An Integrated Hydrogeological–Geotechnical Framework for Sustainable Road Design in Northern Peatlands - Northern Road Link

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Abstract

The proposed 165 km Northern Road Link (NRL) traverses the Hudson Bay Lowlands, where deep, highly compressible peat deposits, shallow groundwater tables, and strong climate-driven hydrological variability pose significant challenges to roadway design, construction, and long-term performance. Conventional road design approaches that rely on static or steady-state groundwater assumptions are insufficient to capture settlement, stability, and resilience under evolving hydroclimatic conditions. In this environment, embankment behaviour is intrinsically linked to groundwater dynamics.

To address these limitations, an integrated hydrogeological-geotechnical modelling framework was developed to support performance-based roadway design in peat-dominated terrain. The hydrogeological model simulates transient groundwater flow within stratified peat deposits and underlying stratigraphic units. Groundwater level fluctuations resulting from seasonal precipitation and time-varying hydraulic levels in existing rivers are incorporated into the model. Unlike conventional approaches, the framework explicitly resolves the temporal evolution of pore pressures within compressible peat layers, providing a physically based representation of climate- and drainage-driven groundwater behaviour. Transient groundwater heads from the hydrogeological model are used as inputs to hydro-mechanical analyses, whereby changes in pore pressure induce effective stress variations and associated consolidation or expansion of peat deposits. Finite element discretization is refined within deformable strata to resolve vertical deformation gradients, and baseline model behaviour and parameter uncertainty are constrained using satellite-based InSAR ground displacement time series, enabling calibration against observed natural subsidence patterns relevant to linear infrastructure performance.

Embankment deformation and stability are evaluated using the Limit Equilibrium Method (LEM) and Finite Element Method (FEM) analyses to assess construction-stage settlement, stability, and long-term performance under representative peatland conditions. The modelling results inform performance-based comparison of alternative construction and targeted mitigation measures, including geosynthetic reinforcement, staged construction, vertical drains, reinforced flotation embankments, and hydraulic equalization measures.

Preliminary design outcomes indicate that in lower-compressibility zones with thinner peat and lower groundwater tables, geosynthetic reinforcement and preloading can provide adequate strength gain with manageable settlements. In contrast, highly organic terrain characterized by moderate to thick peat, high groundwater tables, and strong seasonal variability may require vertical drains or other pore-pressure management measures. Maintaining natural hydrologic connectivity remains central to design, and reinforced flotation approaches incorporating permeable fills, geogrids, and equalization culverts are adopted where hydrogeological modelling indicates elevated hydraulic gradients.

Application to the NRL demonstrates how integrated hydrogeological-geotechnical modelling supports risk-informed design, construction sequencing, and climate-resilient infrastructure development in sensitive northern peatland environments.

1. Introduction and Project Context

1.1 Northern Road Link and Corridor-Scale Peatland Challenges

This paper builds on the conceptual design framework presented in Road Infrastructure in the Hudson Bay Lowlands: Solutions for the Northern Road Link (Tan & Manoochehri, 2024). While the earlier work addressed corridor-scale constraints and high-level construction and environmental considerations, the present study advances the analysis by introducing an integrated hydrogeological–geotechnical modelling framework. This framework is used to quantitatively inform embankment design, targeted mitigation measures, and hydrologic mitigation along the Northern Road Link (NRL).

The NRL is a proposed 165 km all-season transportation corridor across the Hudson Bay Lowlands of northern Ontario. It would connect the Webequie Supply Road in the north—serving the Webequie First Nation community and the Ring of Fire mineral development area—to the Marten Falls First Nation Community Access Road in the south. Collectively, these links would provide a continuous connection between remote Treaty 9 communities and the provincial highway network, improving year-round access and supporting long-term socio-economic development in a region currently reliant on winter roads and air transport.

From an engineering perspective, the NRL is distinguished by its length, remoteness, and extensive organic terrain. Much of the alignment traverses peatlands characterized by low shear strength, high compressibility, shallow groundwater tables, and limited granular resources. Unlike southern Ontario, where peat deposits are generally localized and avoidable, peat in the Hudson Bay Lowlands constitutes a corridor-scale condition that governs constructability and long-term performance.

Due to the thickness and continuity of peat, large-scale removal or replacement is not feasible. Instead, the design approach focuses on roadway systems that perform reliably while minimizing disturbance to peatland environments. This requires solutions that address settlement and stability while preserving hydrologic connectivity and limiting ecological impacts. Groundwater processes are therefore recognized as a primary source of geotechnical risk, necessitating analytical methods that explicitly capture interactions between groundwater flow, effective stress, and embankment loading over time.

1.2 Engineering and Environmental Sensitivity of the Hudson Bay Lowlands

The Hudson Bay Lowlands comprise one of the world's largest peatland complexes, with peat thickness along the NRL typically ranging from 1 to 4 m and locally exceeding 5 m. These deposits are frequently underlain by fine-grained lacustrine soils that further limit bearing capacity and drainage. Peat mechanical behavior is strongly integrated to groundwater conditions; variations in pore water pressure significantly influence settlement, deformation, and stability. Environmental sensitivity further constrains design, as disruptions to shallow groundwater flow can alter peatland function, with risks potentially amplified by future climate variability. Reliable performance assessment therefore requires transient, integrated hydro-mechanical analysis rather than steady-state or simplified assumptions.

1.3 Limitations of Conventional Design and the Need for Integrated Analysis

Traditional road design over soft soils often relies on geotechnical analyses that represent groundwater effects using fixed pore pressure profiles or unintegrated seepage models. While suitable for short embankments over isolated deposits, these approaches are poorly suited to long, linear infrastructure crossing regionally connected peatland systems such as the Hudson Bay Lowlands.

Geotechnical projects in low-lying peatland environments are characterized by significant uncertainty due to complex subsurface conditions and strong coupling between groundwater dynamics and soil deformation. Groundwater-related processes are consistently identified as a primary source of

geotechnical risk because of their influence on settlement, stability, and long-term performance (NASEM, 2018).

In peatland settings, groundwater flow is predominantly shallow and laterally extensive and is sensitive to climatic forcing and subtle topographic gradients. Embankment loading alters effective stress within the peat, influencing permeability, consolidation rates, and long-term settlement behavior. These interactions form an inherently integrated hydro-mechanical system in which hydraulic and mechanical processes evolve together. Analyses that decouple these processes risk underestimating settlement, overlooking adverse hydraulic gradients, or mischaracterizing the effectiveness of mitigation measures such as vertical drains, permeable embankments, and equalization culverts.

Conventional analyses also frequently assume steady-state groundwater conditions, limiting their ability to capture transient responses and climate-driven hydrologic variability. For the NRL, such simplifications may underestimate impacts on constructability, performance, and long-term resilience. An integrated hydrogeological–geotechnical modelling approach is therefore required to resolve transient groundwater flow and deformation within a consistent framework, enabling direct evaluation of embankment geometry, construction staging, and drainage features on pore pressure response, effective stress, and stability over time.

