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GEOSYNTHETICALLY REINFORCED VEGETATION SPILLWAY ARMOURING; TWENTY YEAR CASE STUDY

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ABSTRACT

The Assiniboine River Diversion is a historic structure built in Manitoba, Canada in the early 1960s. The diversion stretches north from the Assiniboine River at Portage la Prairie to the south basin of Lake Manitoba. It diverts flood water from the Assiniboine River watershed into Lake Manitoba before flooding can reach lower elevations of the heavily populated city of Winnipeg. The diversion is one of three critical flood control structures in the province of Manitoba. The approximately 300m (985') wide structure was originally designed to carry 765m^3/sec (27,000 cfs) and in 2011 received an emergent upgrade to carry 963 m^3/sec (34,000 cfs).
The diversion was designed with an 800m (2,625') failsafe spillway as part of the west levee, that which has failed on numerous occasions and was subsequently armoured in 1997 with geosynthetically reinforced turf.

This case study will outline the twenty year performance of the Assiniboine River Diversion Failsafe overtopping spillway structure. The study will speak to both the advantages and disadvantages of armoring a critical flood control failsafe utilizing Turf and Root Reinforcement Mat (TRM) technology.
The paper will also discuss the role of cost effective TRM technology in delivering 'Green Infrastructure' principles with a quantified comparison of carbon footprint reduction in construction as compared to rock riprap spillway armouring. Spillway failure mechanisms of internal erosion and erosion by persistent and nuisance flow, will also be discussed.

RÉSUMÉ

La dérivation de la rivière Assiniboine est une structure historique construite au Manitoba, Canada, au début des années 1960. La dérivation s'étend du nord de la rivière Assiniboine à Portage la Prairie, jusqu'au bassin sud du lac Manitoba. Il détourne les eaux de crue du bassin hydrologique de la rivière Assiniboine vers le lac Manitoba avant que les inondations ne puissent atteindre des altitudes plus basses de la ville très peuplée de Winnipeg. La dérivation est l'une des trois structures essentielles de lutte contre les inondations dans la province du Manitoba. La structure d'environ 300 m (985 pi) de largeur a été conçue à l'origine, pour transporter 765 m3 / sec (27 000 cfs) et en 2011 a reçu une mise à niveau émergente pour transporter 963 m3 / sec (34 000 cfs).
La dérivation a été conçue avec un déversoir à 800 m (2.625 pi) dans la partie ouest de la digue, celle qui a échoué à de nombreuses reprises et a été par la suite blindée en 1997 avec du gazon géosynthétiquement renforcé.

Cette étude de cas décrira les 20 ans de fonctionnement de la dérivation Assiniboine et son déversement fluvial. L'étude parlera à la fois des avantages et des inconvénients de l'armement d'un système de protection contre les inondations à l'aide de la technologie Turf et Root Reinforcement Mat (TRM).
Le document examinera également le rôle de la technologie TRM rentable dans la fourniture des principes de «l'infrastructure verte» avec une comparaison quantifiée de la réduction de l'empreinte carbone dans la construction par rapport à l'armature de déversoir à roche. Les mécanismes d'échec des déversoirs d'érosion interne et d'érosion par écoulement persistant et nuisible seront également discutés.

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1 PREFACE

The author of this paper enjoys a career as a Subject Matter Expert in the field of civil hydraulic conveyance structure armouring. Fifteen years' experience and observation has resulted in published work that is referenced herein. This Twenty Year Case Study serves as a compendium of discovery and a platform for further exploration. Cited references of topics to date include:
- 2012 International Erosion Control Association; fourteen year case study predating this twenty year Case Study. (Corne and Pack, 2012)
- 2013 Transportation Association of Canada; reduction of greenhouse gas in construction when utilizing reinforced turf, as compared to hard armouring. (Corne 2013)
- 2016 Canadian Geotechnical Society; nuisance flow as failure mechanism of hard armour conveyance. (Corne 2016)

2 INTRODUCTION

This Case Study illustrates twenty years' service of geosynthetically reinforced turf as the surface armouring of a failsafe at the Assiniboine River Diversion, northwest of Portage la Prairie, Manitoba, Canada. This paper's performance observations are augmented with discussion on quantifying 'Green Infrastructure' principles as well as discussion on the potential for reinforced turf to perform more dependably than rock riprap that is routinely undermined by low flow events.

Once considered innovative technology, Turf and Root Reinforcement Mats (TRMs) have become 'State of Practice' in armouring civil hydraulic structures. Reinforced turf solutions are becoming increasingly more commonplace, especially where rock riprap may otherwise have been specified. New innovation in TRM technology comes with quantifying the reduction of carbon footprint of construction when utilizing TRM armouring as compared to traditional rock riprap armouring. Future innovation will come in quantifying carbon sequestration of vegetated structures when compared to hard armoured structures.

