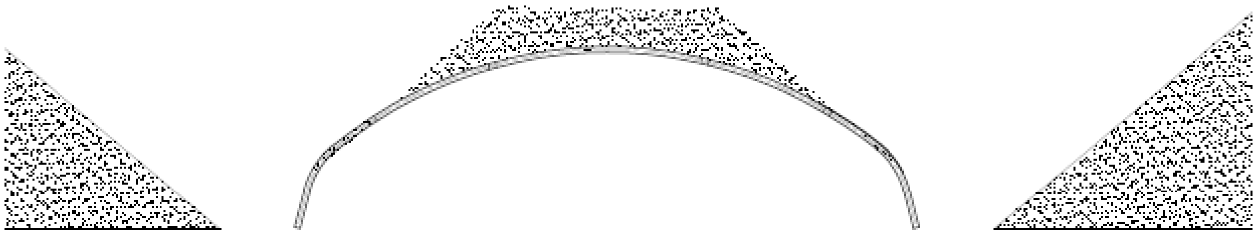


Figure 10 - RLS Combination 2

Case Study: Deep Corrugated Steel Box Structure

A 15 m span deep corrugated box structure will be designed for current CHBDC requirements and the proposed design approach for soil damage but no structure damage. The box structure has a rise of 3.5 m and a height of cover of 1 m. The structure is designed to support a CL-625-ON loading. Seismic loading was not considered as live load is typically the governing load case for box structures. Table 1 outlines the limit states and relevant factors for the case study.

Table 1 - Limit States and Relevant Factors

Loads	Specific Limit State	α_D	α_L	Initial Resistance Factor	U (CHBDC Table 14.15)	Design Resistance Factor
ULS Combination 1	Plastic Hinge	1.25	1.70	N/A	N/A	0.90
RLS Combination 1	Plastic Hinge	*1.20	N/A	0.90	1.00	0.90

*Based on β = 3.75

Refined analysis results are presented in Figure 11, Figure 12, Figure 13 and Figure 14.