This paper presents an integrated hydrogeological–geotechnical modelling framework applied to representative sections of the NRL corridor. By comparing fully integrated, staggered, and conventional approaches, the study demonstrates how integrated analyses reduce groundwater-driven uncertainty and support more robust decision-making for targeted mitigation measures, embankment configuration, and hydrologic mitigation in peat-dominated northern environments.

2. Physical Setting and Baseline Characterization

2.1 Regional Geomorphology and Peatland Systems Along the NRL

The Hudson Bay Lowlands exhibit extremely low relief, with surface gradients typically below 0.1 percent, and are dominated by extensive peatlands overlying post glacial marine sediments. The landscape includes relict shorelines, shallow drainage features, and patterned wetlands formed under persistent poor drainage, cold climate, and slow organic decomposition following marine regression.
Along the NRL alignment, peatland conditions transition among ombrotrophic bogs, minerotrophic fens, and mixed patterned systems, including string fens. These peat types differ markedly in hydraulic connectivity and material behavior. Bogs generally show limited lateral groundwater interaction, while fens and string fens exhibit shallow, laterally continuous flow highly sensitive to minor topographic and drainage changes. These characteristics directly influence pore pressure response, consolidation behavior, and groundwater redistribution around embankments. Figure 1 depicts typical peatland geomorphology along the NRL corridor.

2.2 Climate, Recharge, and Groundwater Regime

The regional climate is sub-arctic to boreal, with long winters, short summers, and moderate precipitation, much of it as snowfall. Groundwater recharge is controlled primarily by spring snowmelt and late-summer rainfall. Due to low hydraulic gradients and high peat storage capacity, groundwater responses are delayed and prolonged.

Groundwater tables remain near ground surface across much of the NRL corridor with limited seasonal drawdown. Slow hydraulic response within peat and underlying lacustrine clays and silts necessitates transient groundwater modelling to capture delayed pore pressure dissipation and time-dependent consolidation under embankment loading.

2.3 Peat Stratigraphy and Subsurface Conditions

Peat thickness along the alignment typically ranges from 1 to 4 m, locally exceeding 5 m in basin bogs and patterned fens. Near-surface peat is predominantly fibrous, transitioning with depth to more decomposed material with reduced strength, lower permeability, and higher compressibility. Underlying fine-grained lacustrine clays and silts further restrict drainage, resulting in low bearing capacity and extended consolidation periods.

2.4 Data Sources and Terrain Characterization

Baseline characterization integrates LiDAR, aerial imagery, airborne geophysics, boreholes, cone penetration testing, and laboratory data. Peat thickness, terrain type, and groundwater conditions were interpreted at the corridor scale to define representative modelling sections and support the integrated hydrogeological–geotechnical analyses presented herein (Table 1).

3. Engineering Challenges of Road Construction in Northern Peatlands

3.1 Mechanical Behaviour of Peat

Peat is characterized by very high compressibility, low undrained shear strength, and strong time dependent behaviour driven by consolidation and creep. Undrained shear strengths typically range from 5 to 20 kPa, severely limiting embankment height without mitigation. Even small load increases can generate large strains, requiring careful control of embankment geometry, staging, and loading rate.

3.2 Groundwater Control of Settlement and Stability

Effective stress development in peat is governed by groundwater conditions. Embankment loading generates excess pore pressures that must dissipate to mobilize strength. Drainage pathways, groundwater gradients, and peat permeability therefore control consolidation rates, settlement magnitude, and stability during construction and long-term operation.

4. Integrated Hydrogeological–Hydro Mechanical Modelling Framework

4.1 Conceptual Hydro Mechanical Behaviour

Peat deformation is regulated by groundwater-controlled changes in pore pressure and effective stress. Groundwater drawdown increases effective stress and induces settlement, while recovery reduces effective stress and may cause partial rebound. Seasonal groundwater fluctuations therefore directly control compressibility and vertical displacement, making embankment performance dependent on cumulative groundwater driven deformation.

4.2 Critical Hydrogeological Scenarios Affecting Embankment Performance

Several hydrogeological scenarios have the potential to influence embankment performance within the peatland corridor. (a) Seasonal groundwater fluctuation causes groundwater levels to rise and decline throughout the year, altering pore pressures, effective stress, and peat deformation. (b) Embankment barrier effects may occur when the roadway partially obstructs lateral groundwater flow, generating upstream mounding, downstream drawdown, and hydraulic gradients beneath the embankment. (c) Groundwater mounding beneath the roadway can develop as embankment loading compresses peat and restricts drainage, resulting in localized groundwater accumulation and elevated pore pressures.

Additional hydrogeological stresses may arise from (d) one-sided flooding and differential head conditions, where flooding, snowmelt, or beaver impoundment produces hydraulic head differences across the roadway, increasing seepage forces and pore pressures. To mitigate these effects, (e) equalization culverts can be incorporated to maintain hydrologic connectivity, reduce head differentials, and limit embankment-induced groundwater disturbance. Long-term changes associated with (f) climate-driven groundwater rise may further elevate groundwater levels through increased precipitation and saturation, reducing effective stress and increasing settlement potential.

Collectively, these scenarios represent the primary groundwater-related mechanisms that may affect embankment behaviour and provide the basis for evaluating mitigation measures and infrastructure performance under both current and future hydrogeological conditions.

4.3 Integrated Hydrogeological–Geotechnical Modelling Philosophy

The assessment adopts an integrated hydrogeological and geotechnical modelling framework that recognizes groundwater conditions as a primary driver of pore pressure evolution, effective stress development, and deformation behavior. Regional and site-scale groundwater flow processes, including recharge, seepage, dewatering influences, and seasonal variability, are first quantified using a transient groundwater flow model. The resulting pore pressure distributions are then used to evaluate geotechnical performance through deformation and stability analyses.

Where project conditions indicate significant interaction between groundwater flow and material deformation, hydro-mechanical coupling may be applied to evaluate stress-flow feedback mechanisms. For most design evaluations, however, the modelling approach emphasizes the use of a physically representative groundwater model to establish realistic hydraulic boundary conditions that support subsequent geotechnical analyses.

This framework leverages the strengths of both hydrogeological and geotechnical numerical models, ensuring that regional groundwater dynamics and local deformation behaviour are evaluated using the most appropriate analytical tools.

4.4 Application of Integrated and Sequential Analyses

The selection of integrated or sequential modelling approaches depends on the project objectives, the complexity of groundwater-deformation interactions, and the required level of design confidence.

Sequential (staggered) analyses are generally used where groundwater flow governs pore pressure conditions but deformation is not expected to significantly alter hydraulic properties or flow patterns. In these cases, transient groundwater simulations provide time-varying pore pressure distributions that are transferred to geotechnical models for settlement, deformation, or stability assessments.