3 ASSINIBOINE RIVER DIVERSION HISTORY

3.1 Introduction

The Assiniboine River Diversion is a flood control infrastructure project on the Assiniboine River near Portage la Prairie, Manitoba. The Diversion is one of three pieces of critical infrastructure protecting the lower Assiniboine River basin and the Red River basin, including the cities of Winnipeg, Manitoba and Portage la Prairie, Manitoba. The Assiniboine River Diversion works in concert with the Red River Floodway around the city of Winnipeg as well as the Shellmouth Dam at the headwater of Assiniboine River. The Diversion has many components, with the focus of this case study on the diversion failsafe.

Historically the Assiniboine River Diversion has been maintained by the Water Resources Branch of the Province of Manitoba under several differently named departments. In January, 2007 Manitoba Infrastructure and Transportation assumed responsibility for the Diversion.

3.2 Background

Following a devastating flood in the Red River Basin in 1950, the province of Manitoba examined hydrological solutions to mitigate the effects of future flood events throughout the heavily populated lower basins of the Red River and Assiniboine River watersheds.

By 1958, plans were in place to execute construction of three critical pieces of infrastructure:
- Red River Floodway around the City of Winnipeg; capacity of 1,700 m^3/sec (60,000 ft^3/sec) was completed in 1968. Post 1997, flood capacity was increased to 2,550 m^3/sec (91,700 ft^3/sec)
- Assiniboine River Diversion from Portage la Prairie to Lake Manitoba receiving basin; capacity 708 m^3/sec (25,000 ft^3/sec), was completed in 1970. 2011 flooding resulted in emergent capacity increase to 963 m^3/sec (34,000 ft^3/sec).
- Shellmouth Reservoir near Russell, MB; constructed to arrest the Assiniboine River headwater and meter flow through the Assiniboine watershed; capacity 480,000,000 m^3 (390,000 acre-foot) was completed in 1972

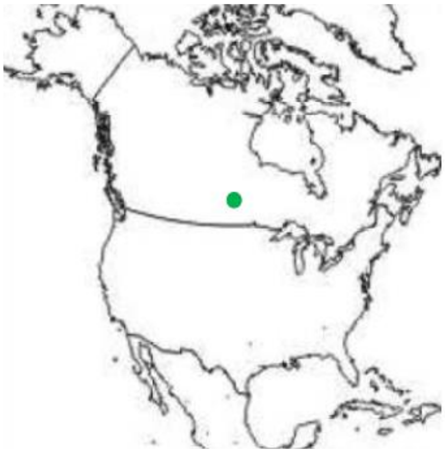

Figure 1: Structure locale

Figure 2: Assiniboine River Diversion context

3.3. Diversion and Failsafe Design

The Diversion, of which the 800m (2,625ft) failsafe is a component, consists of a river control structure and associated reservoir and inlet control structure, a 29km (18 mile) diversion channel, two drop structures along the diversion channel and an outlet structure at the south end of Lake Manitoba.

3.3.1 Diversion Channel

The main flood event diversion channel is a trapezoid approximately 200m (700ft) wide and 2m (6ft) deep defined by berms of approximately 5:1 side slopes. There is a secondary smaller low flow channel in the centre of the diversion.

In the vicinity of the overtopping failsafe the diversion widens to approximately 330m (1,100 ft) with centre of the east dike to the centre of the west dike measured at 400m (1,300 ft).

The section through which the failsafe runs, operates at a reduced capacity of 425 m^3/s (15,000 ft^3/sec). This is a result of economic constraints during construction where dyke construction material could not be borrowed from adjacent marsh areas. The haul cost of competent material governed final design and the reduced capacity.

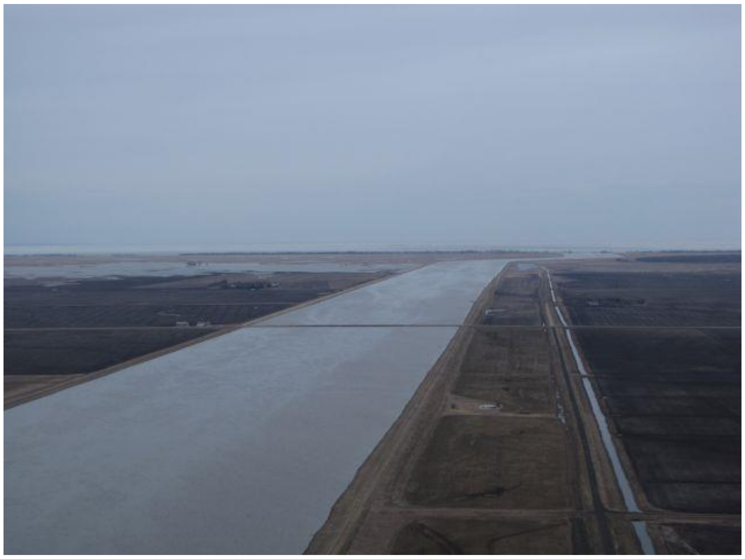

Figure 3: Spring, 2011
Failsafe on west levee (left) at the bend in the structure

3.3.2 Overtopping Failsafe

At approximately 3km (2 miles) from the outlet structure, an overtopping failsafe was constructed to ensure dyke overtopping occurred at a predictable location over the west dyke into a large marsh. Uncontrolled overtopping over the east dyke would result in overland flooding and breach of the intended diversion structure control.

