Performance of Geosynthetic-Reinforced Floating Roads under Cyclic Loading on Canadian Peatlands

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Abstract

Peatlands remain one of the most challenging environments for infrastructure development because of their high compressibility, low shear strength, and typically saturated conditions. These characteristics present particular difficulties in the Canadian subarctic, where major mineral deposits in regions such as the Ring of Fire cannot be developed without reliable, year-round transportation access. In addition to access roads, mine haul roads constructed across peat deposits must support extreme axle loads, yet practical design guidance for these conditions remains limited in current engineering practice.
In prior research conducted by two of the current authors[1] (2018), three approaches for constructing embankments on peat were evaluated: direct placement of granular fill, full excavation and replacement

of peat, and construction of floating embankments reinforced with geosynthetics. That study used finite element modelling under static loading conditions with settlement limited to 50 mm as a serviceability criterion. Material quantities were incorporated into a cost-benefit assessment considering peat thickness, haulage distance, and seasonal excavation constraints. Results indicated that excavation may be more economical where peat is shallow (less than 1 m), whereas reinforced floating embankments are often the most practical and cost-effective option for thicker deposits.

The present paper builds on previous work by examining the cyclic performance of floating embankments reinforced with geosynthetics. To represent a range of mine traffic conditions, two typical haul vehicles are considered: a highway truck with an approximate payload of 40 ton, and a medium mine haul truck with a payload of approximately 75 ton. The performance of a larger mine haul truck with a payload of 150 ton was investigated in earlier work presented at CIM 2018.

By linking the static evaluation from the previous study with new cyclic loading analyses, this paper provides a more comprehensive view of road behaviour on peat. A cost analysis will be conducted to assess the impact of incorporating geosynthetics into the design and to identify potential cost savings (in Canadian Dollar CAD) based on granular fill material and geosynthetics supply costs. The results help define the reinforcement strategies required to maintain road performance over time and contribute to the development of practical design guidance for access infrastructure in peatland regions of northern Canada.

Introduction

Transportation infrastructure constructed on peat and other very weak subgrades presents persistent challenges due to extremely low shear strength, high compressibility, and the potential for rapid strength loss under disturbance or cyclic loading. In Canada, these challenges are particularly encountered in northern and subarctic regions, where economic development depends on the construction of access and haul roads across extensive peatlands.

Traditional mitigation measures—such as full peat excavation and replacement—are often impractical or prohibitively expensive where peat thickness is large, groundwater levels are high, or construction windows are limited by climate. As a result, floating road concepts using mechanically stabilized layers have become increasingly prevalent. These systems rely on geosynthetics placed at or near the base–subgrade interface to improve load distribution, control deformation, and enable construction over soils that would otherwise be unusable.

Despite widespread adoption in practice, confusion persists regarding how geosynthetics improve performance and whether they can be interpreted as increasing subgrade strength, particularly when performance is expressed in terms of design parameters such as California Bearing Ratio (CBR). This paper clarifies these mechanisms and integrates them with classical pavement design method under cyclic loading.

CBR and Strength Improvement

All reviewed design methodologies and supporting literature consistently indicate that geosynthetics do not increase the intrinsic or laboratory-measured CBR of the subgrade soil. The mineralogy, density, and fabric of the soil remain unchanged. However, geosynthetics significantly enhance the effective structural capacity of the subgrade–base system. In engineering practice, this improvement is commonly represented as an increase in equivalent or effective CBR because the reinforced system behaves as

though the subgrade became stronger. This distinction is critical and fundamental to the correct interpretation of reinforced road performance.

Mechanisms of Effective CBR Increase

Mobilization of Higher Bearing Capacity States

Classical bearing capacity theory recognizes different failure modes depending on soil confinement and interface conditions. For weak, saturated subgrades, unreinforced conditions typically mobilize only elastic or local shear resistance while reinforced conditions enable mobilization of general shear failure at much higher stress levels.
Design methods developed by the U.S. Army Corps of Engineers[2,3] (2003, 2008), Giroud–Noiray[4] (1981), and later Giroud–Han[5,6] (2004) explicitly account for this effect through increases in the bearing capacity factor, N_c. According to the literature, for the same undrained shear strength (and therefore the same CBR), reinforcement increases the allowable bearing stress by as much as 70–80%. Since undrained shear strength is commonly correlated to CBR, increasing the mobilized bearing capacity is theoretically equivalent to increasing CBR in design calculations.