Fully integrated hydro-mechanical analyses may be employed where deformation can materially influence groundwater flow conditions, such as through stress-dependent permeability changes, consolidation processes, or significant changes in material structure. These analyses provide a more rigorous representation of hydro-mechanical feedback mechanisms but are typically reserved for scenarios where such interactions are expected to influence design outcomes.

The combined use of sequential and integrated analyses provides both computational efficiency and technical rigor, allowing screening-level evaluations to be supported by more advanced hydro-mechanical assessments where warranted.

4.5 InSAR-Based Calibration and Model Validation

Satellite-based Interferometric Synthetic Aperture Radar (InSAR) data provided an independent, spatially continuous record of ground surface deformation across the project area. The temporal displacement

patterns derived from InSAR were used as a key line of evidence to evaluate the conceptual understanding of groundwater-controlled settlement mechanisms and to support calibration of the integrated hydrogeological-geotechnical modelling framework.

The transient groundwater model was first developed to simulate seasonal and long-term variations in groundwater levels, pore pressures, and moisture conditions within peatland deposits. These hydraulic responses were subsequently incorporated into geotechnical deformation analyses to predict settlement magnitude and temporal behaviour. Model predictions were compared against observed InSAR-derived deformation trends to assess whether the simulated groundwater dynamics and associated hydro-mechanical responses were consistent with measured field performance.

The comparison between predicted and observed deformation patterns supported refinement of hydraulic parameters, groundwater boundary conditions, and material properties where warranted. Particular emphasis was placed on reproducing both the spatial distribution of settlement and the temporal evolution of ground movements observed across monitored peatland sections.

By integrating InSAR observations with groundwater flow and deformation modelling, the assessment established a robust and defensible framework for evaluating future performance. The agreement between observed and simulated behaviour increased confidence in model predictions used for design development, construction staging, and risk management.

5. Hydrogeological Modelling Methodology

5.1 FEFLOW Model Development, Domain Definition, and Mesh Discretization

A three-dimensional (3D) hydrogeological modelling framework was developed in FEFLOW to simulate groundwater flow processes within the peatland corridor and evaluate hydrogeological conditions influencing embankment performance. The regional model incorporates peat deposits, underlying mineral soils, and bedrock units, representing spatial variability in hydrostratigraphy, recharge, groundwater-surface water interactions, and hydraulic connectivity.

The primary objective of the regional groundwater model is to identify hydrogeologically sensitive areas where groundwater responses may influence embankment performance. Model results are used to evaluate regional flow patterns, hydraulic gradients, groundwater mounding, pore-pressure distributions, and the potential influence of roadway construction on surrounding groundwater systems.

Rather than applying computationally intensive hydro-mechanical simulations across the entire corridor, the regional model is used to identify critical sections exhibiting elevated settlement risk, significant groundwater level changes, or complex hydrogeological conditions. These sections are extracted and discretized at higher spatial resolution for detailed hydro-mechanical analysis.

The localized models utilize integrated hydro-mechanical capabilities of FEFLOW to simulate groundwater flow, pore-pressure dissipation, effective stress evolution, and deformation within peat and underlying compressible soils. Embankment loading is represented explicitly, allowing assessment of excess pore-pressure generation, consolidation behaviour, settlement magnitude, and settlement rates under transient groundwater conditions.

This hierarchical modelling approach combines regional hydrogeological simulation with detailed geotechnical analysis, enabling groundwater flow processes and hydrogeological variability to be incorporated directly into settlement assessments. The framework identifies locations where groundwater conditions may influence embankment performance and applies detailed integrated hydro-mechanical analysis of selected critical sections, providing a more realistic basis for infrastructure design

within complex peatland environments than conventional one-dimensional consolidation analyses or traditional stand-alone geotechnical analyses.

The transient groundwater model successfully reproduces observed seasonal hydraulic head variations at monitoring location (Figure 2a), providing confidence in the simulated hydraulic head and pore-pressure distributions used in subsequent integrated hydro-mechanical analyses. The calibrated model generates time-varying hydraulic conditions that support evaluation of effective stress evolution, deformation, and embankment performance under seasonal conditions.

5.2 Representation of Peat Heterogeneity and Unsaturated Flow

Peat was represented as a single, laterally homogeneous hydrostratigraphic unit in a one-dimensional vertical column. Spatial heterogeneity was not explicitly modeled; instead, uniform bulk properties were used, with peat thickness treated as a calibration parameter against InSAR derived settlement.

Groundwater flow was simulated under saturated conditions using a time varying constant head boundary at the ground surface. Unsaturated flow processes were not explicitly represented, and pore pressure and effective stress responses were driven by prescribed groundwater level fluctuations.

Computed pore pressures were used as inputs to the piHMC hydro mechanical framework to evaluate deformation, with peat heterogeneity and unsaturated behavior implicitly captured through bulk hydraulic and mechanical parameters.

5.3 Climate-Responsive Boundary Conditions

Climate driven groundwater variability was represented using a transient constant head boundary at the ground surface, derived from observed seasonal groundwater levels. This approach implicitly captures recharge variability and enables assessment of groundwater-controlled peat deformation under transient conditions.

5.4 Representation of Roads and Drainage

Roads, culverts, and drainage features were not explicitly modelled. Their combined hydraulic effects were incorporated implicitly through the transient surface groundwater boundary, assuming observed groundwater levels reflect integrated infrastructure and drainage influences.

6. Hydro-Mechanical Deformation Modelling

6.1 Fully Integrated Flow–Deformation Modelling

Settlement predicted by the integrated piHMC–FEFLOW model is consistent with InSAR-observed deformation over the 2017–2019 period, supporting the validity of the calibrated hydraulic boundary conditions (Figure 2b).

6.2 Time Synchronization and Numerical Stability

Hydro-mechanical simulations were time-synchronized using consistent transient groundwater boundary conditions, ensuring coherent evolution of pore pressure and deformation. Groundwater flow was solved transiently, with resulting pore-pressure changes iteratively updating effective stress and deformation until convergence. Gradual seasonal groundwater variations promoted numerical stability and reliable convergence throughout the simulations.

6.3 Sensitivity Analysis: Influence of Peat Thickness

A sensitivity analysis evaluated the effect of peat thickness on simulated settlement using the piHMC model. Peat thickness was varied while all other inputs and boundary conditions remained constant. Results show a monotonic increase in settlement with thickness, ranging from approximately 2.1 cm at

1.0 m to 6.8 cm at 6.0 m of peat. Simulated settlements for peat thicknesses of 4.5–6.0 m (approximately 5.2–6.8 cm) closely match InSAR-derived deformation (~5.6 cm). These results confirm peat thickness as a primary control on settlement magnitude and embankment deformation in peat-dominated terrain.

6.4 Hydrogeological Model Results

Representative critical location showing embankment-induced hydraulic barrier effects, hydraulic head contours, and water-table response (Figure 3).

7. Geotechnical Assessment and Construction Performance

The hydrogeological and hydro-mechanical modelling results provide the foundation for detailed geotechnical assessment of embankment performance. In this section, these results are translated into engineering analyses to evaluate construction-stage stability, settlement behaviour, and the effectiveness of targeted mitigation measures under representative peatland conditions.