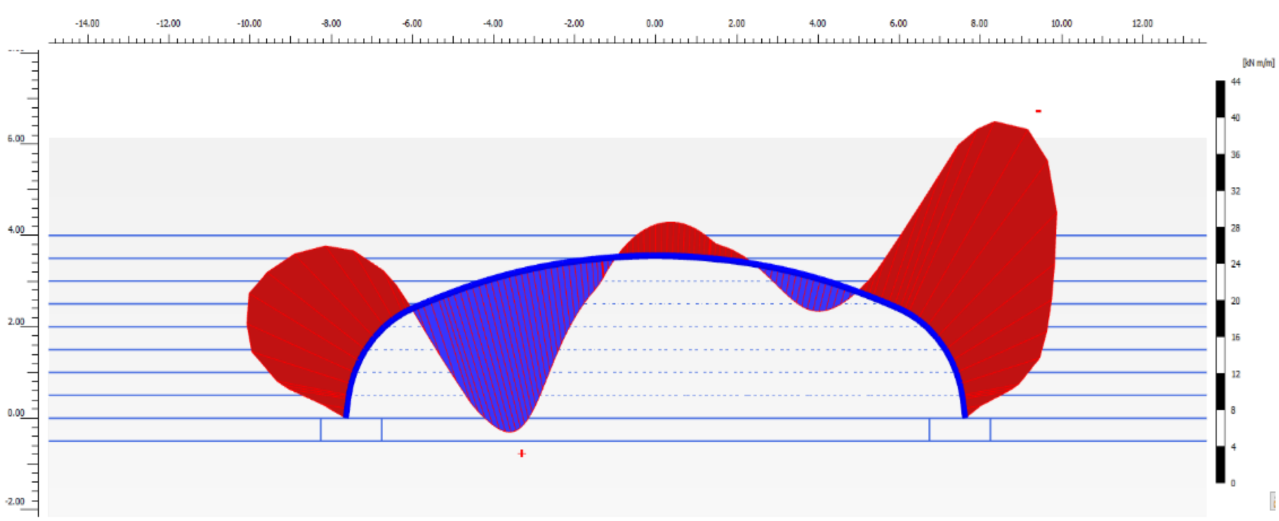


Figure 11 - Normally backfilled box structure, dead load only

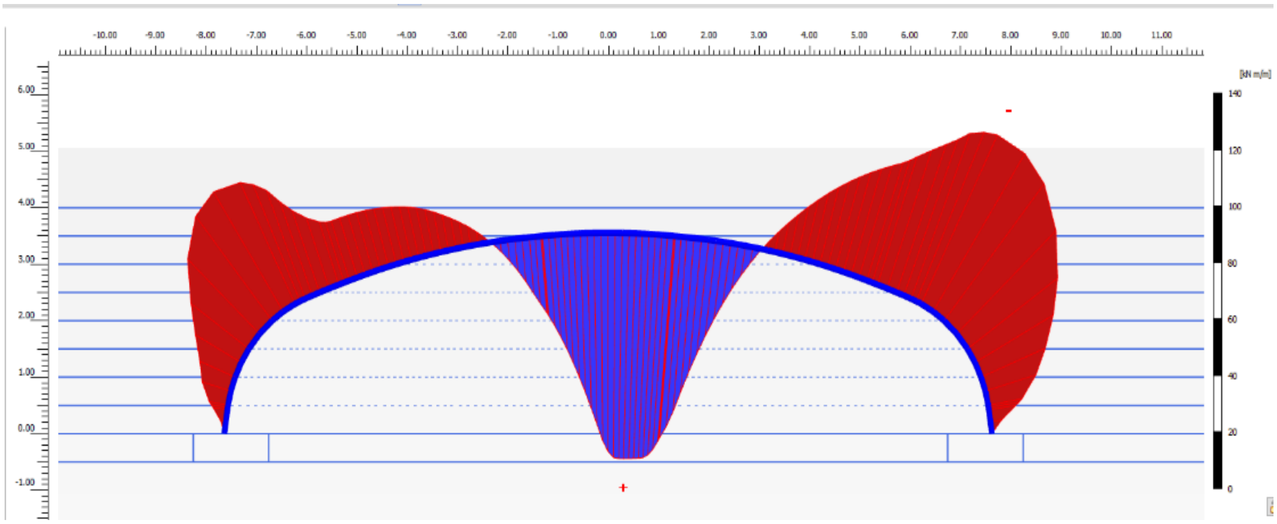


Figure 12 -ULS Combination 1 with Axle 2 of CL-625-ON Centred over Crown

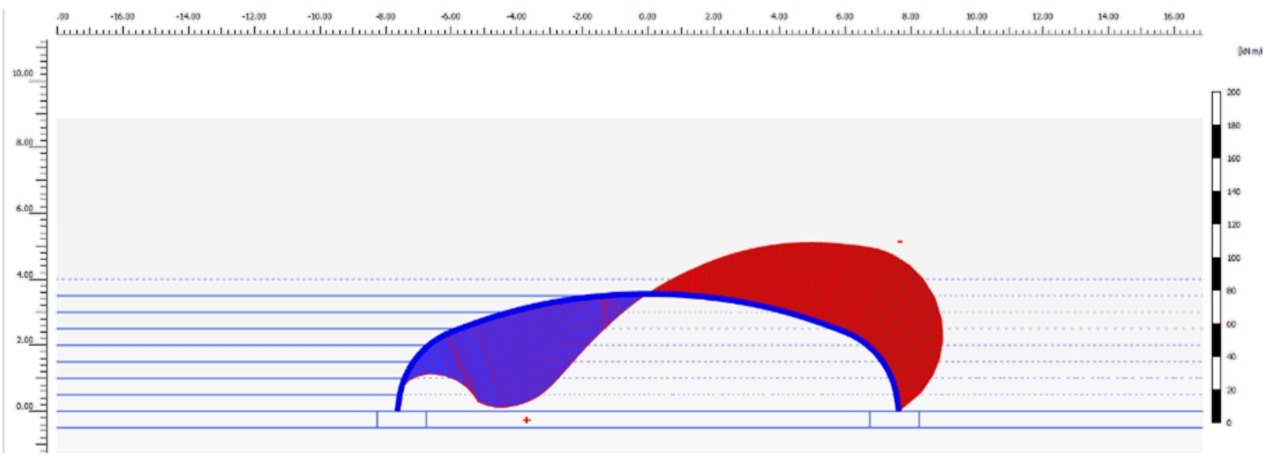


Figure 13 – RLS Combination 1: Backfill removed from right hand side, fill on top and left side remains

