Responsible Culvert Design, Evaluating Culvert Design Life from a Sustainable Perspective

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GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
In this paper there will be an examination of the relationship between culvert design life and sustainability. The design standards that apply to culvert design are AASHTO (American Association of State Highway and Transportation Officials), CHBDC (Canadian Highway Bridge Design Code), and AS/NZS (Australian and New Zealand Standards). These regulatory frameworks will be analyzed through the lens of sustainability. Sustainability will be addressed from the standpoint of climate change and the effect of storm events and through the four system conditions, created by "The Natural Step", as part of the framework for sustainable development. An analysis of culverts functioning as wildlife crossings will also be discussed. The literature that will be reviewed and cited from is; "The Sustainability Imperative", Harvard Business Review, David A. Lubin, and Daniel C. Esty, a study conducted by the City of Toronto about "Climate Change Vulnerability Assessment for Culverts", and also literature that is examining highway improvements to minimize environmental impacts in Canadian Rocky Mountain National Parks and animal crossings across highways. Factors influencing design life are often neglected, and as a result can have hidden costs of repeated installation and ecological damage. In this paper based on our research, we have discussed that it is probable that culverts that have a longer design life will have a better sustainable position pertaining to ecological impacts.

RÉSUMÉ
Dans cette étude, il y aura une analyse de la relation entre la durée de vie des ponceaux et le développement durable. Les conceptions standards qui s'appliquent à la conception des ponceaux sont l'AASHTO (American Association of State Highway and Transportation Officials), le Code canadien sur le calcul des ponts routiers, et l'AS/NZS (Australian and New Zealand Standards).Ces cadres réglementaires seront analysés sous l'angle du développement durable. Le développement durable sera abordé du point de vue du changement climatique et de l'effet des tempêtes, et à travers les quatre conditions du système créées par «The Natural Step», en tant que cadre pour le développement durable. Une analyse des ponceaux utilisés comme écoducs sera aussi développée. La source documentaire qui sera examinée et citée est «The Sustainability Imperative », Harvard business Review, David A. Lubin, et Daniel C. Esty, une étude menée par la ville de Toronto à propos de « L'évaluation de la vulnérabilité changement climatique pour les Ponceaux », et également une documentation examinant l'amélioration des autoroutes pour minimiser les impacts environnementaux dans les Parcs Nationaux des Montagnes Rocheuses Canadiennes et les passages des animaux sur les autoroutes. Les facteurs influençant la conception sont souvent négligés, et par conséquent cela peut cacher des coûts d'installation répétés et des dommages écologiques. Dans cette étude, d'après nos recherches, nous avons mis en évidence qu'il serait probable que les ponceaux qui ont une plus longue durée de vie devraient avoir une meilleure position durable concernant les impacts écologiques et l'empreinte carbone

1 INTRODUCTION

In this paper there will be important questions addressed through literature review when it comes to culvert design with sustainability in consideration. What is a culvert and why are they important pieces of infrastructure in our urban and rural environments? What are some of the tensions that exist within the current codes and standards that hinder a sustainable approach in designing culverts? Does sustainability or climate change influence designers of culverts? Is this it a viable option for the supply chain to engage sustainability in their business models?

2 CULVERT DESIGN

2.1 Culverts

A culvert is a soil structure that differs from a bridge that is structural by definition. A culvert is characterized by being circular or semi-circular in geometry, its function allows a stream or open drain to flow under a road or railroad (Figure No.1). A culvert optimizes the soil surrounding it with the thinnest possible element to support the soil. This effect is called soil arching. Some of the most common culvert applications include bridge replacements, storm sewers, stream crossings, animal crossings, and other hydraulic applications. Typically the culvert is manufactured from Corrugated Steel Pipe (CSP) or reinforced concrete. CSP culverts are a popular choice based on their apparent affordability and availability.