7.1 Modelling Approach and Assumptions:

7.1.1 Integrated Hydrogeological–Geotechnical Assessment

Deformation and stability analyses were conducted using SEEP/W, SIGMA/W, and SLOPE/W analyses within GeoStudio 2023, applying both the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM).

Based on desktop studies and hydrogeological investigations in peatland terrain (AtkinsRéalis, 2025), groundwater levels were observed to vary from near the ground surface to approximately 2 m below grade. For preliminary analysis, the groundwater table was represented by water pressure head boundary condition located at the peatland surface in both LEM and FEM analyses.

Geotechnical investigations indicate peat thicknesses ranging from less than 1 m to greater than 5 m. Analyses were therefore performed for representative peat thicknesses of 0.4 m, 1.4 m, 2.6 m, 4.0 m, and 5.0 m to evaluate feasible staged-construction scenarios.

Embankment construction on saturated peat induces excess pore water pressures and undrained behavior, limiting effective stress and shear strength during loading. To ensure stability, intermediate consolidation periods were incorporated between construction stages to allow dissipation of excess pore pressures and gradual strength gain. Embankment staged construction and consolidation behavior were evaluated through integrated geotechnical analyses .

Embankment stability was evaluated using the Limit Equilibrium Method (LEM) in SLOPE/W (GeoStudio 2023). The Morgenstern–Price method of slices was selected, as it accounts for both interslice normal and shear forces and satisfies force and moment equilibrium (Seequent, 2022). A two-dimensional stability model for the representative case of 4 m peat thickness is shown in Figure 4.

Transient and long-term groundwater flow through the embankment will be assessed in the next design stage once FEFLOW outputs become available. Horizontal drainage blankets and equalization culverts will be designed to mitigate upstream to downstream surface water flow based on the FEFLOW results.

Preliminary screening has been completed using LEM and simplified FEM analyses in GeoStudio 2023. Detailed stress–strain behavior and fully integrated flow–deformation analyses will be conducted using advanced FEM in PLAXIS 2D and 3D, employing Soft Soil and Soft Soil Creep constitutive models to simulate primary consolidation and secondary creep of peat.

7.1.2 Construction-Stage Settlement and Stability

Peat presents significant challenges for road embankments due to its high compressibility and low shear strength, which lead to excessive deformation and stability concerns during construction. Over the long

term, peat degradation can also contribute to pavement distress and increased maintenance requirements.

Under the current floating-road design concept, the embankment is constructed directly on peat, with geosynthetics used for separation and subgrade reinforcement, relying on the in-situ peat to support applied loads. Settlement analyses using FEM indicate that approximately three years are required to allow pore-pressure dissipation (Figure 5a), with predicted settlement beneath the embankment footprint reaching roughly 50% of the peat thickness for a 4.0 m peat layer (Figure 5b) in the absence of subdrains or targeted mitigation measures. These results indicate that targeted mitigation measures are necessary to accelerate consolidation and improve embankment stability.

Implementation of geogrid reinforcement within the embankment fill significantly improves slope stability, increasing the factor of safety (FoS) from approximately 0.9 to greater than 1.5. Additional targeted mitigation measures, including wick drains and stone columns, were also evaluated. Results from the different modelling scenarios are summarized in Table 2.

Wick drains alone were not effective for the modeled conditions, as fibrous peat—observed during geotechnical investigations—exhibits low drain effectiveness. The combination of geogrids and stone columns provides both adequate stability (FoS > 1.5) and substantially reduced construction time and is therefore recommended.

Based on the integrated deformation and stability analyses, the combined use of geogrids and stone columns significantly accelerates embankment construction and reduces anticipated settlement beneath the embankment footprint from approximately 50% of peat thickness to less than 10% (The model with stone columns is illustrated in Figure 6 and the settlement at the base of embankment is presented in Figure 7).

8. Design Implications and Targeted Mitigation Measures

8.1 Performance Based Zoning Along the NRL Corridor

The results of the integrated modelling and geotechnical analyses were synthesized to inform performance-based design decisions along the NRL corridor. Rather than applying uniform design solutions, the approach enables classification of the corridor into zones governed by distinct controlling mechanisms, allowing targeted mitigation strategies to be tailored to site specific hydrogeological and geotechnical conditions.

8.2 Low to Moderate Compressibility Zones: Reinforcement and Staged Construction

In areas with thinner peat deposits and relatively rapid consolidation, geosynthetic reinforcement combined with staged embankment construction is sufficient to meet performance requirements. Along lower risk NRL segments with reduced groundwater sensitivity, basal reinforcement provides adequate construction stage stability while limiting total and differential settlement.

Reinforcement improves load distribution at the peat–embankment interface, reduces lateral spreading, and enhances short to medium term embankment performance with minimal disturbance to the peatland surface. These measures align well with NRL constructability constraints by minimizing excavation, avoiding large scale peat removal, and reducing reliance on imported granular materials. Accordingly, reinforced, staged construction is the preferred design approach in lower risk corridor segments identified through integrated modelling.

8.2.1 Reinforcement

Reinforcement techniques improve embankment stability by distributing loads and controlling deformation where embankments are constructed directly on peat. While several systems are available, including rigid rafts and reinforced pavement layers, geosynthetics are preferred for the NRL (Figure 8).

Geosynthetic materials—such as geogrids, geotextiles, and geofabrics—offer favourable constructability, compatibility with peatland environments, and proven performance on soft soils. They are easily installed with limited ground disturbance, eliminate the need for excavation and spoil management, and provide effective basal reinforcement during construction. These characteristics support a floating road design consistent with NRL sustainability and environmental objectives.

8.3 Highly Organic Zones: Vertical Drains, Stone Columns, and Hybrid Solutions

In areas with thicker peat deposits, persistently high groundwater tables, and strong lateral hydraulic connectivity, reinforcement and staged construction alone are insufficient to control settlement magnitude or construction duration. In these higher risk NRL segments, additional targeted mitigation measures such as vertical drainage or localized load transfer systems are required to enhance embankment performance.

Targeted mitigation measures is applied selectively based on results from integrated hydrogeological–geotechnical modelling. This performance driven approach ensures that interventions are proportional to site specific risk, minimize peat disturbance, and preserve hydrologic connectivity across the corridor.

8.3.1 Stone Columns

Stone columns offer a multifunctional targeted mitigation solution by providing both vertical drainage and structural reinforcement. As drainage elements, they shorten pore water flow paths, accelerating dissipation of excess pore pressures and reducing consolidation time. As structural inclusions, they increase bearing capacity, improve stability, and limit settlement and lateral deformation (Figure 9).

Along the NRL, stone columns are most effective where thick peat overlies weak mineral soils and groundwater conditions strongly control consolidation behavior. When applied selectively and combined with basal reinforcement, stone columns can significantly reduce predicted settlement and construction duration while maintaining acceptable stability and limiting impacts on surrounding peatland hydrology.