The failsafe is approximately 800m (2,625 ft) long with a dike top elevation approximately 0.5m (1.5 ft) lower than the remainder of the dykes. Further, the failsafe has a slight gradient to the north end of the structure where overtopping flows are concentrated during an entire overtopping event.

Primarily in service during spring freshet, the failsafe always overtops with large ice flows in addition to other sizable woody debris.

The failsafe was originally armoured in agronomic grasses which proved insufficient armouring for design flows. Subsequent to seven over-topping events between 1970 and 1997 and detrimental heavy sediment loading of the adjacent marsh, it was decided the levee was to be armored to perform more dependably as an overtopping failsafe with the intent to stop the levee breaches. The failsafe was armoured in 1997 with a permanent turf and root reinforcement mat (TRM) to increase the failsafe performance. While no history was maintained as to the decision process, it is assumed rock riprap armouring was prohibitively expensive; the TRM solution, albeit softer than rock riprap, would have been more cost effective.

The TRMs specified to armour the failsafe against surficial erosion were composite turf reinforcement mats that combine a 3-dimensional permanent netting structure along with a fiber erosion protection / vegetation establishment matrix. The composite design offers an initial soil cover and mulching benefits to protect the soil and aid in vegetation establishment. The permanent structure is designed to provide long term support and reinforcement of vegetation roots and stems. The incorporation of the composite TRM increases the shear performance up to four times that of vegetation alone.

Considering the overtopping performance of the cost effective TRM originally specified, all subsequent re-armouring of the failsafe has utilized composite turf and root reinforcement technology.

Figure 4: Summer, 1997
Failsafe armoured utilizing TRM technology

3.4. Flood Event Chronology

The Assiniboine River Diversion was completed in 1970 and experienced seven over-topping events before TRM armouring in 1997. Post armouring, nine flood events have occurred as follows:

Table 1: Assiniboine River Diversion Overtopping Performance

Year	Diversion Flow	Overtopped	Performance
1999	481 m^3/sec (17,000 ft^3/sec)	Overtopped	Performed
2001	538 m^3/sec (19,000 ft^3/sec)	Overtopped	Performed
2005	566 m^3/sec (20,000 ft^3/sec)	Overtopped	Numerous breaches
2007	340 m^3/sec (12,000 ft^3/sec)	Limited Overtopping	Performed
2009	595 m^3/sec (21,000 ft^3/sec)	Overtopped	Limited Breaches 300mm (1 ft) angular riprap section conveyed
2011	963 m^3/sec (34,000 ft^3/sec)*	Overtopped	Limited Breaches
2013	530 m^3/sec (18,700 ft^3/sec)	Overtopped	Numerous washouts
2014	966 m^3/sec (34,100 ft^3/sec)	Overtopped	Mechanically breached in numerous locations (See section 4.3)
2017	609 m^3/sec (21,500 ft^3/sec)	Overtopped	Partially washed-out / north end spillway weir level mechanically lowered to ensure overtopping

*While the majority of the diversion runs at this rate, the area in the vicinity of the failsafe runs a reduced capacity of 425 m^3/s (15,000 ft^3/sec). (See section 3.3.1 'Diversion Channel')

4 SIGNIFICANT LESSONS AND PERFORMANCE

Vegetated TRM performance is impressive. This failsafe has provided many lessons in TRM performance over the twenty years recorded. Lessons learned, both positive and negative are detailed in the following:
- Erosion, both surficial and internal
- Performance in 2011, 360 year flood event
- Necessary mechanical breaching of TRM in 2014 flood event
- High performance in lieu of rock riprap
- TRM performance on the ‘wet’ side of the diversion (not the failsafe side)

4.1 Erosion

4.1.1 Failure Mechanism, Surficial Erosion

Until recent compelling evidence of internal erosion became apparent, TRM design shortcomings resulting in system breaches and soil loss have been presumed to be a large contributing factor in the dyke failures. Past dyke failures have shown evidence of localized surficial erosion resulting from net breach. The relatively delicate plastic net can be susceptible to breach from overtopping ice and woody debris, mowing and road grading operations. To be fully effective, TRMs must exhibit complete system coverage consisting of a vegetation root zone reinforced by the three dimensional plastic TRM netting.

Care was taken in the 2009 reconstruction to address mowing and grading breaches with a sign directing operators to contact the owner's representative. Upon pre-flood inspection prior to the 2011 flood, one significant winter windrow grader breach was discovered. Despite good intention and apparent simple instructions, TRMs are light plastic systems and should be considered as such in areas where the types of breaches outlined are probable.

4.1.2 Failure Mechanism, Internal Erosion

With the high overtopping shear stress throughout the failsafe, it is easy to explain the failsafe breaches as functions of surficial erosion. Agronomic Grasses, Turf and Root Reinforcement Mats and 300mm (1 ft) riprap have shown that while they appear to provide armouring against event flows, each has succumbed to varying degrees of surficial erosion.