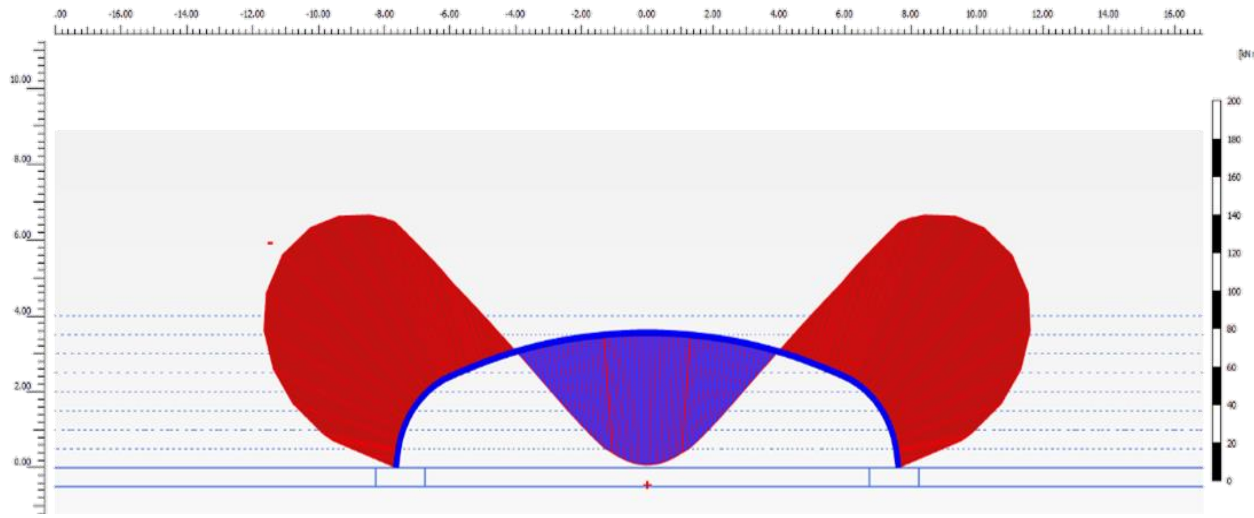


Figure 14 – RLS Combination 2: Backfill removed from both sides, fill on top remains

Design results for specific limit states of focus are presented in Table 2.

Table 2 – Box Structure Case Study Demand/Capacity Ratios

Limit State	Specific Limit State	Loading Scenario	Demand/Capacity Ratio (< 1 = pass)
ULS Combination 1	Plastic Hinge	CL-625-ON with Axle 2 centred over the crown	0.76
RLS Combination 1	Plastic Hinge	Soil embankment on one side washed away. Soil above structure remains.	0.67
RLS Combination 2	Plastic Hinge	Soil embankment on both sides washed away. Soil above structure remains.	0.73

For this structure all limit states were satisfied with ULS combination 1 producing the highest demand/capacity (D/C) ratio and RLS combinations producing demand/capacity ratios comparable to ULS combination 1. As a result, the structure in an extreme hydraulic event the structure will minimize societal disruption if soil is damaged. Structure damage is not expected if soil damage occurs meaning functionality is restored once the embankment has been either rehabilitated or removed/replaced.

Case Study: Deep Corrugated Metal Arch Structure

A 16 m span deep corrugated metal arch structure was designed for current CHBDC requirements and the proposed design approach for soil damage but no structure damage. It is noted the arch is a two-pin structure with pins at the structure/footing connection. The arch structure has a rise of 7 m and a height of cover of 1 m. The structure is designed to support a CL-625-ON loading. Seismic loading was not considered as live load is typically the governing load case for low cover arch structures. Table 1 outlines the limit states and relevant factors for the case study.

