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Presentation Paper:

Infrastructure Improvements within Challenging Soils

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Soils and Materials Conference Session

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1. Introduction:

In many areas of Western Canada, infrastructure construction occurs in areas of undesirable native materials. Concerns such as yielding or friable soils, differential consolidation, subsurface wetland charging, intense freeze thaw cycles, and variable subsurface water levels create substantial challenges for construction. Undeniable changes in the climate are also creating concerns that affect the performance of transportation assets which should be addressed as part of a full life cycle analysis. As an example, in northern Alberta regular freeze thaw cycles are a normal and anticipated condition. These concerns are typically accounted for in design, material selection and construction practices. However, in recent years there have been instances where the full design life is not being achieved which may partially be attributed to previously unpredicted changes to the climate.

This paper & presentation will discuss advancements in the areas of design, material management, product selection and construction practices which are intended to effectively meet these needs. Topics will include parameters such as analysis of phreatic surfaces, circular failures and finite elements. Discussion will include construction material considerations including the use of different soil types for various applications and the use of engineered products such as structural geogrids and geotextiles which may be used to separate materials and increase overall material strengths. In addition, these concepts will be tied into the Climate Change theme by suggesting ways to mitigate these concerns. A case study will be reviewed; the grading and paving work completed on Range Road 183 in Yellowhead County which included construction over significant lengths of deep muskeg with several drainage and pipeline crossing concerns. This type of terrain, once avoided at all costs, often caused significant route selection concerns. However, with proper consideration and analysis of the soils and materials, use of advanced products and proven, effective construction methods, roads and other infrastructure assets may now be successfully built within areas that were previously not considered suitable.

2. Soil & Materials Causing Concern for Subgrade Construction

There is a wide range of native soils and materials found within Western Canada which create unique challenges in many regions and often require the application of sound engineering principles. When reviewing the Unified Soil Classification System (USCS) in Table 2.1, there are several material types that stand out as problematic, most of which are found lower on the table within the fine-grained soils and organic soil division. For the purposes of this paper, the coarse-grained soils will only be touched upon occasionally as they generally perform quite well as subgrade materials and are often utilized in surfacing treatments, whether on roads surfaced with gravel or as part of a pavement structure on roads with a higher classification.

In many regions, including large portions of Alberta, fine-grained soils are the native materials commonly found and used for subgrade embankment and construction. In general terms, they may be described as clays, silts and unsuitable materials such as organics, however they are often found in various combinations with vastly different performance characteristics which are usually tied to the liquid limit properties. Sometimes referred to as yielding or friable soils, these materials are especially susceptible to freeze thaw concerns, differential consolidation and moisture level issues.

Table 2.1: Unified Soil Classification System - Major Divisions, Symbols & Names

Major divisions			Group symbol	Group name
Coarse grained soils more than 50% retained on or above No.200 (0.075 mm) sieve	gravel > 50% of coarse fraction retained on No.4 (4.75 mm) sieve	clean gravel <5% smaller than No.200 Sieve	GW	well-graded gravel, fine to coarse gravel
			GP	poorly graded gravel
		gravel with >12% fines	GM	silty gravel
			GC	clayey gravel
	sand ≥ 50% of coarse fraction passes No.4 (4.75 mm) sieve	clean sand	SW	well-graded sand, fine to coarse sand
			SP	poorly graded sand
		sand with >12% fines	SM	silty sand
			SC	clayey sand
Fine grained soils 50% or more passing the No.200 (0.075 mm) sieve	silt and clay liquid limit < 50	inorganic	ML	silt
			CL	lean clay
		organic	OL	organic silt, organic clay
	silt and clay liquid limit ≥ 50	inorganic	MH	elastic silt
			CH	fat clay
		organic	OH	organic clay, organic silt
Highly organic soils			Pt	peat

Materials found in the organic soils division are typically various types of peat or topsoil and are a major concern when building civil improvements. Standard practice is to remove all topsoil when preparing the subbase for subgrade construction. However, it is not always practical to remove all of the peat in an area when preparing the subbase. The material is less predictable in performance and often introduces additional concerns such as heave/swell and subsidence due to variations in moisture levels and freeze thaw patterns. In worst case scenarios, peat is found in areas with high and fluctuating water levels, creating muskeg sections where peat and other organic matter essentially floats in variable depths of water. Previous practice has usually tended to avoid construction within muskeg zones. On occasions, where it was unavoidable and the muskeg was isolated and not overly deep, the practice was to remove the peat and replace it with more suitable materials, up to a maximum of 1.0m depth. However, this often caused a significant displacement of water over a short time period and sometimes resulted in environmental concerns.