9. Hydrologic Connectivity and Sustainable Embankment Design

9.1 Hydrologic Compatibility in Peatland Environments

Peatlands along the Northern Road Link (NRL) corridor function as integrated hydrologic systems characterized by shallow groundwater tables, laterally connected flow paths, and strong coupling between water levels and peat mechanical behavior. Disrupting this connectivity through linear embankments can cause persistent head differentials, leading to ponding, drying, altered consolidation behavior, progressive settlement, and long-term ecological degradation.

Because groundwater levels directly control effective stress and settlement rates in peat, small sustained hydraulic gradients across embankments can induce long-term deformation well beyond construction. Accordingly, the NRL design philosophy emphasizes hydrologic compatibility rather than isolation. Embankments are designed to function within intact peatland systems, preserving groundwater flow while meeting deformation and stability requirements. This approach is supported by the integrated hydrogeological–geotechnical modelling framework, which quantifies groundwater–embankment interactions under transient climatic conditions.

9.2 Roadway Embankments and Flood Interaction in Peatland Environments

In Ontario practice, roadway embankments are fundamentally different from flood control structures and are not intended to contain or control floodwaters. They typically consist of permeable fill materials and lack impervious cores, seepage cut offs, freeboard allowances, and structural redundancy, making their performance under flooding sensitive to seepage, uplift, and foundation instability—particularly where founded on soft or organic soils.

These considerations are especially important along the Northern Road Link, which traverses peatland terrain characterized by shallow, laterally connected groundwater systems where even small hydraulic head differentials can generate sustained seepage forces. Accordingly, NRL embankments are designed as hydraulically interactive systems, with groundwater and floodwaters assumed to pass over, through, or beneath the roadway during extreme events. Design measures therefore emphasize resilience and hydrologic compatibility, including permeable embankment fills, basal geosynthetic reinforcement to control deformation, and equalization culverts installed where indicated by integrated modelling.

The integrated hydrogeological–geotechnical modelling framework provides a quantitative basis for managing these interactions in a manner consistent with sustainable peatland infrastructure objectives. Rather than attempting to suppress natural hydrologic processes through inappropriate flood control assumptions, the framework enables informed evaluation of groundwater driven deformation, stability, and long-term embankment performance under transient climatic and hydraulic conditions.

9.3 Equalization Culverts and Hydraulic Gradient Control

Equalization culverts are incorporated where integrated hydrogeological–geotechnical modelling predicts elevated hydraulic gradients adjacent to the roadway. In peat dominated terrain, embankments can disturb shallow groundwater flow, creating persistent head differences across the footprint that may adversely affect embankment performance and peatland hydrology if unmanaged.

Equalization culverts mitigate these effects by allowing lateral groundwater and surface water flow beneath the roadway, reducing head differentials and seepage gradients. Unlike conventional drainage features, culvert locations and sizing are determined based on subsurface flow patterns derived from transient groundwater modelling. Their role is not flood control, but preservation of hydrologic connectivity and moderation of embankment induced hydraulic disturbance.

Within the integrated framework, culvert needs are identified from simulated pore pressures, flow vectors, and gradient magnitudes under seasonal and climate driven conditions. Design parameters such as spacing, invert elevation, and diameter are selected to balance hydraulic performance, constructability, and long-term stability while avoiding over drainage of peat.

By reducing seepage forces, equalization culverts also enhance geotechnical performance by lowering the risk of internal erosion, uplift, and localized instability, particularly in areas underlain by thick organic deposits. This illustrates the close linkage between hydraulic mitigation and embankment stability in peatland environments.

10. Integrated Decision-Making Framework

10.1 Balancing Geotechnical Performance, Hydrology, and Environmental Stewardship

Sustainable road development in peat-dominated environments requires balancing geotechnical performance, hydrologic function, and environmental stewardship. Along the Northern Road Link (NRL), these objectives are closely linked, as measures used to improve stability or reduce settlement can alter groundwater flow, while groundwater conditions directly influence peat strength, consolidation, and long-term embankment performance.

A key principle of the framework is that roadway embankments are not intended to function as flood-control structures and must therefore be designed to interact safely with groundwater and surface-water systems under transient hydraulic conditions. The integrated hydrogeological–geotechnical approach provides a quantitative basis for evaluating groundwater connectivity, settlement, consolidation, and stability while minimizing peat disturbance and preserving hydrologic connectivity. The overall decision-making process used to integrate hydrogeological assessment, hydro-mechanical analysis, geotechnical evaluation, and mitigation measure selection is summarized in Appendix A.

10.2 Constructability and Risk Based Selection of Construction Methods

Constructability and risk management are integral to the decision-making framework, reflecting constraints such as corridor remoteness, limited granular resources, short construction seasons, and peatland sensitivity.

The integrated hydrogeological-geotechnical framework supports risk-based selection of construction methods by identifying whether embankment behaviour is primarily strength-controlled, time-controlled, load-controlled, or hydrology-controlled. Lower-risk sections with thin peat deposits and limited groundwater sensitivity may be addressed using geosynthetic reinforcement and staged construction. Higher-risk sections characterized by thick peat, prolonged consolidation periods, high groundwater tables, or elevated hydraulic gradients may require vertical drains, stone columns, reinforced flotation embankments, groundwater management measures, or hydraulic equalization features. By matching mitigation measures to the governing control mechanism and predicted level of risk, the framework supports proportional intervention, minimizes environmental disturbance, and promotes acceptable constructability, stability, settlement performance, hydrologic compatibility, and long-term resilience.

10.3 Alignment with Previous TAC Work

This framework builds on the conceptual and sustainability focused approach presented in Road Infrastructure in the Hudson Bay Lowlands: Solutions for the Northern Road Link (TAC, 2024). Whereas the earlier work emphasized corridor scale challenges and candidate solutions, the present study provides a quantitative analytical foundation by explicitly coupling groundwater flow, effective stress, and embankment deformation.

Together, the TAC (2024) paper and the integrated hydrogeological–geotechnical framework presented herein establish a coherent progression from conceptual corridor planning to performance-based design for sustainable road infrastructure in northern peatland environments.

11. Application to Representative Critical Sections

Representative sections along the Northern Road Link (NRL) corridor were selected to demonstrate how the integrated hydrogeological–geotechnical framework informs construction method selection, staging, and hydrologic mitigation while minimizing ground disturbance and environmental impacts.

11.1 Selection of Representative NRL Sections

Section selection was based on corridor scale terrain mapping, borehole data, interpreted peat thickness, and observed groundwater conditions along the alignment between the Webequie Supply Road and the Marten Falls Community Access Road.

The selected sections represent recurring corridor conditions, including:

(i) thin peat over lacustrine clays in elevated terrain;

(ii) moderate peat thickness in fen and string fen environments with laterally connected shallow groundwater; and

(iii) thick, highly organic peatlands with persistently high water tables and limited natural drainage.

