Nuisance Flow as Failure Mechanism of Conveyance Structures and the Contribution of Geosynthetic Design Practice

Ian Corne, CPESC, M.Land.Arch., B.E.S.
Application Specialist, Erosion and Sediment Control
Nilex Civil Environmental Group

Paper prepared for presentation at the
Fundamentals, Risk & Reliability Session

Of the 2016 conference of the
Canadian Geotechnical Society
Vancouver, British Columbia

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Ian Corne, CPESC, M.Land.Arch., B.E.S.
Nilex Civil Environmental Group, Abbotsford, B.C., Canada

Abstract
The use of rolled geosynthetic woven and non-woven geotextiles in the construction of civil engineering structures is state of practice. Ranging from filtration to soil reinforcement, geosynthetic use in civil engineering is prevalent.
Where filtration governs in horizontal roadway applications, nonwoven geosynthetics have appropriately replaced well-graded aggregate filters in horizontal applications subject to vertical pumping under dynamic loading conditions.
Where filtration governs in sloped gradient conveyance structures not subject to pumping, well-graded aggregate filters are required to carry non-storm-event nuisance and/or persistent sub-structure flows as they occur below the conveyance storm event rock armoring.
In hydraulic conveyance applications, civil and hydraulic designers have inappropriately adopted wide-spread specification of nonwoven geotextiles in lieu of well-graded aggregate filters.

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.

The author surmises that nuisance and/or persistent sub-structure flows running below the geotextile manifests as erosion below the structure and/or reduced civil structure shear capacity of saturated subgrades. The result is failed conveyance structures where failure is initiated in the first rainfall after the geotextile is placed and ultimately presents in five to ten years after continual structure weakening and erosion below the geotextile by sub-structure water flow; the conveyance armouring finally yields to the additional weight of water in a ‘storm event’.
The author surmises failure is incorrectly attributed to the storm event flow when the true failure is the long-propagating erosion gully below the geotextile. The high tensile strength geotextile spans the resultant erosion gully and carries the weight of the rock above. In time, the additional weight of water running in the channel causes the geotextile to break, presenting as an apparent ‘catastrophic failure’ that has been long propagated.

1.0 Introduction

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* questions 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, this paper discusses the potential for water to run below the geosynthetic, resulting in sub-structure erosion.

1.1 Qualifiers

The concepts and questions outlined herein are borne of empirical evaluation of 'failed' hydraulic conveyance structures; both in person and by photographic documentation.
The subject focus of this investigation is common, non-critical, rock riprap lined hydraulic conveyance structures.

1.1.1 Filter Design

A broad tertiary literature review of common riprap revetment illustrated a lack of research on the topic of potential sub-structure erosion by filter design in an incline condition.
With more critical infrastructure such as bridge abutment and piers, proper consideration of granular filter properties was found to include; particle size distribution, permeability, porosity, thickness and filter material quality and durability. Filter design was found to be in consideration of a horizontal condition only.

1.1.2 Storm Event Design

Common, non-critical, rock riprap lined hydraulic conveyance structures are typically designed to convey a quantified 'storm event'; this paper considers non-storm-event flow.

2.0 Surficial, Internal and Sub-Structure Erosion

The study of erosion is well supported on the subjects of surficial and internal erosion.
Surficial erosion is well understood and erosion mitigation on slopes and in-flow is a reasonably exact science of flow equations, roughness coefficients and particle erosivity.
Internal erosion, with less opportunity for collection of empirical data, is also known in dam design in terms of soil conductivity and piping with mitigation by internal drain design.

In both surficial and internal erosion design, direction exists for consideration of the interface between designed structure and the parent material. The more critical the structure, the higher level of prudence exercised in design and construction. As design of conveyances moves from critical structures, 'flexible liner' armouring with rock riprap is employed to accommodate launching and settlement. Continued monitoring of degradation of flexible liners, no matter the level of diligence, is metered by the liner flexibility inherent in design.

By the author's observation, the failure of flexible liners by benign long-acting surficial conveyance events is to be questioned by owners and designers. It is argued herein that more active forces of sub-structure erosion degradation by flowing water below the filter, aggregate or geotextile, are a result of non-storm-event water flow.