Phreatic surfaces are a major concern when considering construction in muskeg zones. The peat layer is the primary base for all construction above and must be investigated to be effectively understood. Probes may be used to measure the depth of the peat and to collect samples for visual characterization. The depth of the peat layer and the underlying water may vary dramatically throughout a project section requiring careful analysis of the predicted displacement when loaded to ensure uniform embankment and to avoid shear failures. Concerns arise if the organic peat layer of a muskeg is damaged before, during or after construction as it significantly weakens the strength properties of the base. When this occurs, it is critical that efforts are made to repair the area with appropriate products to remediate it back to a continuous surface as much as possible.

Since friable and yielding soils are considered cohesive when compared to well drained materials like sand and gravel, trapped moisture within the material or variable groundwater levels may be a major concern. With good construction practices, ideal clay materials can be conditioned and compacted into a very dense embankment with controlled moisture levels that are sufficient to contain water such as Compacted Clay Liners (CCL) on lagoon facilities. In roadway and other typical infrastructure applications, good clay materials are often the best material available for subgrade construction, although they are often naturally found in mixtures including silt that degrade their performance characteristics.

3. Grade Performance Improvement Products

Ongoing research and development by numerous agencies has made ground-breaking advances over the years that have revolutionized the way civil infrastructure projects are designed and constructed. In simple terms, there are two main products that work to separate, filter, reinforce, drain and protect the materials they are incorporated into. Separating materials with different strength characteristics by using geotextile products is a key aspect of managing engineered fills. The insertion of structural geogrids at optimal embankment depth(s) may significantly increase the grade stability, often reducing the fill requirements to achieve a desired end product.

Geotextiles, geogrids and similar products are often used successfully within the upper layers of infrastructure asset construction of operational pads, laydown yards, camp facilities and linear projects including roadways, airstrips, railways and facilities along pipeline or utility corridors. The application of a geotextile layer or geo-grid product at key depth(s) within a gravel cap on these types of projects may reduce the required aggregate thickness, reducing cost and construction time while still delivering a quality product.

In the subgrade and subbase preparation phases of construction, these types of products can make the difference between a project being viable for construction or not. When used effectively, they help with:

- Separation: geotextiles can prevent the intermixing of soils with different properties
- Filtration: geotextiles can effectively filter water through while stabilizing soils
- Reinforcement: structural geogrids add strength properties to weak soil materials
- Drainage: well drained soils reduce moisture concerns like freeze thaw cycle issues
- Protection: cushioning properties for lining applications with sharp materials

Geotextiles:

Suitable native materials should always be considered as a first choice in civil construction however, when necessary, geotextile products are very useful for separating and filtering materials and allowing for effective drainage. They are available in woven and non-woven varieties and numerous grades, each with a wide range of properties. For typical subbase and subgrade applications, a standard arrangement is to place a woven geotextile product on top of the subbase and then begin backfilling and compaction operations in uniform lifts with suitable materials. This application primarily serves to separate the engineered fill above from the materials below which may be considered marginal and have less predictable performance characteristics.

Table 3.1: Sample Specifications for Standard Woven Geotextile Fabric

TESTED PROPERTY	TEST METHOD	UNIT ENGLISH (METRIC)	MARV VALUE ENGLISH (METRIC)
Grab Tensile	ASTM D 4632	lbs (N)	270 (1201)
Grab Elongation	ASTM D 4632	%	15
Trapezoidal Tear	ASTM D 4533	lbs (N)	100 (440)
CBR Puncture Resistance	ASTM D 6241	lbs (N)	850 (3783)
Permittivity*	ASTM D 4491	l/sec	0.05
Water Flow*	ASTM D 4491	gpm/ft^2 ($l/min/m^2$)	4 (163)
Apparent Opening Size (AOS)	ASTM D 4751	U.S. Sieve (mm)	40 (.425)
U.V. Resistance	ASTM D 4355	%/hrs	70/500