Figure 1. Walsh River, NF Train Overpass

2.2 Design Standards

Three codes that are commonly used for designing bridges and culvert crossings are the CHBDC S6-06 (2006), AASHTO 2013, and NS-SZA 1998. These codes pay special attention to the design life of the structures. Specifically for CSP culverts the steel elements are protected against corrosion by galvanizing and the codes regulate minimum thickness of zinc coating in order to meet with the expected service life. *"Corrosion damage for the steel can cause loss of stability of the corrugated plate shell leading to premature failure*." (Beben, 2014). If the safety of the structure is compromised there can be significant hazards if the culvert is under a road or railway. Codes have different approaches to estimate the rates of corrosion and methods in which to evaluate zinc and steel loss.

2.3 Evaluation of CHBDC S6-06, AASHTO 2013 and NS/SZA

A recent study has been conducted by Damian Beben, of Opole University of Technology, in which he analyzed six CSP culverts all located under either national or provincial roads in Poland for their corrosion rates taking into account resistivity, soil pH, and moisture content. The culverts were then examined to verify if they met the minimum service life (40 years) and compared with the durability assumed for bridges (100 years) according to AASHTO.

First examining the AASHTO standards, the actual amount of steel thickness after the loss of the zinc coating is 12µm per year. *"Therefore it was calculated that with the use of anticorrosion (zinc thickness amounting to 85µm and the steel surplus, because of corrosion, amounting to 0.5 mm (500µm), the durability of all culverts is about 58 years."* (Beben, 2014) Using the CHBDC S6-06 the calculations are slightly different as this code gives allowance for 15µm/year for the loss of thickness of steel. *"The loss of thickness in the case of saturated soils or the side of the water amounts to 15µm/year for the zinc coating and 20µm/year for steel (after the loss of zinc coating)*." (Beben 2014) It was then calculated that the durability of the analyzed culverts on the side of the backfill is 60 years, and on the side of the water 31 years. (Beben, 2014).

The Australian standard varies from AASHTO and CHBDC S6-06 in its method of evaluation. The AS/NZS takes into account the soil pH and the moisture content, which gave the culverts a durability of 43-55 years. (Beben, 2014) This method, as validated by Damian Beben's study appears to be the most accurate method for predicting the loss of thickness of steel as it takes into account all three aspects that are influencing corrosion.

2.4 Discussion

Based on the results of the Beben study (2014) regarding the corrosion rates that are summarized in the Table 1, it is confirmed that for the studied conditions the culvert design methods are in accordance with the expected life of the structures of about 45 years. In terms of sustainability, a CSP structure shall be replaced 3 times in the same span of life for a 100 year reinforced concrete culvert.

Figure 2. Damage to a CSP culvert due to corrosion (DTMR, 2013).

3 SUSTAINABILITY

Within the confines of this paper the lens of sustainability that will be used is the methodology of the four system conditions, originated by "The Natural Step" as part of the framework for strategic sustainable development.

1. The systemic increase of concentrations of substances extracted from the earth's crust (for example heavy metals and fossil fuels).
2. The systemic increase of concentrations of substances produced by society (for example, plastics, dioxins, PCBs and DDT).
3. The systemic physical degradation of nature and natural processes (for example, overharvesting forests destroying habitat and overfishing).
4. Conditions that systemically undermine people's capacity to meet their basic human needs (for example, unsafe work conditions and not enough pay to live on).

It would appear that the construction of culverts that meet the minimum design service life would touch on the first, second and third step of the process. Metals would need to be extracted in order to manufacture the culvert, and the zinc coating would be considered a pollutant that adds to the concentration of substances produced by society. The environmental impacts from constructing a culvert can be significant if there is a stream that needs to be diverted or land that needs to be cleared by means of grubbing or tree removal. A conclusion that can be drawn is that culverts that meet the 100 year design life standard would be considered a better sustainable choice. The reason for this conclusion is that the culvert would only need to be constructed once, eliminating replacement costs and ecological damage. Touching on the the third step, where physical degradation of an area in which construction takes place will affect animal habitats, vegetation and fish bearing streams keeping construction to a minimum is essential. .

Figure 3. Animal Crossing overpass

3.1 Animal Crossings and Sustainability

When a transportation network is constructed, such as a highway or access road, step three of the natural step is directly affected. The highway or access roads divide the habitat into patches that can have negative effects on the local species. One such way to mitigate the ecological effects of habitat destruction is to create animal crossings. There are many complex factors to consider in the design. The purpose of a wildlife crossing structure is to allow an animal's safe passage across a road without coming into contact with traffic.