With graded aggregate filters in place to mitigate for parent soil fine loss in a storm event, the *filter serves an incidental role of incline drain*. The filter ultimately clogs by introduction of sediments in the flowing water where the filter was originally designed considering the particle size of the parent soil and not the particles carried in the storm, and non-storm water flows.

With geotextile filters, the non-storm-event water more quickly finds route below the planar textile, thereby expediting sub-structure soil erosion.

3.0 Filter and Drain Design

The USDA *National Engineering Handbook; Chapter 26, Gradation Design of Sand and Gravel Filters* defines (page 35):
Filter—Sand or sand and gravel having a gradation designed to prevent movement of soil particles from a base soil by flowing water.
Drain—A designed pervious zone, layer, or other feature used to reduce seepage pressures and carry water.

Legasse et. al. in *Riprap Design Criteria, Recommended Specifications, and Quality Control* states (page 140):
Correct filter design reduces the effects of piping by limiting the loss of fines while simultaneously maintaining a permeable free-flowing interface.

Design manuals commonly direct that aggregate filters must retain the coarser particles of the subgrade while remaining permeable enough to allow infiltration and exfiltration to occur freely, where the filter functions in the retention of fill materials behind the filter and allows for water to move to an outlet without further erosion. Fine migration is considered with water movement *through* the filter, water migration is considered *within* the drain.

In the case of incline structures, the three-dimensional nature of a graded aggregate filter has served as an incidental function of water flow within the filter / drain and below the surface armour in non-storm-event flows.

4.0 Relative Interchangeability of Graded Aggregate and Geotextile Filters

Nonwoven geotextiles have had a tremendous impact on civil design practice and construction in terms of manufactured product design certainty and constructability. Design of a graded aggregate filter to protect civil infrastructure constructed over poor, yielding subsoils is based on known theory. Construction of aggregate filters is very difficult and results in low quality construction where the filter ultimately mixes with the subgrade during machine placement. Construction with nonwoven geotextile in place of graded aggregate filter over poor / yielding subgrades is accomplished by simply rolling out the geotextile and placing the base material above. Construction with geotextiles results in higher quality construction realizing the intended filter and base material separation. Over the last half century geotextiles have come to commonly replace graded aggregate filters in construction.

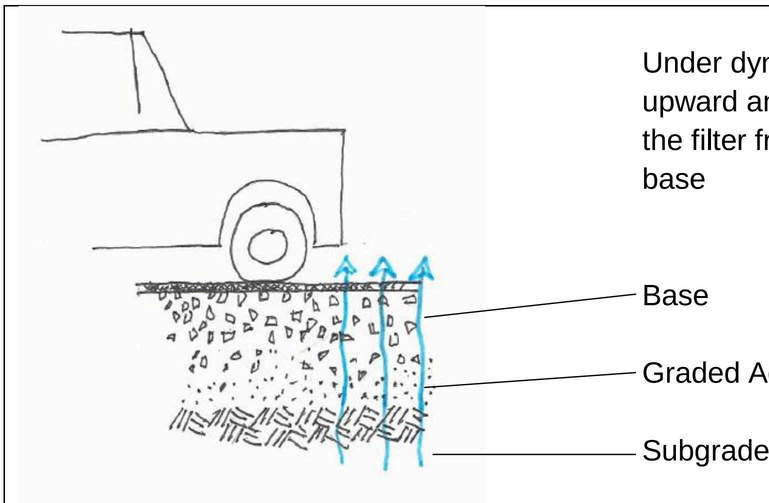
4.1 Geotextile Permeability

Replacing the graded aggregate filter with non-woven geotextile has resulted in the quantification of geotextile permeability. As with aggregate filters, permeability measures the ability of a geotextile to transmit water across its thickness.