The example product shown in Table 3.1 illustrates key parameters which are used in determining product suitability. These are compared against specification requirements (ie: Alberta Transportation Standard Specifications for Highway Construction, Specification 5.31, Geotextile) and matched up with the specific application requirements for the situation. A High Strength Woven Geotextile Fabric option (Table 3.2) is well suited for conditions where additional strength such as puncture resistance may be desired

Table 3.2: Sample Specifications for High Strength Woven Geotextile Fabric

TESTED PROPERTY	TEST METHOD	UNIT ENGLISH (METRIC)	VALUE ENGLISH (METRIC)
Tensile Strength (Grab)	ASTM D 4632	lbs (N)	450 x 350 (2003 x 1558)
Elongation	ASTM D 4632	%	15 x 6
Wide Width Tensile	ASTM D 4595	lbs/ft (kN/m)	3600 x 3600 (52.5 x 52.5)
Wide Width Elongation	ASTM D 4595	%	15 x 10
Wide Width Tensile (5% strain)	ASTM D 4595	lbs/ft (kN/m)	1392 x 1740 (20.3 x 25.4)
CBR Puncture	ASTM D 6241	lbs (N)	1600 (7120)
Trapezoidal Tear	ASTM D 4533	lbs (N)	180 x 140 (801 x 623)
UV Resistance	ASTM D 4355	%/hrs	80/500
Apparent Opening Size (AOS)*	ASTM D 4751	US Std Sieve (mm)	30 (0.60)
Permittivity	ASTM D 4491	sec^{-1}	0.52
Water Flow Rate	ASTM D 4491	gpm/ft^2 (lpm/m^2)	40 (1630)

Geogrids:

Structural geogrids are commonly used to add strength in yielding soils by utilizing their high tensile properties. While they are available in biaxial and triaxial products, the use of biaxial geogrids is most prevalent in subgrade construction. Triaxial geogrids are well suited for applications within granular layers as the rock binds very effectively within the triangle shaped apertures although fine grained soils work effectively with biaxial grids for most applications within subbase.

Many classifications of biaxial geogrids are available and selection criteria depend on the loading requirements, depth of cover, soil material type above and below the geogrid and the relative strength of the materials. Field and laboratory tests such as the Standard Penetration Tests (SPT's) and Atterberg Limit Tests are common methods for determining subbase and subgrade properties. For standard highway construction, the subgrade should have a minimum load bearing capacity, otherwise the subbase may deflect under traffic loading and transfer the movement through the grade causing surface deformation and deterioration over time.

When the desired subbase strength is not achievable through typical methods such as moisture conditioning and compaction, the addition of a structural geogrid can often be effectively used to bump up the strength to a suitable level. Table 3.3 illustrates a sample specification for a biaxial geogrid which would be suitable for subbase and subgrade stabilization in many typical roadway projects. One important consideration is the aperture size which should be considered based on the soil material being used for embankment.

Table 3.3: Sample Specifications for Biaxial Geogrid

Product Properties

Index Properties	**Units**	**MD Values**	**XMD Values**
▪ Aperture Dimensions	mm (in)	25 (1.0)	30.5 (1.2)
▪ Minimum Rib Thickness	mm (in)	1.78 (0.07)	1.78 (0.07)
▪ Tensile Strength @ 2% Strain	kN/m (lb/ft)	8.5 (580)	10.0 (690)
▪ Tensile Strength @ 5% Strain	kN/m (lb/ft)	17.5 (1,200)	20.0 (1,370)
▪ Ultimate Tensile Strength	kN/m (lb/ft)	27.0 (1,850)	30.0 (2,050)
Structural Integrity			
▪ Junction Efficiency	%	93	
▪ Flexural Stiffness	mg-cm	2,000,000	
▪ Aperture Stability	m-N/deg	0.75	
Durability			
▪ Resistance to Installation Damage[7]	%SC / %SW / %GP	95 / 93 / 90	
▪ Resistance to Long Term Degradation[8]	%	100	
▪ Resistance to UV Degradation[9]	%	100	

Photo 3.1:

Placement of biaxial geogrid within lower level subbase/subgrade construction. Rolls of geogrid product are overlapped and spread out evenly across the grade and then uniform layers of suitable fill materials are placed and compacted above to create a stable surface for further grade construction.