Evidence is mounting to indicate that overall structural failure may be a function of internal erosion. The failsafe section of the diversion is constructed through a marsh where it has been assumed that porous marsh subgrade materials were not all removed prior to the clay dyke core being placed. Considering the 1960s design decision to reduce the diversion flow capacity through this section as a result of high construction costs associated with clay haul distances, it is safe to assume the poor subgrade material was not completely removed prior to clay placement. Dyke clay core failures since 1997 (and possibly earlier but records do not exist) have been replaced by large angular rock which have remained stable in subsequent overtopping events / dyke failures.

The 2011 dyke failure exhibited a 9m (30 ft) deep scour hole revealing a layer of poor subgrade below the clay dyke. There is great potential for piping failure occurring below the failsafe dyke.

4.2 High Performance in 2011, 360 Year Flood Event

Spring 2011 saw significant flooding throughout the Assiniboine River watershed, evaluated as a 1-in-360 year event.

While the Province was very busy throughout the region attending to many emergency situations, they did manage to inspect the Assiniboine River Diversion channel and failsafe periodically. Helicopter video and photographic records illustrate complete overtopping with ice and debris. Thirteen days into the flood overtopping continued over 60% of the failsafe as breaches formed. The failsafe ran for fourteen days.

It is important to qualify the 2011 performance by illustrating this performance was achieved with only one year of vegetation establishment. 2009 reconstruction was completed in November as winter set in. There was only one growing season before the flood began in the spring of 2011.

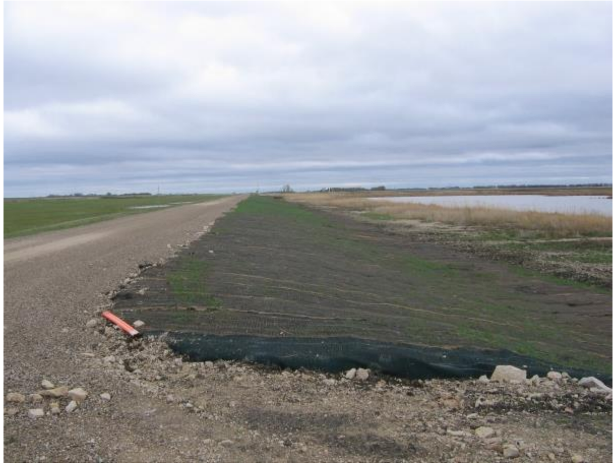

Figure 5: April, 2010
Early spring vegetation after fall 2009 re-armour

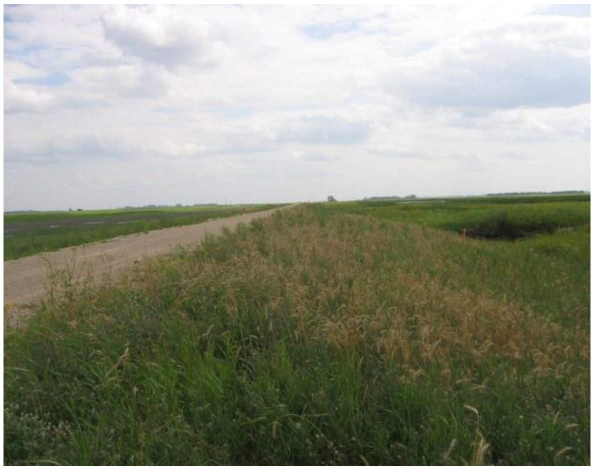

Figure 6: October, 2010
One year vegetation establishment

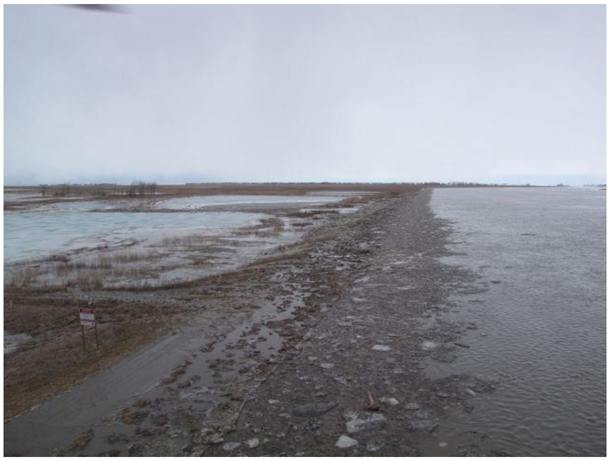

Figure 7: Spring, 2011
Failsafe overtopping

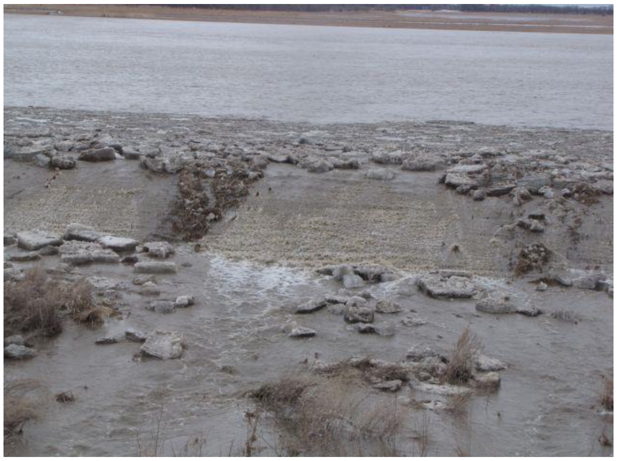

Figure 8: Spring, 2011
Ice overtopping detail

4.3 Summer 2014 Mechanical Breaching of Anticipated-to-Perform TRM

Summer of 2014 was an exceptionally wet season and the Province of Manitoba needed to quickly remove water from the Assiniboine River Diversion. Given known performance and proven dependability of the TRM armouring, a decision was made to mechanically breach the TRM as the product was expected to withstand overtopping where the province needed to rapidly reduce water levels.