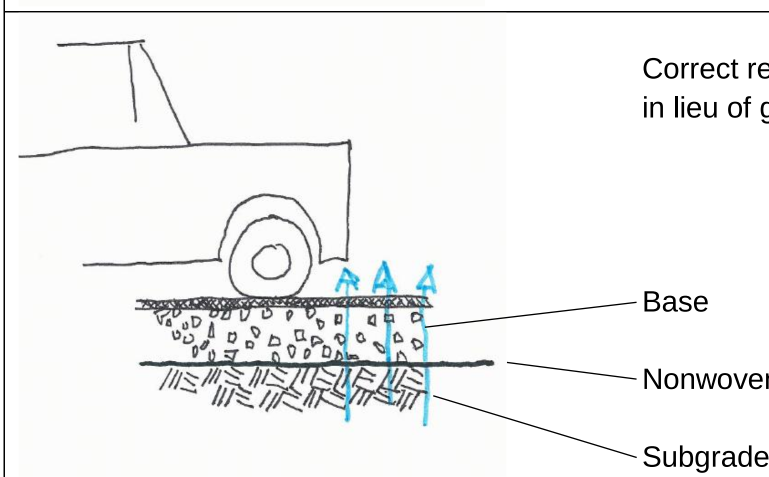
4.2 Geotextile Filter Thickness

In the case of incline structures, two-dimensional geotextiles do not enjoy the incidental benefit of the three-dimensional filters they have replaced. *Water cannot run within a geotextile and the path of least resistance for the water will, in certain circumstances, be below the geotextile. The result is expedited sub-structure erosion.*

4.3 Geotextile in Lieu of Aggregate Filter, Under Dynamic Loading in Horizontal Condition

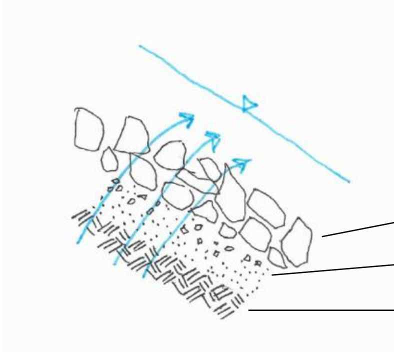


Under dynamic loading, grade water pumps upward and subgrade fines are stopped by the filter from passing upward into the road base



Correct replacement of non-woven geotextile in lieu of graded aggregate filter.

4.4.1 Geotextile in Lieu of Aggregate Filter, Under Storm Event Flow Condition

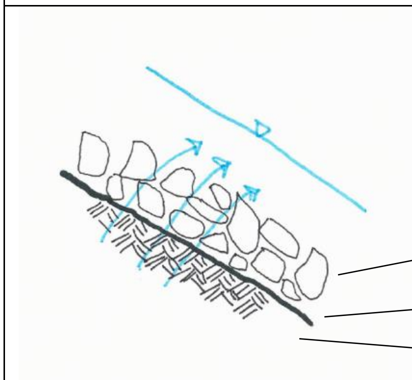


During high flow event, graded aggregate filter keeps the subgrade fines from passing upward through the riprap.

Riprap

Graded Aggregate Filter

Subgrade



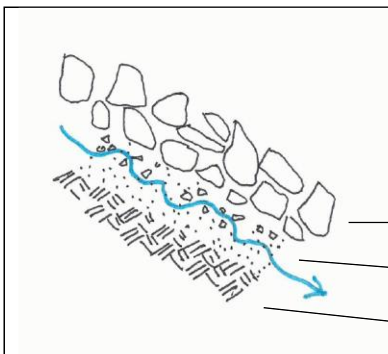
Correct replacement of non-woven geotextile in lieu of graded aggregate filter.

Riprap

Non-woven Geotextile

Subgrade

4.4.2.1 Geotextile in Lieu of Aggregate Filter, Under Non-Storm Event Flow Condition

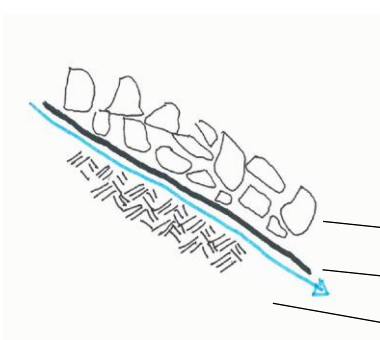


In non-storm-event flows, graded aggregate filter has serves as an incidental function of water flow within the filter / drain and below the surface armour.