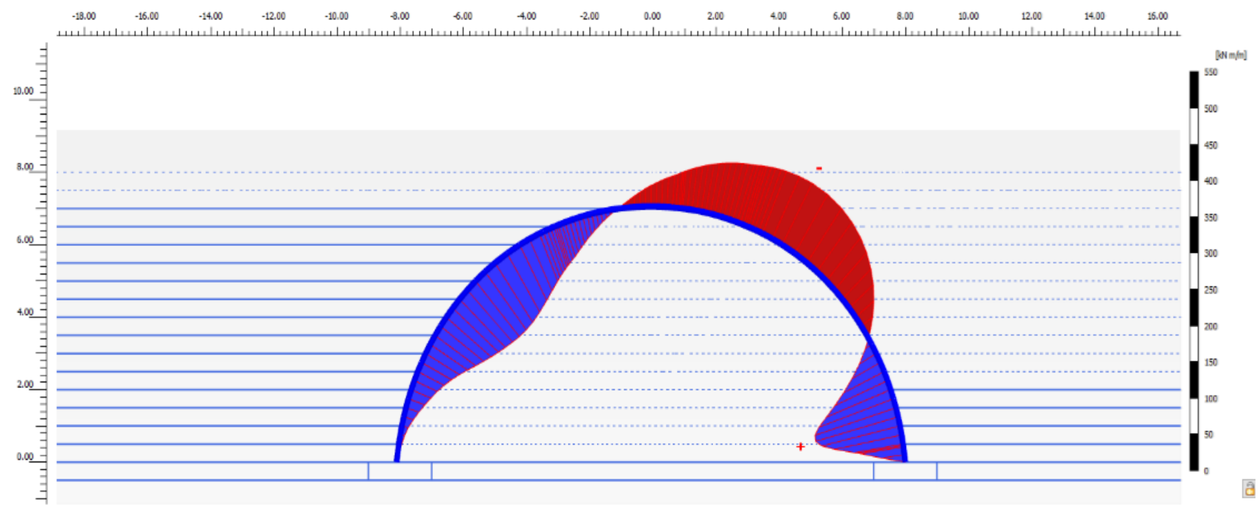


Figure 15 – RLS Combination 1: Fill Removed on Right Side, Fill Remains on Top and Left Side. Demand Capacity Failure

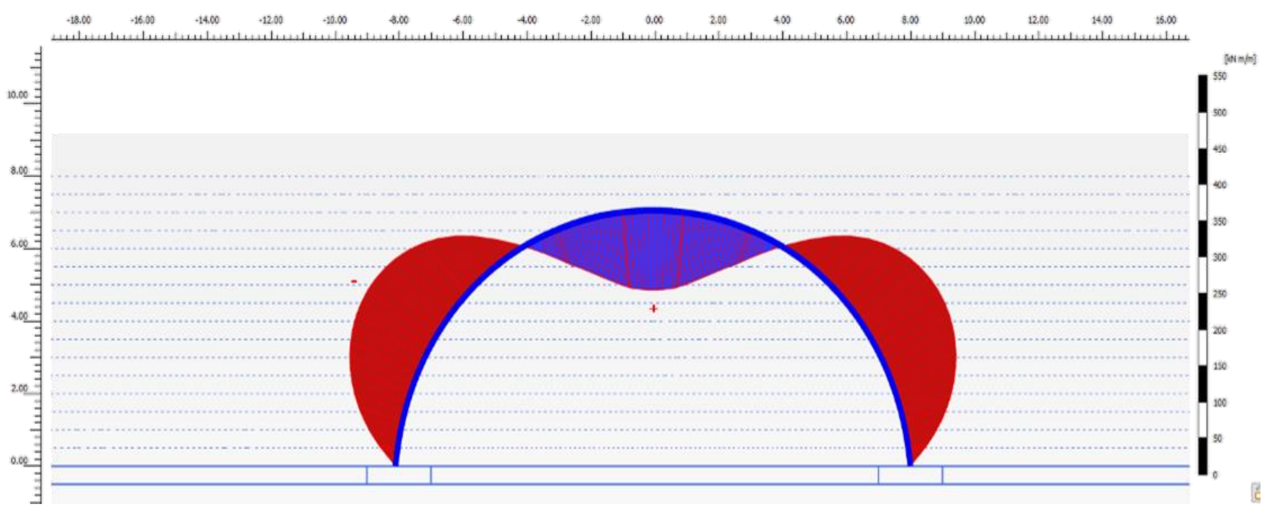


Figure 16 – RLS Combination 2: Fill Removed on Both Sides, Fill Remains on Top

Design results for specific limit states of focus are presented in Table 3.

Table 3 - Arch Structure Case Study Demand/Capacity Ratios

Limit State	Specific Limit State	Loading Scenario	Demand/Capacity Ratio (< 1 = pass)
ULS Combination 1	Plastic Hinge	CL-625-ON with Axle 2 & 3 centred over the crown	0.47
RLS Combination 1	Plastic Hinge	Soil embankment on one side washed away. Soil above structure remains.	> 1 – Fails
RLS Combination 2	Plastic Hinge	Soil embankment on both sides washed away. Soil above structure remains.	0.81

Only results for the plastic hinge limit state are shown. For metal arches, two additional specific limit states need to be assessed: connections and compression. For compression, means to determine capacity through other means such as refined analysis is required as current CHBDC compression capacity equations are based on undamaged soil.