Reorientation of Interface Shear Stresses

A critical advancement introduced by Giroud and Han[5,6] (2004) is the recognition of shear stress direction at the base–subgrade interface:

- Outward-directed shear stresses reduce subgrade bearing capacity.
- Inward-directed shear stresses increase bearing capacity.

Geogrids, through aggregate interlock and confinement, restrain lateral movement of the base course. This eliminates outward shear stresses and induces inward shear at the interface, raising the bearing capacity factor beyond that achievable with separation alone. This mechanism explains why geogrids consistently outperform geotextiles in very soft ground conditions.

Load Distribution and Stress Reduction

Reinforced bases exhibit increased stiffness due to a wider stress distribution angle through the granular layer. Loads imposed at the surface are spread over a larger area before reaching the subgrade, reducing vertical stress and subgrade strain. From performance perspective, a reduction in subgrade stress level produces the same outcome as increasing subgrade CBR: reduced rutting, lower settlement accumulation, and improved traffic capacity.

Preservation of Performance under Cyclic Loading

Without reinforcement, weak subgrades often experience progressive degradation due to pore pressure generation, loss of confinement, and aggregate intrusion into soft subgrade. This process results in an effective reduction of CBR over time. Geosynthetics reinforced pavements maintain their effective strength under traffic by:

- Limiting subgrade deformation
- Maintaining base integrity
- Preserving stress distribution characteristics under repeated loading

Implications for Static and Cyclic Performance on Peat

Static Conditions

Previous RS2 analyses conducted by the authors[1] (2018) demonstrated that floating embankments reinforced with geosynthetics can satisfy serviceability criteria (e.g., 50 mm settlement) over peat deposits where unreinforced options fail. These findings align with established bearing-capacity-based design methods.

Detailed numerical modelling results were presented in authors[1] (2018) and form the basis of the design assumptions adopted in the present study.

Cyclic Loading Conditions

The present study extends this work by incorporating cyclic loading representative of highway and mine haul trucks. Under repeated loading, settlement accumulation and excess pore water pressure generation govern long-term performance. Theoretical and field evidence consistently show that:

- Reinforced systems accumulate settlement at a much slower rate.
- Dual reinforcement configurations further improve performance by distributing load and controlling shear at multiple depths.
- These improvements correspond to subgrade behavior normally associated with significantly higher CBR values.

Full-scale Case Studies

Full-scale construction projects in New York and Arizona provided[7,8] (2009) compelling validation of the effective CBR concept. In both cases, extremely weak, saturated silty subgrades—characteristic of very low CBR—were successfully bridged using geogrid-reinforced mechanically stabilized layers. Key observations identified as:

- Immediate creation of a stable working platform
- Elimination of pumping and rutting under construction traffic
- Significant reductions in excavation depth and aggregate volume
- Performance equivalent to sections constructed with massive over-excavation and replacement

Cost Comparison of Geosynthetic Alternatives for Canadian Peatland Roads

This paper includes the study of the pavement structure to be placed over a peat layer with thickness varying from 1 m to 6 m. Other assumptions made in this study include:

- Design life of 20 years

Since all pavement alternatives were designed to satisfy the same service life requirement, the analysis focuses on comparative construction costs rather than a formal benefit-cost assessment.

- No traffic growth
- Two-way traffic direction
- Lane distribution factor: 1.0 (single haul road, critical lane governs)
- 365 days/year operation (typical for mine access / haul roads)

Two traffic cases are defined as:

Pavement thicknesses were determined using CBR-based design procedures consistent with the Giroud-Han methodology for weak subgrades. The reinforced alternatives reflect the improved performance of the pavement system rather than an increase in measured peat strength.

Case 1: Highway truck: Gross Vehicle Weight (GVW): ~ 40 ton Assumed Traffic Level= 500 trucks/day; 20-yr ESAL (Equivalent Single Axle Load) =3.7 million

Case 2: Mine Haul Truck: Gross Vehicle Weight (GVW): ~ 75 ton; Assumed Traffic Level= 100 trucks/day; 20-yr ESAL =22 million

Design was performed for the following pavement structure scenarios:
For cost estimation purposes, for two of the options, geosynthetics were assumed beneath the roadway footprint and costs were estimated using benchmark unit rates from comparable northern Ontario transportation and mining infrastructure projects. The rates include material supply and installation costs. The objective of the analysis is to compare alternative design approaches rather than evaluate specific geosynthetic products.