Figure 9: July, 2014
Mechanical breaching of TRM on failsafe slope

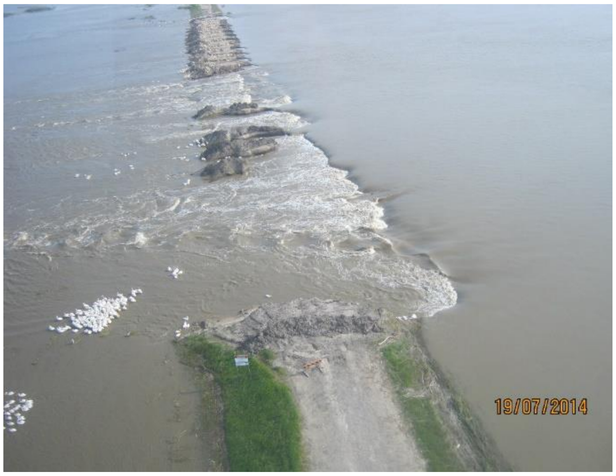

Figure 10: July, 2014
Failsafe left, wet side right

4.4 High Performance in Lieu of Rock Riprap

The 2005 reconstruction and re-armouring included a test section approximately 30m (100 ft) long which was armoured with 300mm (1 ft) angular limestone rock riprap over woven geotextile. In the 2009 overtopping, the angular riprap was conveyed off the 5:1 backslope and deposited in the marsh beyond the toe. The adjacent vegetated turf and root reinforcement mat performed.

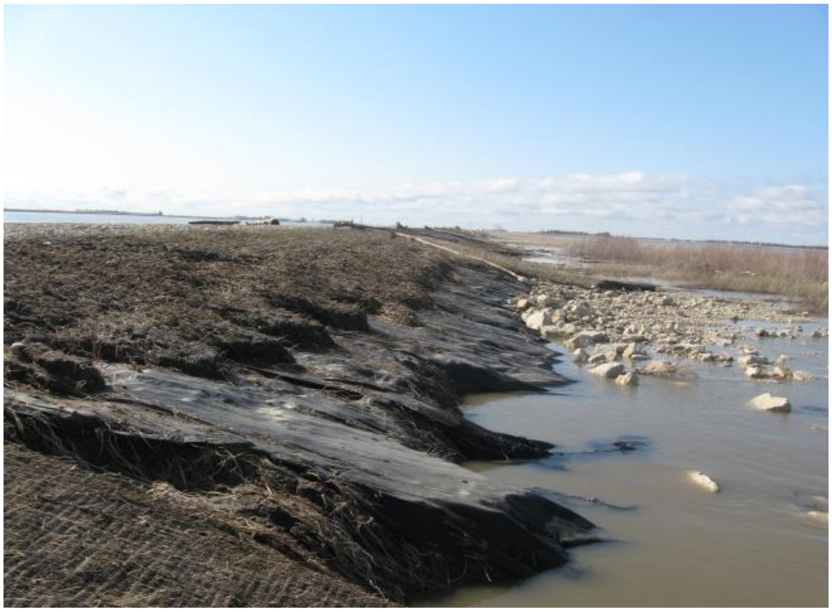

Figure 11: Spring, 2009
300mm (1ft) riprap conveyed in overtopping, adjacent TRM in the foreground performed

4.5 Diversion Channel 'Wet Side' Armour Performance

Until 2009, all TRM application was on the failsafe side of the structure. In 2009 under Federal Emergency Relief funding regulation, the wet side of the structure was funded to be brought as close as possible to pre-flood armouring levels. As the unvegetated TRM performs in permissible shear roughly equivalent to unreinforced vegetation, TRM was utilized for the first time on the wet side of the structure. As soil fine loss under spring flow was a concern, two layers of TRM were employed.

2010 was a wet summer and the TRM was mostly submerged for a majority of the summer which precluded full vegetation establishment prior to the 2011 flood. No appreciable soil fine loss was detected upon 2010 inspection. This section of in-channel treatment performed in the 2011 flood event.

5 TURF AND ROOT REINFORCEMNT MAT COST EFFECTIVENESS

Turf and root reinforcement armouring at the Assiniboine River Diversion has been very cost effective. The following describes known project costing.

5.1 1997 Original Installation by Penitentiary Work Crew

Original TRM armouring was completed by a work crew supplied by the local female Federal Penitentiary. Compared to riprap installation by heavy machinery and experienced operators, TRM mats can be installed with unskilled labour.