For this structure the limit states were met with ULS combination 1 but the RLS combination 1 was not satisfied. Unbalanced fill has the structure behaving more like a retaining wall than a ring compression style buried structure. When the unbalanced fill height becomes large the retaining wall type behaviour may become large enough to damage the structure. While it may be unreasonable to expect RLS Combination 1 to occur on a tall structure, RLS Combination 1 failure indicates the structure has greater potential to be damaged during an extreme hydraulic event. If this is a concern to the owner, resilient enhancing features outlined in Section 3.0 Undamaged Buried Structures, are recommended to mitigate the risk of both structure and soil damage.

Case Study: Cougar Creek (Prychitko, 2013)

In 2013 record flooding washed out the Trans-Canada highway where it crossed Cougar Creek. With the Trans-Canada highway and CPR crossing closed from the extreme hydraulic event, the 9.5 m span horizontal ellipse buried bridge crossing below was the only remaining East-West passageway in the Canmore area.

During the extreme hydraulic event the road embankment was damaged and washed out. However, the buried bridge was not damaged. It is believed one of the keys to protecting the buried bridge were the concrete headwall end treatments which shielded the structure from direct impacts and provided additional support to the buried bridge when the backfill was damaged.

When water levels had receded, backfill was reconstructed and the crossing was reopened in a relatively short time period. Debris accumulation inside the conduit was also removed as part of the rehabilitation process. This crossing served as the only East-West crossing in the Canmore area until the Trans Canada crossing was rehabilitated.

Figure 17 - Cougar Creek Washout During Extreme Hydraulic Event

Figure 18 - Debris Accumulation Inside Conduit from Event (Before and After)

Figure 19 - Cougar Creek Crossing with Rehabilitated Soil

Trends

Desktop studies and practical knowledge indicate the RLS for avoiding structure damage while undergoing soil damage is highly dependent upon fill volume, structure shape, structure system, and end treatments.

Fill Volume: Vertical loading is a function of fill depth over the conduit and span. Greater volumes of fill require greater structure capacities.

Structure Shape: Low rise shapes have lower depths of unbalanced loads from one side of the structure to the other applied during RLS combination 1. Horizontal loading increases with structure rise, with taller structures resulting in higher demand.

System Stiffness: Structures with higher levels of redundancy and/or stiffness are better able to resist loads without soil support, including unbalanced loads. Concrete headwalls rigidly connected to the buried structure are an effective means for reducing the probability of soil loss, protecting the structure from debris and flowing water impacts in addition to offering additional resistance when soil is damaged. It is noted that three pin arch systems, which are used for some precast concrete structures, may be considered as single load path structures in the RLS combinations and are not recommended when designing for RLS combinations. Increasing structure stiffness will increase resistance during the RLS conditions (assuming the degrees of freedom for the structure remain constant). For example, deep corrugated steel plate offers more stiffness than shallow corrugated plate. Finally, monolithic structures or segmental structures mechanically connected at joints will offer a higher level of resilience compared to segmental structures not mechanically connected. Monolithic and mechanically connected structures are better able to provide a level of resistance across joints and are less prone to backfill material loss through joints.

5.0 Conclusions

The 2014 CHBDC details hydraulic design requirements which generally consist of expecting the structure and embankment to be undamaged during predictive hydraulic events. The 2019 CHBDC will be adding resilience design requirements which expect designers to consider events which are beyond predictive events. Buried structures rely on soil-structure interaction to resist load. Extreme hydraulic events have the potential to damage both the structure and surrounding soil. Extreme hydraulic events put a buried structure's functionality at risk and with this, the potential for disrupting society increases. The intent of this paper is to increase the resilience of buried structures in extreme hydraulic events. Utilizing the best practices and resilient limit state design approach outlined in the paper will more likely provide owners with buried structures having no or minimal societal disruption during an extreme hydraulic event.

Two approaches to minimize societal disruption are outlined: increase resilience to reduce the risk of soil and structure damage, or design the structure such that it will not undergo structure damage even when the soil is damaged. Soil damage was deemed acceptable from a resilience perspective as although soil damage takes a buried structure out of service for a time, the soil can be repaired in a relatively quick time, thus minimizing societal disruption. Structure damage on the other hand takes longer to repair and the potential impact on society is considered significant and undesirable.

Best practices for achieving a buried structure which has undamaged structure and soil after an extreme hydraulic event include:

- *Structure Sizing:* Size structures such that their span is greater than the natural stream width to reduce water exposure and risk of debris/sediment choking the inlet. A clear span at least 1.2 times the natural stream width has been used more successfully.
- *End Treatments:* Utilizing low permeability end treatments to reduce the volume and flow rate of water seeping through the soil.
- *Backfill:* Reducing the risk for backfill material migration through use of well graded material and/or the use of geotextile reinforced structures to sandbag the soil.