- Peat removal: where the entire peat is excavated to build the road on a competent subgrade with CBR=6
- Granular on peat: where the granular is directly placed on peat layer with CBR=1
- Geotextile on peat: assumed the placement of a geotextile layer over the peat results in enhanced CBR=2
- Combined geotextile and geogrid on peat: assume the placement of combined geosynthetic layer results in enhanced CBR=3.5

From practical experience, the sacrificial granular layer sinks or migrates into the voids of the peat layer is typically 150 mm to 500 mm (6 to 20 inches) thick, depending on the gradation of the granular, the peat type and construction methodology. In this study, for the "granular on peat" scenario, a sacrificial granular thickness of 250 mm is assumed when granular is directly placed on the peat layer (with no geotextile layer used for separation).

The cost estimates developed for this study rely on benchmark unit rates obtained from comparable Hatch projects in northern Ontario. These rates are limited to direct material supply and construction costs and exclude indirect cost items. The cost and design assumptions adopted in the analysis are summarized in Table 1 and Table 2.

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Table 1 Cost Assumptions Used in the Analysis

Item	**Unit Rate (CAD)**	**Unit**
Granular B Supply and Delivery	$45	per m^3
Compaction	$8	per m^3
Peat Excavation	$13	per m^3
Geotextile (GTX) Supply & Install	$6	per m^2
Geotextile + Geogrid (GTX+GRD) Supply & Install	$15	per m^2

Table 2 Additional Design Assumptions

Items	**Assumption**
Granular Bulk Density	1.9-2.1 t/m³
Compacted Lift Thickness	300 mm
Additional Sacrificial Granular Thickness	250 mm
Highway Truck Traffic Loading	3.7 million ESAL
Mine Haul Truck Traffic Loading	22 million ESAL

Figures 1 and 2 provide the unit cost (CAD) calculated for construction of the pavement structures for 2 traffic cases under defined scenarios. The results indicate that the use of geosynthetics placed directly over peat is an effective and economical alternative to conventional peat excavation down to competent subgrade, particularly where peat thickness exceeds approximately 2 m. Results also indicate that the excavation of peat layers in excess of 4 m may not be economically feasible, in which case, building the road over peat layer could be more cost effective even when geosynthetics are not considered in the design and construction.

Figure 1. Unit construction cost of pavement structure for Case 1 (highway truck)