5.2 2005 Re-armouring

2005 TRM re-armouring was performed by a labour crew without prior TRM installation experience. TRM supply and installation was accomplished at approximately \$8/m^2 CAD. By comparison, 300mm (1 ft) angular riprap delivered to site and not placed was budgeted at approximately \$19/m^2 CAD.

5.3 2009 Re-armouring

2009 TRM re-armouring was performed by a labour crew without prior TRM installation experience. TRM supply and installation was accomplished at approximately \$12/m^2 CAD.

6 GREEN INFRASTRUCTURE

Carbon footprint impact and the reduction of greenhouse gas emissions is beginning to pervade modern civil construction and operational practices. Designers, owners, communities and nations are struggling to incrementally reduce greenhouse gas emissions. Green armouring of civil structures, historically hard armoured in rock, holds promise for significant reduction of the carbon footprint of construction and also hold great promise in sequestering carbon; carbon positive infrastructure.

6.1 Carbon Footprint Reduction in Construction

Reduction of Greenhouse Gas Emissions Through Utilization of Turf and Root Reinforcement Mat (TRM) Technology in Green Armouring of Civil Structures as Compared to Traditional Rock Armouring (Corne, 2013) explored the reduction of greenhouse gas emissions in construction by utilizing TRM technology in armouring civil structures as compared to traditional rock armouring. The paper outlined the generally accepted use of geosynthetics in civil structure construction, and surveyed the current greenhouse gas reduction strategies in construction.

6.1.1 Performance Equivalency Benchmark

The 2013 Corne paper presumed the acceptance of Turf and Root Reinforcement Mats as an equal performance alternative to rock riprap structure armouring. Many different styles of TRMs combined with varying levels of vegetative establishment address nearly any permissible shear performance benchmark. The assumptions are predicated on the ability of a partially vegetated TRM to perform to the same permissible shear as 300mm riprap and beyond.

The United States Army Corps of Engineers have defined the permissible shear of 300mm d_{50} as 245 Pascal, 450mm d_{50} as 365 Pascal and 600mm d_{50} as 485 Pascal (Fischenich,2001. P. 5). By comparison, TRMs perform, per manufacturers' specifications, in the range of 145 Pascal in the unvegetated state to over 700 Pascal in the fully vegetated state. In considering TRM as a viable design alternative, it is best to always consider design alternatives as unvegetated as structures are normally commissioned as soon as they are completed. A number of velocity reduction and energy dissipation strategies can be employed to meet permissible shear values up to approximately 400 Pascal in the unvegetated state. Risk-based evaluations can consider very high permissible shear values of fully vegetated TRM solutions if a structure is not commissioned until full vegetation has established.

6.1.2 Comparison of TRM to Rock Riprap in Reduction of Greenhouse Gas in Construction

The comparative evaluations outlined below consider a thorough investigation of design and construction input parameters as well as carbon produced in riprap and TRM production, transport and placement. Complete structure armourings were compared utilizing general engineering 'budget' costs for placement rates and machine charges (Corne 2013).

Two comparisons are outlined:
- 'Armouring on Grade' compares a TRM with d_{50} 300mm riprap placed 300mm thick over geotextile directly onto the grade as was trialed in the 2005 re-armouring.
- 'Subcut and Spoil' compares a TRM with more traditional riprap armour methodology of rock placed at $1.5d_{50}$. This comparison considers d_{50} 300mm riprap placed respecting the general riprap rule of 1.5 depth, or 450mm deep. Further, this comparison considers the carbon utilized in sub-cutting the grade by 450mm. For the calculations in this example, haul distance of subcut material considers only on-site spoiling. Off-site spoiling increases the carbon footprint of earth-moving.

Both examples consider the approximately 18,000 m^2 project size of the Assiniboine River Diversion Failsafe. This example is accentuated by the 200km round-trip riprap haul distance. It is important to note that shorter riprap haul distances also yield high percentages of carbon savings.

Table 2: Reduction of Carbon in Construction Utilizing TRM Technology when Compared to Rock Riprap

	Armouring	Transportation tCO_2	Material tCO_2	Installation tCO_2	Total tCO_2	Carbon Saving
Armour on Grade	300mm rock armour	47.19	494.02	3.48	544.69	
	TRM	4.16	23.33	1.68	29.17	95%
Subcut and Spoil	450mm rock riprap	69.62	735.09	10.45	815.16	
	TRM	4.16	23.33	1.68	29.17	96%

6.2 Carbon Sequestration

Carbon footprint reduction of construction can be easily quantified by calculating emission reduction of lessening aggregate production, hauling and placement. Carbon sequestration and quantification of same are more general in nature. Kristin Ohlson in *The Soil Will Save Us* outlines very general carbon sequestration values. In evaluating cover crops for traditional agricultural practices, it is estimated a metric tonne of carbon dioxide per acre can be sequestered (Ohlson, 2013. p 108). Further, in evaluating the value of compost, which can easily be specified in TRM systems, it was found that the carbon sequestered in the plants and ground increased by 25 to 70 percent, not including the carbon in the compost (Ohlson, 2013. p 207).

There is significant latent value for structure owners, both private and public, to employ this accessible technology in posting positive carbon sequestration while armouring necessary water conveyance infrastructure.