Riprap

Graded Aggregate Filter / Drain

Subgrade



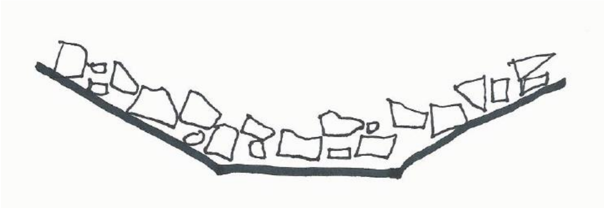
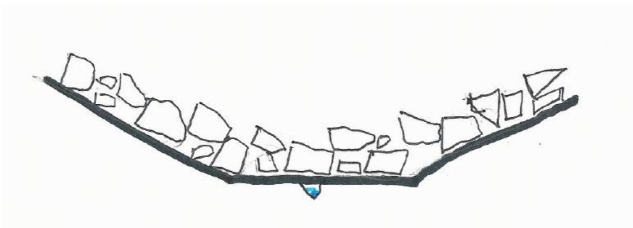
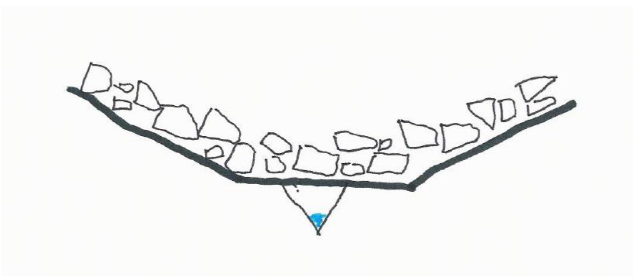
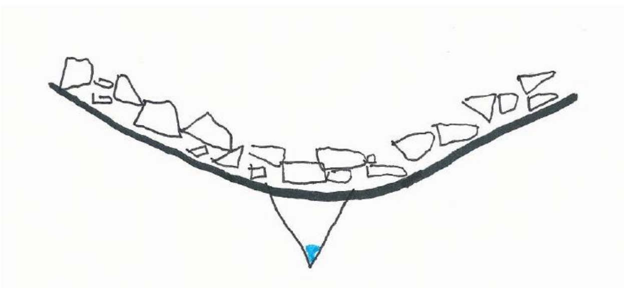
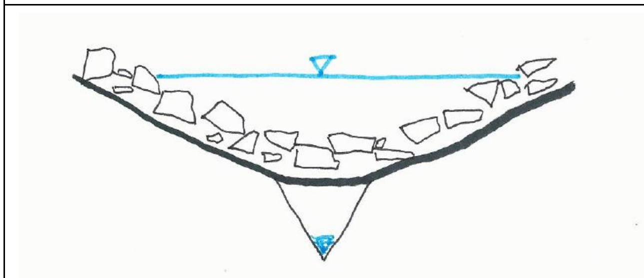
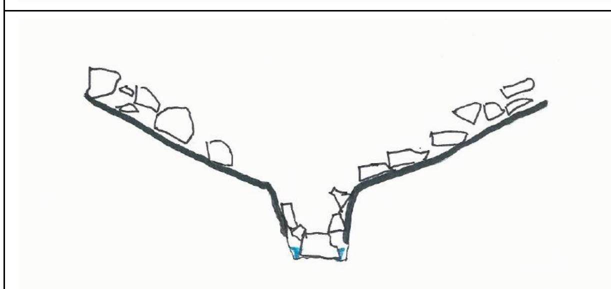
In non-storm-event flows *water cannot run within a geotextile and the path of least resistance for the water will, in certain circumstances, be below the geotextile. The result is expedited sub-structure erosion.*
Incorrect replacement of non-woven geotextile in lieu of graded aggregate filter.

Riprap

Non-woven Geotextile

Subgrade

4.4.2.2 Geotextile in Lieu of Aggregate Filter, Under Non-Storm Event Flow Condition

	Completed structure; rock riprap over non-woven geotextile.
	Substructure erosion initiated immediately post-construction with the first rain event.
	1 – 5 years sub-structure erosion, depending on erosivity of civil grade or parent material
	Continued sub-structure erosion; geotextile stretches (and becomes stronger as it stretches), rocks lock to form a bridge, and sub-structure erosion gully grows.
	Storm event occurs placing extra weight of water on the geotextile.
	Geotextile and bridge-locked riprap yield under weight of storm water revealing the long-propagated erosion gully below.

5.0 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.