These conditions correspond to locations where embankment performance is most sensitive to groundwater driven deformation and where decisions related to reinforcement, construction staging, and hydrologic mitigation have the greatest influence. In this study, the integrated hydro mechanical model is applied to one representative critical section to demonstrate the framework, with application to additional sections intended in subsequent design phases.

11.2 Model Results and Design Outcomes

Groundwater modelling results were integrated with integrated geotechnical analyses to evaluate settlement, lateral deformation, and embankment stability during construction and operation. Using data from ongoing geotechnical investigations, the analyses supported preliminary embankment design and assessment of targeted mitigation effectiveness for representative sections.

FEFLOW results indicate that groundwater–surface water interaction, expressed through seasonal groundwater level fluctuations in shallow peatlands, is a primary control on pore pressure evolution, effective stress, and vertical deformation. Transient groundwater head variations govern subsurface storage and lead to time dependent settlement responses within peat and underlying soils.

These processes are explicitly captured in the integrated FEFLOW–piHMC framework through vertically discretized soil profiles and time varying hydraulic boundaries. Simulations show that transient pore pressure propagation directly controls settlement magnitude and consolidation timing, confirming that embankment performance is strongly influenced by groundwater connectivity and seasonal variability.

In NRL segments with thinner peat and lower groundwater sensitivity, staged construction with basal geosynthetic reinforcement satisfies settlement and stability criteria. In contrast, sections underlain by thicker peat and laterally connected groundwater systems exhibit excessive deformation, longer consolidation periods, and reduced stability, justifying the use of reinforced flotation embankments, selective stone columns, and hydraulic equalization measures.

Across all sections, elevated modelled head differentials and seepage gradients informed placement of equalization culverts and permeable embankment zones, ensuring hydraulic continuity and improved long-term performance.

12. Conclusions and Recommendations

This paper applies an integrated hydrogeological–geotechnical modelling framework to the Northern Road Link (NRL), a 165 km all season corridor traversing peat dominated terrain in the Hudson Bay Lowlands. Results indicate that embankment performance along the NRL is governed primarily by groundwater-controlled peat behaviour, with seasonal pore pressure fluctuations exerting a dominant influence on effective stress development, consolidation rates, and long-term settlement.

Analyses show that steady state groundwater assumptions commonly used in conventional design underestimate both settlement magnitude and consolidation duration, particularly in segments underlain by thick peat and laterally connected fen and string fen systems. Transient groundwater modelling is therefore required for realistic assessment of embankment response during construction and operation. Coupling transient groundwater flow with hydro mechanical deformation modelling enables direct evaluation of the interaction between embankment loading, construction staging, and peatland hydrology. Qualitative calibration and validation using InSAR derived surface deformation provide independent support for predicted settlement behaviour and reduce uncertainty associated with peat thickness, compressibility, and seasonal groundwater variability observed along the corridor.

Preliminary modelling indicates that embankment performance varies substantially along the NRL in response to spatial differences in peat thickness, groundwater connectivity, and hydraulic gradients. Current evaluations suggest that lower risk segments with thinner peat and reduced hydrologic sensitivity are likely to be accommodated using basal geosynthetic reinforcement and staged construction, whereas sections underlain by thicker, highly organic peat with strong groundwater connectivity may require reinforced flotation embankments, selective stone columns, and hydraulic equalization measures. Ongoing application of a performance-based zoning approach is being used to translate integrated modelling results into corridor scale design decisions by classifying NRL segments according to dominant controlling mechanisms, including strength, time, and hydrology-controlled behaviour.

Table 1. Terrain Classification, Peat Stratigraphy, and Relative Constructability Ranking along the NRL corridor.

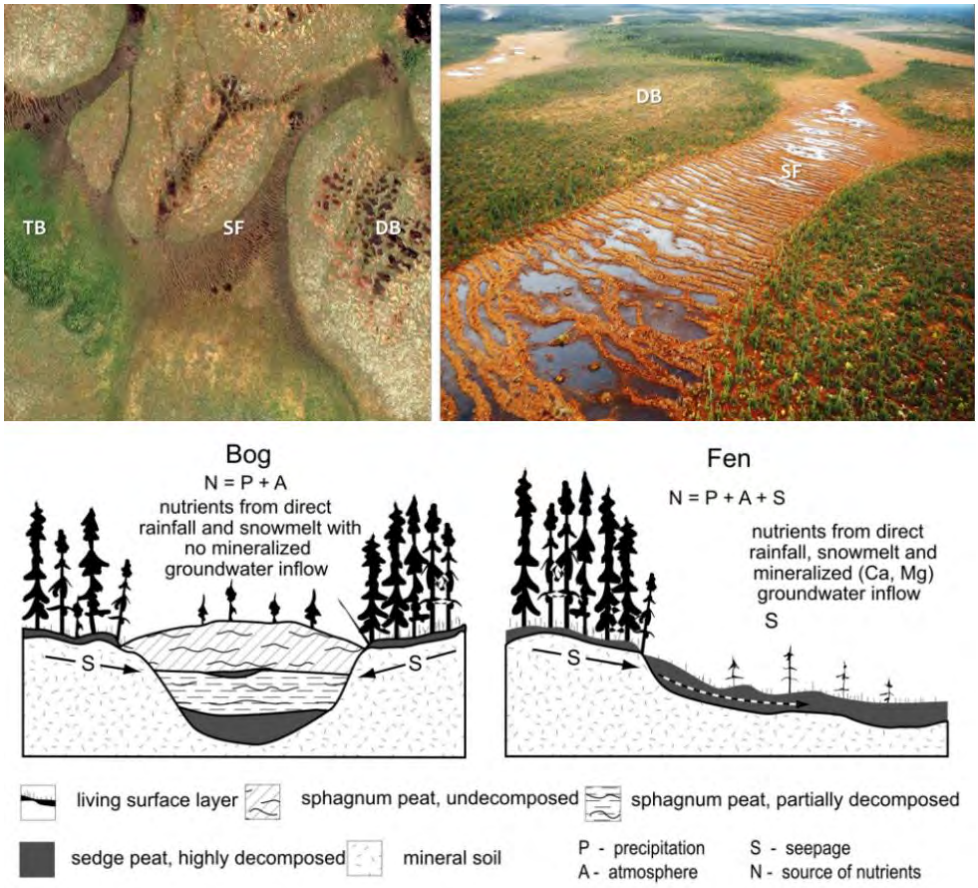
Terrain Type	Peat Depth (m)	Expected Peat Type	Expected Groundwater Depth	Terrain Ranking Constructability[1]
GF	0-0.5	N/A	Variable	1
TB	0.5-2.0	Fibrous - coarse	0.5-1.0	2
PB	2.0-4.0	Fibrous – coarse to fine	0.5-1.0	3
HF	0.5-5.0	Fibrous – fine to amorphous	0-0.5	4
SF	3.0-5.0	Fibrous – fine to amorphous	0.-0.5	4

1) 1 - most favourable; 4 – least favourable

Table 2. Model Results with Different Targeted Mitigation Measures

Analysis Trial	Targeted Mitigation Measures Applied in the Model			Duration of Construction of Each Lift (0.3m) (Days)	Slope Stability FoS	Remark
	Geogrid	Wick Drain	Stone Column			
1	No	No	No	300	0.8	Long construction duration, stability does not meet requirement
2	Yes	No	No	90	>1.5	Long construction duration
3	No	Yes	No	300	0.8	Long construction duration, stability does not meet requirement
4	Yes	No	Yes	10	>1.5	Recommended

Figure 1. Typical peatland geomorphology along the NRL corridor.