Reinforced vegetation lined conveyance also reduces peak load of receiving water bodies by slowing water in grass while contributing to recharging immediately local groundwater within the watershed of the lined channel. Further, grass lined channels are known to reduce environmental pollutants. The United States Environmental Protection Agency 'Stormwater Technology Fact Sheet; Vegetated Swales' outlines the performance characteristics of vegetated swales; including the ability of a vegetated swale to mitigate for pollution as compared to hard-lined swales. The Fact Sheet states; "a conservative estimate would say that a properly designed vegetated swale may achieve a 25 to 50 percent reduction in particulate pollutants, including sediment and sediment-attached phosphorus, metals, and bacteria." (USEPA, 1999. p 4)

7 STRUCTURE FAILURE MITIGATION

Filter and drainage design have long been quantified in the design detailing and the construction of civil and hydraulic structures as an interface between the parent soil and the engineered structure. *Nuisance Flow as Failure Mechanism of Conveyance Structures and the Contribution of Geosynthetic Design Practice* (Corne, 2016) questioned the focus on filter design of water passing perpendicular to parent soils along incline structures where aggregate filters may be performing incidentally as drains. Further, where a graded aggregate filter has been replaced by a nonwoven geosynthetic, the paper discussed the potential for water to run below the geosynthetic, resulting in sub-structure erosion.

7.1 Nuisance and Persistent Flow

Civil and hydraulic structures are typically designed to hydraulic stability in a particular storm event. Conveyance channels are sized and armoured to carry predictable hydrologic events. Outside of critical structure design, common conveyance structure design rarely considers non-storm event water flow as it occurs by smaller rain events, persistent source water or grade water / piping.

Nuisance and persistent water, combined with non-performing geotextile filter in the incline orientation, create the scenario of long-propagating sub-structure erosion gullies below conveyance armourings.
Sub-structure erosion by water flowing below the non-woven geotextile filter is exacerbated by insidious non-storm-event water flow.

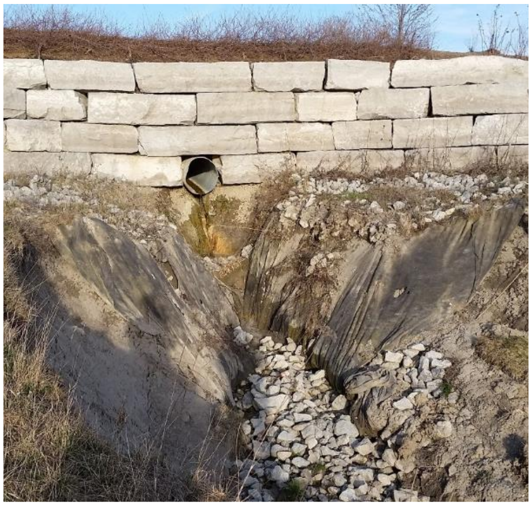

Figure 12: Apparent storm flow ‘catastrophic failure’

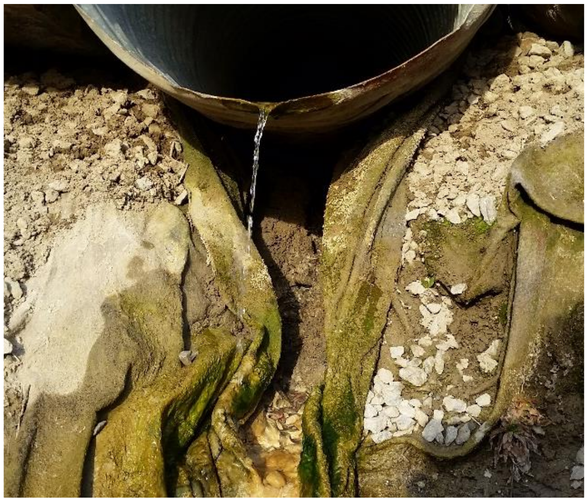

Figure 14: Persistent nuisance flow cause of failure

7.2 Contribution of Rootzone to Structure Stability

Well-graded aggregate filters designed to mitigate fine loss in civil infrastructure grades are no longer specified in common conveyance structures as nonwoven geotextiles, mostly inappropriately, replaced their use. Further, well-graded aggregate filters have become difficult and costly to produce to particular designed specifications.

A well-developed fibrous rootzone may serve to keep subgrade fines in place, thereby arresting civil grade material fine migration.

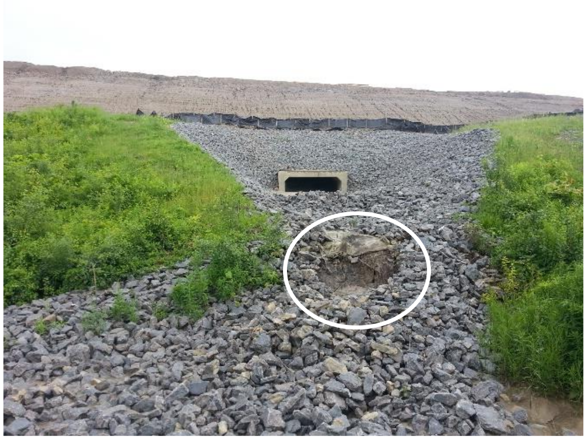

Figure 15: Storm flow out of a 1.5m high box culvert conveyed the riprap armour and ripped the geotextile.