Photo 1a. Apparent storm flow failure

Photo 1b. Persistent nuisance flow

Photo 2. Water flow below geotextile

Photo 3. Yielded geotextile over wet grade

6.0 Rock Riprap Failure

Legasse et. al. in *Riprap Design Criteria, Recommended Specifications, and Quality Control* describe four riprap revetment failure mechanisms as (pages 111 - 112):
- Particle erosion; individual particles are dislodged by the hydraulic forces generated by flowing water.
- Translational slide; downslope movement of a mass of stones, with the fault line on a horizontal plane.
- Modified slump failure; mass movement of material along an internal slip surface within the riprap blanket.
- Slump failure; rotational-gravitational movement of material along a surface of rupture that has a concave upward curve.

Legasse et. al. describe modes of more critical bridge structure pier riprap failure by review of Chiew (1995) as (pages 114 – 115)
- Riprap shear failure; riprap stones cannot withstand the downflow and horseshoe vortex associated with the pier scour mechanism
- Winnowing failure; the underlying finer bed material is removed through voids or interstices in the riprap layer
- Edge failure; instability at the edge of the coarse riprap layer and the bed sediment initiates a scour hole beginning at the perimeter and working inward

6.1 Winnowing

While ‘winnowing’ closely describes the failure mechanism discussed herein as sub-structure erosion, the Y.M. Chiew’s definition of winnowing as summarized by Legasse, describes only riprap failure of pier armouring. Revetment armour laboratory testing must be expanded in evaluating winnowing as a contributing factor in revetment armour failure.

6.2 Throughflow

Similar to subgrade erosion by winnowing, C.D. Smith, in *Hydraulic Structures* (chapter 8, page 25) discusses filter design as it relates to water flowing within the rock gradation of the flexible riprap liner. While examining flow within riprap gradations, it was found that erosive subgrades would be eroded at the subgrade surface by the throughflow discharge and transported through the voids of the riprap.
Smith stated the importance of a filter layer to address this condition, and also discussed commercial filter fabrics being used as a substitute for graded aggregate filters.

7.0 For Consideration in Addressing Sub-Structure Erosion

The intent of this paper is to bring attention to the prevalence of sub-structure erosion of flexible riprap armour liners where the failure mechanism appears to be subgrade erosion by nuisance flow below geotextile or by clogging / erosion of incline aggregate filters.

7.1 Measures for Moving Forward and Possible Area of Research and Further Study

7.1.1 Failure Mechanism Acknowledgement

The geosynthetic industry and the hydraulic conveyance community needs to acknowledge this as a failure mechanism. Forensic evaluation of liner armour failure needs to consider sub-structure erosion.

7.1.2 Filter / Drainage Design

Current filter design considers vertical water movement *through* the filter from the parent material and then drainage design considers water movement *within* a more openly graded drainage layer.

Design methods need to be developed to address compound functioning of aggregate filter / drainage design to address incline applications as found in civil infrastructure applications.

7.1.3 Alternative Filter / Drainage Design

Exploration is required to find alternative drainage media capable of compound filtration and drainage.

7.1.4 Vegetation Rootzone Contribution

Evaluation of a well-developed vegetated liner rootzone is required. A well-developed fibrous rootzone may serve to keep subgrade fines in place, thereby arresting parent material fine migration.

Photo 4a. Storm flow out of a 1.5m high box culvert conveyed the riprap armour and ripped the geotextile.

Photo 4b. Grade remained stable because of remnant shrub rootzone left in place below the geotextile.

8.0 Conclusion

Legasse et al, in *Riprap Design Criteria, Recommended Specifications, and Quality Control,* provide a pertinent concluding recommendation (page 140):

“Filter design criteria are the most overlooked aspect of riprap design. More emphasis must be given to compatibility criteria between the filter (granular of geotextile) and the soil.”

This paper presented discussion supporting the needed expansion of the Legasse statement as above to include “…*as well as lateral and incline filtration and drainage mechanisms within the filter / drain* ”

By the author’s observation, it has been found that sub-structure erosion is prevalent in non-critical hydraulic conveyance structures affected by nuisance and / or persistent flow below / within three dimensional graded aggregate filters.

Further, it has been found that sub-structure erosion is expedited where geotextile has been specified in lieu of graded aggregate where non-storm-event water more quickly finds route below the planar textile, thereby expediting sub-structure soil erosion.

This paper questions the attribution of conveyance structure failure as ‘catastrophic failure in a storm event’ when forensic evaluation after a storm event empirically illustrates sub-structure erosion presenting as an erosion gully that has long been propagating below the rock riprap liner geotextile.

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