When additional resilience is required, the structure can be designed to not realize structure damage even if soil is damaged. A design procedure outlining an approach for two resilience limit states was presented. Case studies based on field experience and desktop modelling suggest buried structures can be designed to not realize structural damage even when the backfill is damaged. Influential parameters for resilience limit states include:

- *Fill Volume:* Vertical loading is a function of fill depth over the conduit and span. Greater volumes of fill require greater structure capacities.
- *Structure Shape:* Low rise shapes have lower depths of unbalanced loads from one side of the structure to the other applied during RLS combination 1. Horizontal loading increases with structure rise, with taller structures resulting in higher demand.
- *System Stiffness:* The greater the structural system stiffness the greater the resilience resistance. System stiffness is a function of the degrees of freedom, structure stiffness, and rigidly connected end treatments such as concrete headwalls. Systems such as three pin arches which rely on the surrounding soil to avoid being single load path structures lose that redundancy when soil is damaged and behave more like a single load path structure.

Buried structures can be intentionally designed to be more resilient to extreme hydraulic events and satisfy 2014 CHBDC hydraulic requirements and expected 2019 CHBDC resilience expectations.

6.0 Recommendations

When feasible, it is recommended best practices for eliminating or minimizing societal disruption from extreme hydraulic event damage be implemented. Of these features, sizing a structure for debris and sediment passage is deemed the most impactful. Recommended best practices for achieving a buried structure which is likely to be undamaged in an extreme hydraulic event are as follows:

- Clear span is at least 1.2 times the natural stream width
- The structure has end treatments such as clay seals, concrete headwalls or metal faced headwalls
- Use backfill with low susceptibility to piping and or use geotextile reinforced structures to restrict particle movement.

When additional redundancy is desired, it is recommended the buried structure be designed to not realize structure damage even when the surrounding backfill is damaged/removed. Based on the time involved to reconstruct backfill, this approach is only recommended when distance from top of footing to road grade is less than 5 m. When the footing to road grade distance is greater than 5 m, best practices to achieve undamaged structures are highly recommended.

Three pin arches are not recommended when designing for soil damage.

The resilience of existing structures may be increased by adding or enhancing headwalls, or by adding a planned overflow structure in place of increased span.

Further study on the key parameters influencing resilience are recommended. Additional study on the impacts of scour are also recommended.

References

Bahkt, B. (2007). Evolution of the Design Methods for Soil-Metal Structures in Canada. *First European Conference "Buried Flexible Steel Structures"* (p. 16). Rydzyna, Poland: Archives of Institute of Civil Engineering.

Chichak, M. (2012, February 2). *Bridge Hydraulics*. Retrieved from Canadian Consulting Engineer: https://www.canadianconsultingengineer.com/features/bridge-hydraulics/

Duhatschek, P. (2018, February 26). *Port Bruce's collapsed bridge has become its latest tourist attraction*. Retrieved from CBC News: http://www.cbc.ca/news/canada/london/port-bruce-s-collapsed-bridge-has-become-its-latest-tourist-attraction-1.4552860

Flanagan, S. (2018, May 11). *How Culverts Fail.* Retrieved from California Board of Forestry and Fire Protection: www.bof.fire.ca.gov/board_committees/monitoring..._/samflanaganmspres.pdf

John Hopkins University. (2014, June 20). *Sustainability vs. Resilience: Why Bouncing Back is the Way of the Future*. Retrieved from John Hopkins University: http://www.sustainabilitydegrees.com/blog/sustainability-vs-resilience-why-bouncing-back-is-the-way-of-the-future/

Moudrak, N. (2017, December 7). *Climate Change and Credit Risk*. Retrieved from Canadian Investment Review: http://www.investmentreview.com/analysis-research/climate-change-and-credit-risk-8023

Prychitko, R. (2013, December 3). *Alberta Flooding: Local Knowledge and Intelligent Design of Culvert Structures Yield Improved Efficiency and Durability*. Retrieved from Corrugated Steel Pipe Institute: http://www.cspi.ca/node/445

Standards Council of Canada. (2017, May 5). *About the Standards Council of Canada*. Retrieved from Standards Council fo Canada: https://www.scc.ca/en/about-scc

Wong, S. (2016, November 8). Senior Biologist, BC MoTI. (P. Carroll, Interviewer)