Source: NWWG (1988)

Figure 2. Calibration of the integrated hydrogeological-geotechnical model. (a) Observed and simulated groundwater level time series at monitoring location, illustrating model reproduction of seasonal hydraulic head variability. (b) Comparison of observed (InSAR-derived) and simulated settlement from May 2017 to November 2019 following calibration to seasonal groundwater level fluctuations.

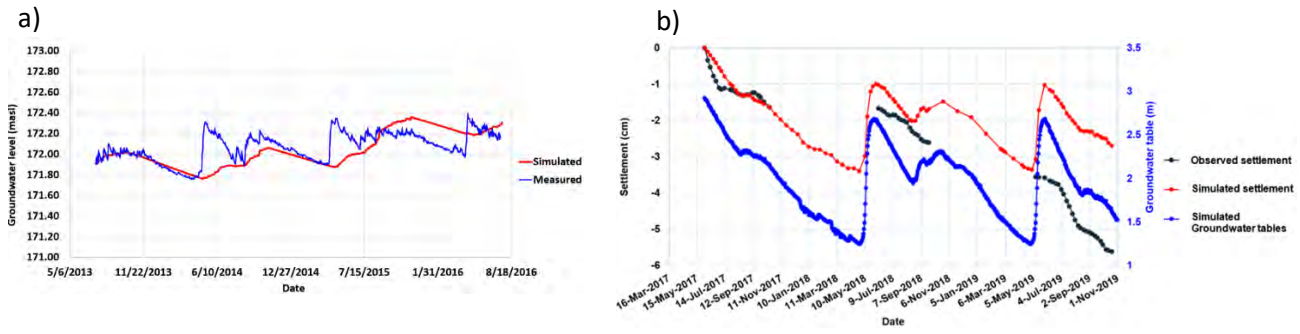


Figure 3. Representative critical location showing embankment-induced hydraulic barrier effects, hydraulic head contours, and water-table response.

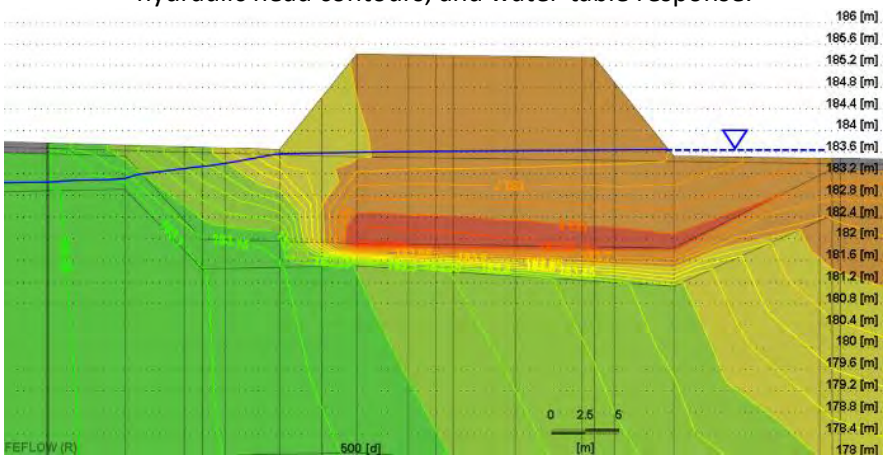


Figure 4. Embankment Cross-Section without stone column (4m Peat Thickness)

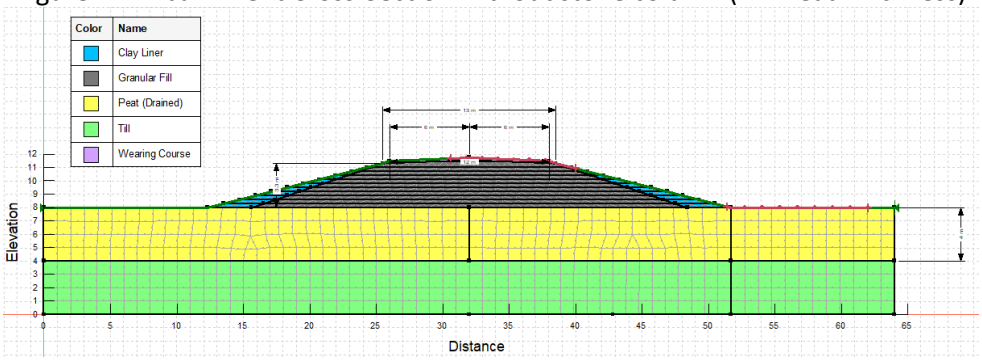
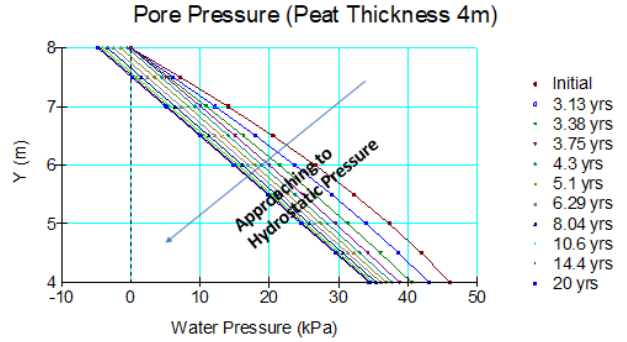


Figure 5. Staged Construction and Settlement Analysis Results without stone column (4m Peat Thickness) (a)Pore Pressure Dissipation with Time (b) Settlement at the Base of Embankment without Stone Columns

(a)



(b)

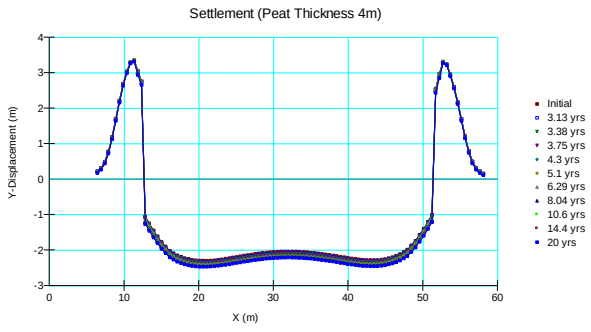


Figure 6. Embankment Cross-Section with Stone Columns (4m Peat Thickness)