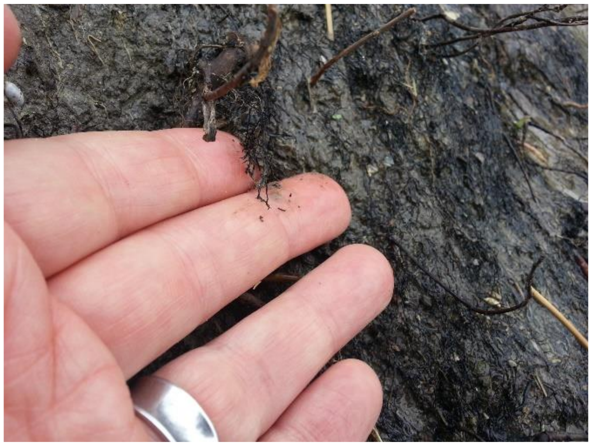

Figure 16: Grade remained stable because of remnant shrub rootzone left in place below the geotextile.

7.3 TRM Structure Design Detailing

Conveyance structure failure by nuisance and persistent flow is common, as observed in the short term where erosive subgrades exist, or on the long term where structures are constructed with relatively non-erosive material. Design complacency is a contributing factor. Design employing new technology and / or techniques causes care to be taken in the design process to ensure proper detailing and overall structure performance increases. Further, cognizance of hydraulic conveyance structure failure causes diligence in design.

7.4 Substructure Erosion Mitigated with TRM Structures

The goals of a well-developed reinforced rootzone are to mitigate for fine loss by the fibrous rootzone and ultimately, to drive water to the surface to run on top of the reinforced vegetation. While unvegetated TRM lined conveyance structures are susceptible to the same forces of substructure erosion as riprap over geotextile, once a fibrous rootzone is established, substructure erosion is greatly diminished, if not eliminated.

Given the known exceptional performance benchmarks of vegetated TRM liners, widespread adoption is limited by lower performance benchmarks of unvegetated TRMs. Research is required to develop methods for increasing unvegetated TRM performance.

Figure 17 illustrates a TRM structured designed for a channel that was subjected to constant flow by both nuisance groundwater wellings as well as persistent source water from offsite contribution; neither of which were properly considered in the design process. Construction proceeded with substructure erosion resulting within one week. The erosion below the TRM was repaired with a custom-fabricated biodegradable, flexible filter within which water ran until vegetation rooting ultimately caused the nuisance and persistent flows to surface.

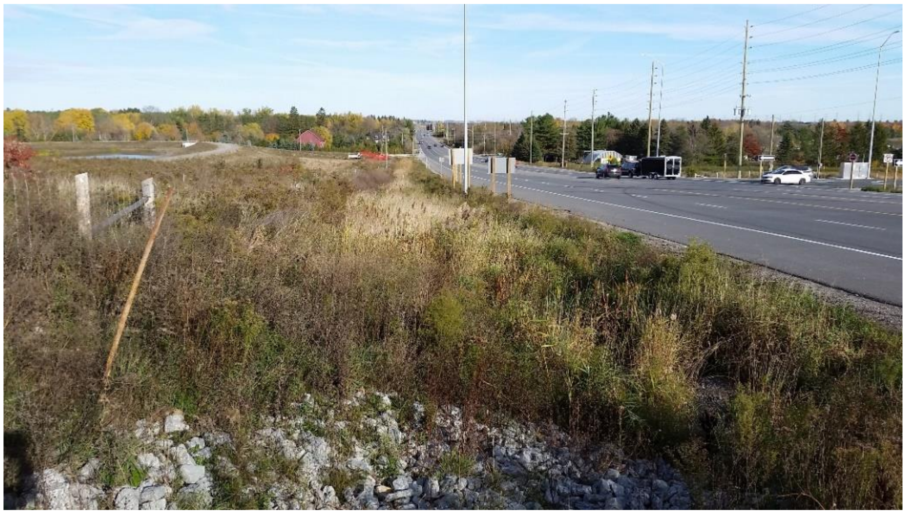

Figure 17: Stable, high performance conveyance structure utilizing TRM technology

8 CONCLUSION

Vegetated turf and root reinforcement mat performance, as evidenced at the Assiniboine River Diversion Failsafe is impressive. TRM performance directly adjacent to conveyed 300mm (1 ft) angular riprap illustrates this technology as a viable alternative to traditional rock armour where site conditions allow for vegetation growth through a three-dimensional composite netting. Further, the cost effectiveness of these vegetated systems can make them very attractive as compared to hard armouring techniques.

Twenty years' experience at the Assiniboine River Diversion critical flood protection infrastructure has provided valuable resource in Turf and Root Reinforcement Mat performance in protecting this failsafe component against surficial erosion. Most importantly, experience in this case has illustrated the necessity to always consider the root cause of structural failure as surficial treatments cannot address the destructive energy of internal or substructure erosion.

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