The design of animal crossings must consider safety concerns for humans and animals as vehicle collisions with animals can be fatal to both. This safety issue is related to step three and four. "*Successful highway mitigation projects may be defined by a substantial reduction in wildlife–vehicle collision rates and restoration of animal movement patterns from one side of the road to the other."* (Ford et al. 2009) The crossing still allows for increasing human migration and transportation needs through road construction, while providing connectivity of wildlife patches of habitat. The use of adequate animal fencing and diversion measures are very important in the design factors for these types of structures. Another important aspect is lighting in the culvert crossing as many animals will not enter a dark tunnel. The figure No.3 shows an example of how the necessary natural light for an animal use crossing could be implemented.

Figure 4. Top Windows in a concrete culvert

From the perspective of sustainability, it is palatable to consider whether the conversion of existing culverts to be adapted for the purpose of an animal crossing is possible. In a study conducted on the A-52 motorway in Spain…*"differences of use were detected among passage types, with wildlife underpasses being the most used structures and adapted culverts the least."* (Mata et al. 2009) Based on this research, this option would appear to be less desirable.

Examining the first step from the "Natural Step" sustainable framework, the use of substances extracted from the earth's crust are inevitable in order to design an animal crossing using materials such as steel or concrete. The durability of the animal crossing structures is an important factor in limiting the consumption of these structural materials.

3.2 Climate Change and Culvert Design

An issue of safety, linking to step four, a person's ability to meet their basic human needs of transportation is climate change. With the fluctuations in precipitation and severe storms, insufficient design life and flow parameters for culverts can have devastating effects on societal conditions such as transportation. There was a collapse of a culvert on Finch Avenue in Toronto during a storm event on August 19th 2005 that caused the closure of Finch Avenue for 14 months. As a result there were both social and financial impacts resulting in direct costs of millions of dollars. The City of Toronto owns over 150 culverts with diameters larger than 3 meters and countless other smaller culverts (Genivar, 2011).

The analysis of climate change and its effect on culverts has been performed using the The City of Toronto Climate Driver's Study. This study differs from other studies as its timeframe is lapsed over 10 years from 2000-2009 rather than a standard study that focus on parameter "means" and a 30 year period – the most current study spanned from 1971-2000. Also, it combines a Global Climate Model (GCM) output as "fed" through a Regional Climate Model to drive a Weather Research Forecasting (WRF) model of much finer spatial resolution capability (Genivar, 2011). This model of GCM-RCM-WRF has since been adopted by the Ontario Ministry of the Environment, the University of Toronto, and the

University of Regina. The output of the model has been validated as being "within the expected range of results" when compared to 30 year normal based climate model outputs (Genivar, 2011).

One of the driving purposes for the study was to mitigate future impacts resulting from culvert failures. The study chose three culverts to be analyzed, a cast in place box structure, a CSP culvert under a large embankment and a CSP buried under a road. The City of Toronto estimated that 60% of their large diameter culverts are made of concrete and 40% of are CSP. The three culverts were labelled as Ellesmere (located on Ellesmere Road at West Highland Creek), Albion (located under Albion Road at the intersection of Albion Road and Todd Brook Crescent) and Grandravine (located at Grandravine Drive, west of Keele St.). The Ellesmere culvert is a double box concrete culvert, and Albion and Grandravine are both CSP culverts.

The study followed a specific method to follow as set out by the Public Infrastructure Engineering Vulnerability Committee. (PIEVC) The Protocol is as follows:

> "*There is definitive evidence to suggest that the climate has changed, and is continuing to change. Climate change affects infrastructure, creating potential vulnerability in the operation and design of engineered systems. Vulnerability may exist because historic climate data is often used to form the basis of the design for public infrastructure. However, due to a changing climate, historic data used to design critical infrastructure may not reflect the climate of the future. As a result, infrastructure may be vulnerable since it may not have sufficient capacity or resiliency to accommodate the conditions created by the changing climate."* (Genivar, 2011)

The PIEVC oversees the engineering assessment nationally for the vulnerability of public infrastructure. The step by step process includes: Project Definition, Data Gathering and Sufficiency, Risk Assessment, Engineering Analysis, and finally recommendations.