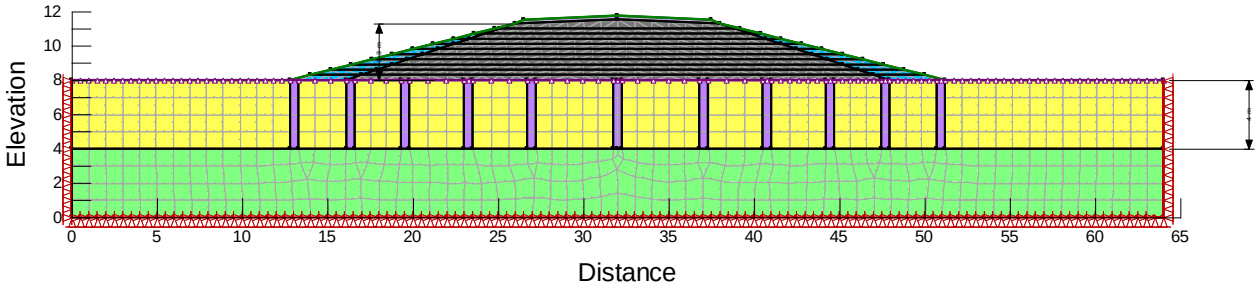


Figure 7. Settlement at the Base of Embankment with Stone Columns (4m Peat Thickness)

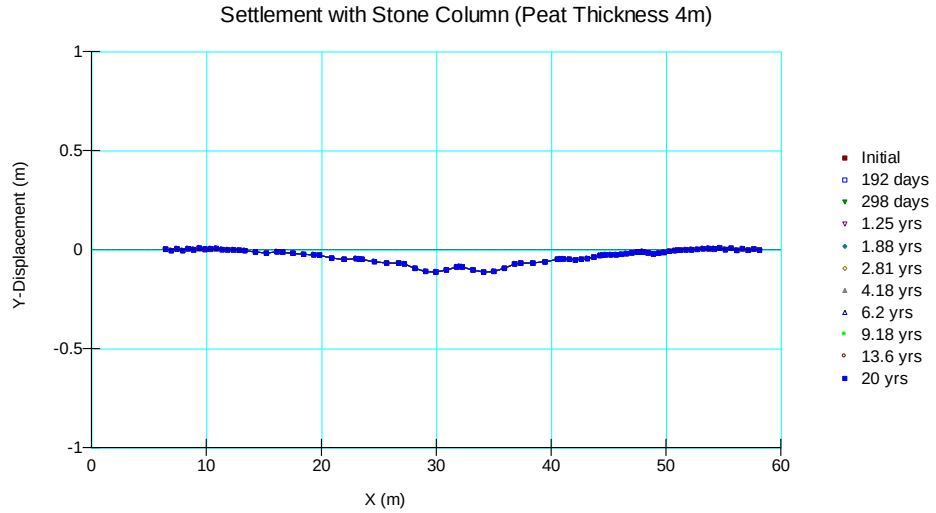


Figure 4. Recommended Design Option 1

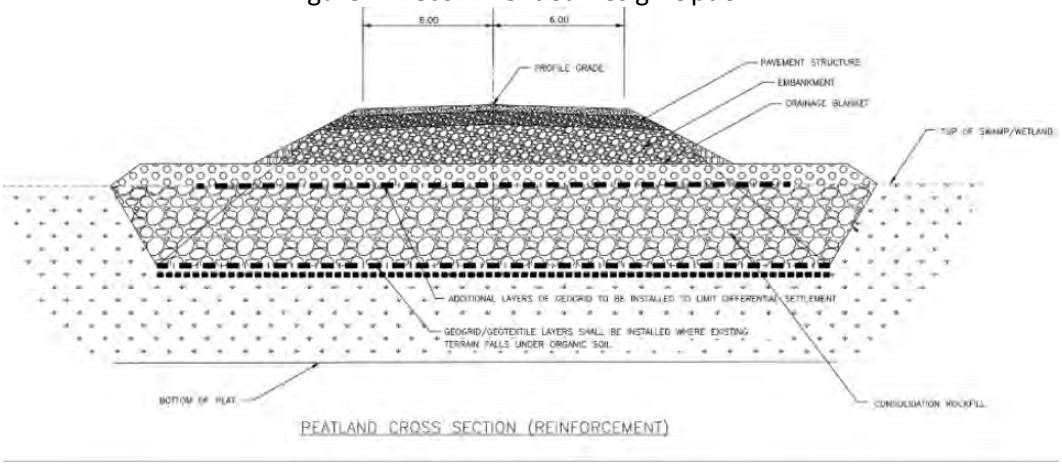
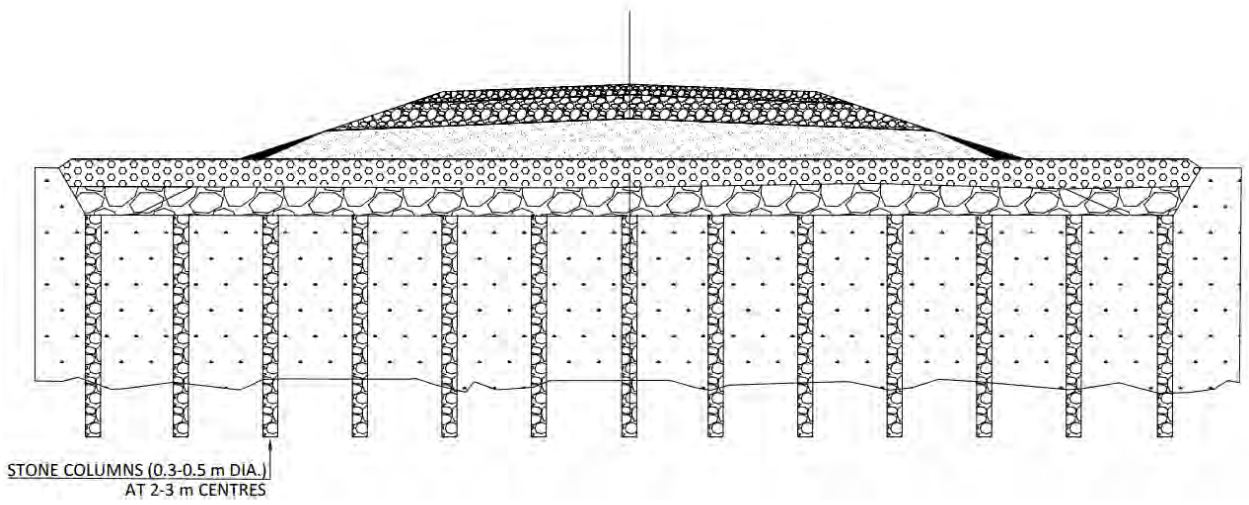


Figure 5. Recommended Design Option 2



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Appendix A
Hydrogeological-Geotechnical Decision-Making Workflow for Construction Method Selection Along the Northern Road Link