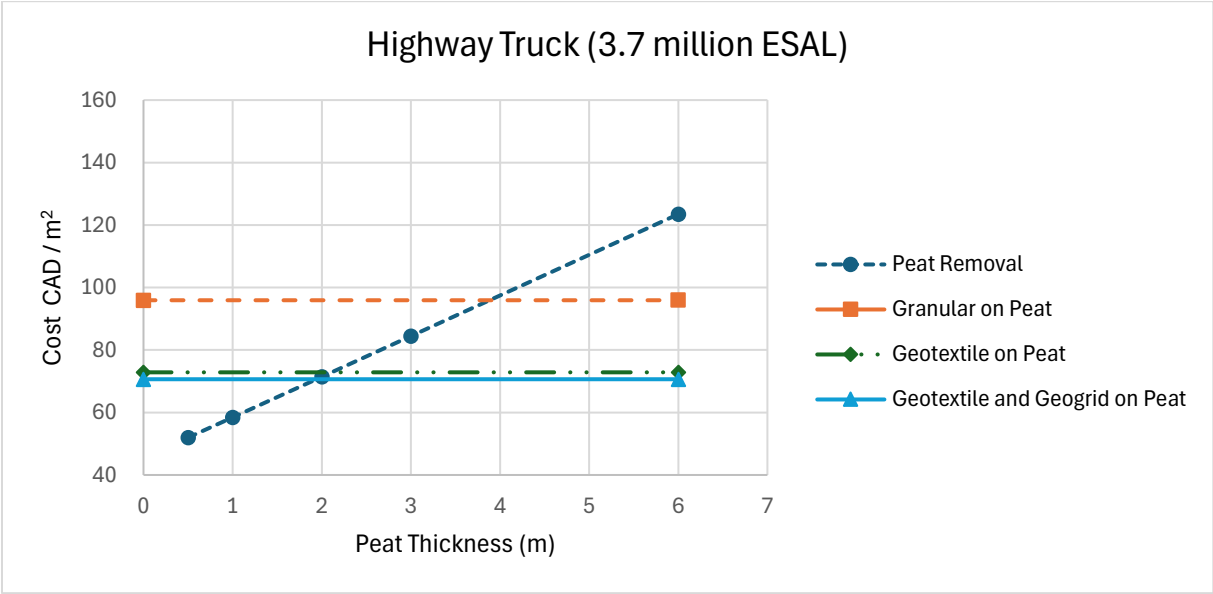
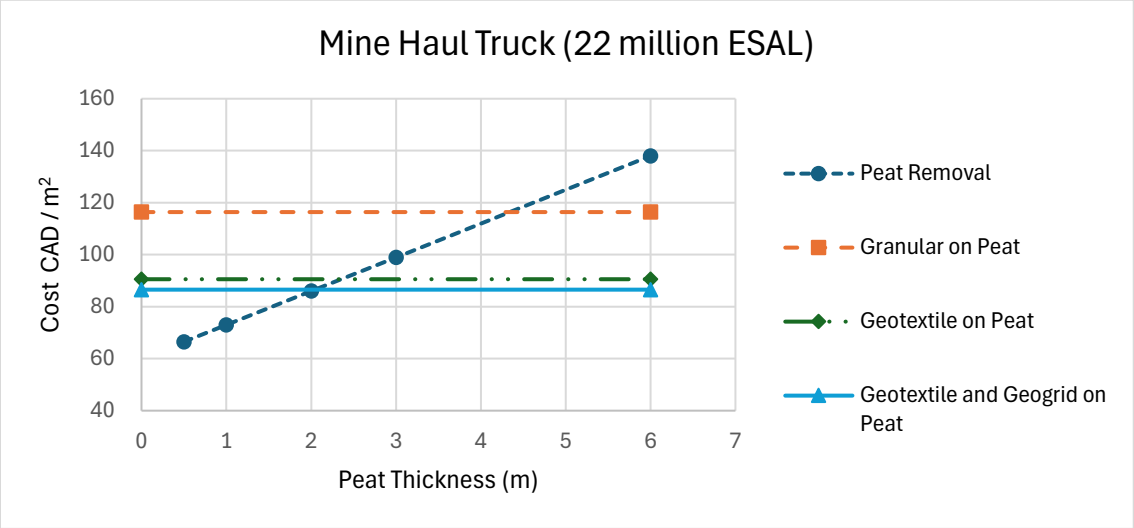


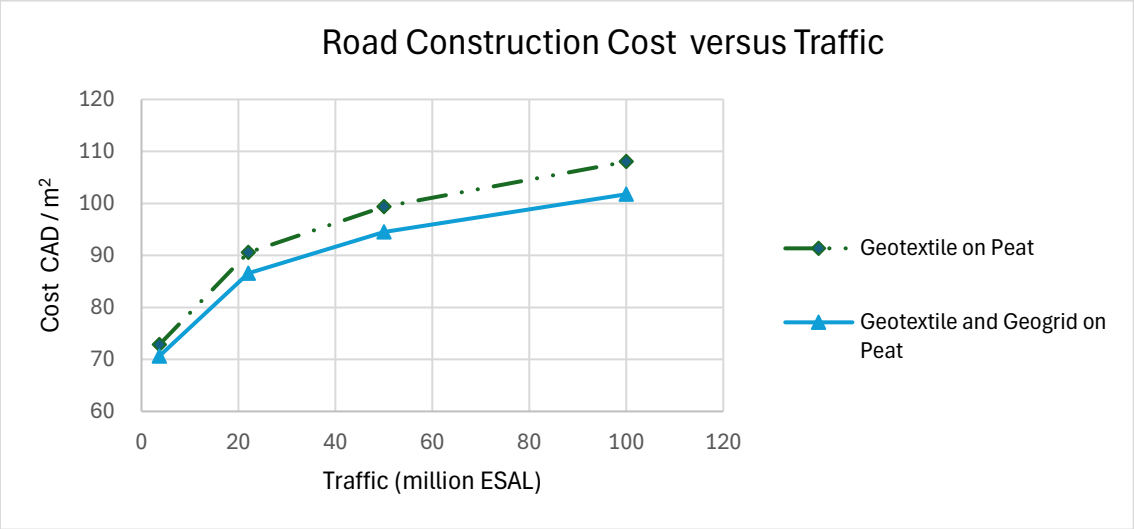
Figure 2. Unit construction cost of pavement structure for Case 2 (mine haul truck)



While the use of the "geotextile" on peat layers consistently results in lower construction cost compared to peat removal option, the use of "combined geotextile and geogrid" provides a marginal additional cost benefit over using geotextile alone. Beside some potential cost saving, implementing a geogrid layer provide lateral confinement and better load distribution which results in enhanced overall performance of the road structure, particularly over variable soft subgrade conditions typical of peatlands. Although the combined geotextile-geogrid alternative includes an additional cost of geogrid layer, the reinforcement effect allows a reduction in granular thickness. The resulting savings in aggregate supply, transportation, and placement offset the cost of the geogrid, producing a lower overall construction cost.