There were some specific recommendations that emerged from this study as related to climate change. The first was that the hydraulic capacity of the three culverts should be reviewed and compared with the anticipated flow conditions during large storm events. Currently the culverts that were modelled do not meet the design criteria to withstand the predicted flows. Due to the age, and the lack of detailed design information, it was not possible to determine what flows the culverts were designed to carry (Genivar, 2011). These results could be similar in many large cities across Canada if the data used for climate modelling GCM-RCM-WRF was used in the analysis of the flow parameters directly relating to the design life of such structures.

There were many other recommendations; noteworthy was an interesting regional problem. The City of Toronto has a significant issue with the infestation of its ash trees by Emerald Ash Borer. The trees infected with Emerald Ash Borer they are more susceptible to damage during severe storm events. There are some significant issues with the damage to the trees; severe erosion caused by exposed soil, another issue is the fallen branches and trees blocking the flow of the channels and culverts leading to failures. In other Provinces, such as Nelson Creek, British Columbia debris channels have been used to mitigate damage from trees and rocks.

Figure 5. Debris Channel – Fraser Creek, B.C.

3.3 Sustainability and Economics

The concept of sustainability is not a passing fad as major corporations are adopting these principals into their business planning. Manufacturers of products such as culverts can adopt a sustainable position and profit. Following and investing in a sustainability model doesn't mean that costs will skyrocket with no return. In a recent article titled "The Sustainability Imperative," published by the Harvard Business review the authors address this point. *"Why do we think sustainability qualifies as an emerging megatrend? Over the past 10 years, environmental issues have steadily encroached on businesses' capacity to create value for customers, shareholders, and other stakeholders*." (Lubin, Esty 2010). Many corporations are engaging in benchmarking practices to track results. "*Fujitsu, for instance, employs a performance assessment scorecard its cost green index that assesses the potential cost, productivity, and environmental impacts of eco- efficiency initiatives across the firm."* (Lubin, Esty 2010).

In many cases successful corporations can use their existing quality tools to measure greenhouse gas emissions, and reductions in waste. 3M had been using the Six Sigma quality system, rather than bring in a new data management system, they re-tooled and trained their 550 000 employees to use the Six Sigma process and are working on meeting their five year sustainability targets (Lubin, Esty 2010). Other corporations, such as Dow, go as far as making sustainability a function of their employee's role, tying it to compensation models and reviews. With the added costs of sustainability, there is an ability to gain on the bottom line. *"Notably, Julie Fox Gorte's analysis of a 2009 Mercer research survey examining several dozen studies found that firms with*

better social and environmental performance tend to have lower costs of capital associated with lower risk." (Lubin, Esty 2010).

However, the current state of practice in the engineering and design of culverts does not account for sustainability or changes in climate. In the current public tendering process frequently the lowest bidder is awarded the project, putting aside the environmental considerations in lieu of price. Despite this challenging environment, there are culvert suppliers who are implementing sustainable practices such as carbon calculators, and extended design life capabilities.

4 RECOMMENDATIONS

Based on the review of the literature in this paper, codes should be modified for culverts to meet the 100 year design life. Additionally, designers should educate themselves about regional external factors that could influence the serviceability of the culvert structure. Sustainability should be taken into considered when owners are tendering projects. By using a sustainable framework such as the Four Step system created by the Natural Step or equivalent, it gives a common language for owners and environmental agencies; this is a suggested method to bridge the comprehension gap. When designing animal crossings, lighting, geometry, and animal fencing should be part of the design requirements. A good starting point for an owner to start specifying sustainability is through design life. Owners should reward sustainable options through a credit system; this way awarded projects will not only be based on the lowest bid price, but on environmental credits.

CONCLUSION

In conclusion, current codes allow culvert systems with a short service life, this is not sustainable option. Additionally, current culvert designs do not account for climate change and are under-designed to handle the growing demand. Animal crossings are a good solution for creating connectivity between habitat patches divided by highways and roads. Other industries are adopting sustainability into their business models; however the majority culvert suppliers are behind the curve.

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