Figure 3, illustrating road construction cost versus traffic loading, confirms that cost increases with ESAL demand for both geosynthetic configurations. However, with increasing traffic level, the cost associated with the "combined geotextile and geogrid" scenario remains consistently lower than that of the "geotextile" only scenario. This trend highlights the value of combined reinforcement and separation functions in high-traffic or heavy haul applications, where long-term performance and rutting resistance govern design.

Figure 3. Construction cost of road on peatland designed for various traffic levels



The pavement design under various traffic conditions indicates that, for lower traffic levels, the cost difference between “geotextile” and “combined geotextile-geogrid” is relatively small, suggesting that GTX alone may be sufficient where performance demands are moderate. At higher traffic (ESAL) levels, the “combined geotextile-geogrid” option becomes increasingly advantageous, indicating improved structural efficiency under heavy and repetitive loading. This economically justifies the inclusion of geogrids primarily under higher traffic loads, despite common misconception that material costs may increase overall construction costs.

Conclusions

Geosynthetic reinforcement does not alter the intrinsic properties of weak subgrades such as peat; however, it fundamentally changes how these soils interact with imposed loads. By enabling mobilization of higher bearing capacity states, reorienting interface shear stresses, improving load distribution, and preserving performance under cyclic traffic, geosynthetics allow weak subgrades to perform as though they possess substantially higher CBR values.

When geosynthetics are incorporated into pavement structural design and cost analysis, these mechanisms contribute to more sustainable road infrastructure in peatland environments. The findings from the cost benefit study carried out on Canadian peatland support the strategic use of geosynthetics as a practical subgrade improvement measure for road construction over peat deposits, particularly in remote or high-cost excavation environments. Main conclusions are:

- “Geotextile” alone is suitable for lower to moderate traffic volumes, offering a cost-effective solution with simplified construction logistics.
- "Combined geotextile-geogrid” is recommended for high-traffic or heavy haul roads, where performance requirements justify the marginal increase in construction complexity.
- Both solutions significantly reduce sensitivity to peat thickness, improving constructability and cost efficiency compared to peat removal mainly for peat thickness more than 2 m.
- Removing thick peat layers exceeding thickness of approximately 4 m is typically not economically viable; in these cases, road construction over the peat layer is more cost-effective than peat removal, even in the absence of geosynthetics.
- From this study, geosynthetic reinforcement offers a positive environmental co-benefit by reducing granular fill requirements by 27 to 53% compared to unreinforced alternatives (depending on peat thickness and traffic demand) as floating road designs requires lower volume of aggregate extracted, hauled, and placed for road embankment construction. In ecologically sensitive peatland environments such as the James Bay Lowlands, this reduction in material volume directly translates to a smaller disturbance footprint, lower greenhouse gas emissions from haulage, and reduced risk of drainage-induced peat degradation along the road corridor.
- For design practitioners, the following guidance thresholds are supported by the analyses presented in this paper: (a) use geotextile separation alone where peat thickness is 1 to 2 m and design ESAL is below approximately 5 million; (b) adopt a combined geotextile-geogrid system where peat exceeds 2 m or design ESAL exceeds 5 million; (c) consider dual geosynthetic layers (upper and lower reinforcement planes) where peat thickness exceeds 4 m and haul truck GVW exceeds 75 ton, as the cyclic loading analyses indicate that single-layer reinforcement may be insufficient to prevent progressive settlement accumulation under these combined conditions.

Taken together, these findings support a shift in standard engineering practice for northern access road design: from a default assumption that peat must be removed or stabilized in place, toward a performance-based framework in which geosynthetic floating road systems are evaluated as the primary design candidate wherever peat thickness exceeds 2 m. Such a shift would improve cost outcomes, reduce environmental impacts, and enhance the long-term resilience of transportation infrastructure supporting resource development in Canada's north.

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