Table 3.4 illustrates a sample specification for a triaxial geogrid which would typically be suitable for placement below or within a granular capping application such as for a laydown yard or parking lot. A layer of geogrid is often placed between aggregate classes, to bind and contain the materials and also to maintain separation between material classes (ie: a 50mm nominal size material below a 20mm crush aggregate). Based on cost benefit analysis, the triaxial geogrids are not seen as a significant improvement over biaxial products for subgrade or subbase applications.

Table 3.4: Sample Specifications for Triaxial Geogrid

Index Properties	Longitudinal	Diagonal	Transverse	General
▪ Rib pitch[2], mm (in)	40 (1.60)	40 (1.60)	-	
▪ Mid-rib depth[2], mm (in)	-	1.6 (0.06)	1.4 (0.06)	
▪ Mid-rib width[2], mm (in)	-	1.0 (0.04)	1.2 (0.05)	
▪ Rib shape				Rectangular
▪ Aperture shape				Triangular
Structural Integrity				
▪ Junction efficiency[3], %				93
▪ Radial stiffness at low strain[4], kN/m @ 0.5% strain (lb/ft @ 0.5% strain)				300 (20,580)
Durability				
▪ Resistance to chemical degradation[5]				100%
▪ Resistance to ultra-violet light and weathering[6]				70%

Photo 3.2:

Triaxial geogrid placement with granular fill material. Crushed aggregate material (fractured faces) bind well with the triangular apertures to ensure a consolidated spread of granular material. Following the manufacturers recommendations can significantly reduce the amount of gravel required to produce

Use of Geotextiles and Geogrids in Combinations, including Combi-Grids:

Site specific considerations may require different product application scenarios. Many circumstances simply require material separation with the placement of a geotextile layer to achieve the desired outcome. However, in many situations, it is deemed most suitable to separate soil materials with a layer of geotextile fabric and also to provide stabilization with a layer of structural geogrid. While it may seem most practical to place them at the same time and at the same level (geotextile on bottom, geogrid on top), the recommended method for maximum results is to place them with a zone of embankment material between.

In typical grade construction, unsuitable materials are removed to a pre-determined minimum depth or to the satisfaction and judgement of the construction engineer. Where possible, select natural materials such as sand may be used effectively to provide drainage and stability. However, if the desired conditions are not yet achieved and additional measures are needed, geotextile fabric is often placed at the lowest point of the sub-excavation area to provide separation between the marginal materials below and the suitable materials to be placed above. In ideal situations, it is preferred to place three or four lifts (min. 0.5m) of subgrade material and then place the structural geogrid followed by additional subgrade material. This works well to create a strong bridging surface when the subbase is marginal or slightly weak.

In more extreme situations such as wet muskeg zones, it may be difficult to place a layer of subgrade over geotextile fabric without some degree of support from a structural geogrid. In these cases, placement of the geotextile and geogrid usually occurs directly on the weak soils or peat and then subgrade backfill begins. When required, a second layer of geogrid may still be placed at a higher level to assist in the performance of load distribution. Another option is to place a combi-grid instead of two separate products. This type of single product provides similar separation and strength characteristics as the individual geotextile and geogrid products but i quicker and more cost efficient to install as it combines the two steps.

Table 3.5 and Photo 3.3: Combi-Grid Sample Specifications & Installation

Property	Test Method	Units	md	cmd
Polymer Type			PP	
Structure			welded straps	
pH range			2-13	
Tensile strength				
Ultimate	ASTM D 6637	kN/m **lbs/ft**	30 **2,055**	30 **2,055**
Elongation @ ultimate*	ASTM D 6637	**%**	**8**	**8**
Strength @1%	ASTM D 6637	kN/m **lbs/ft**	6.6 **453**	6.6 **453**
Strength @2%	ASTM D 6637	kN/m **lbs/ft**	10 **686**	10 **686**
Strength @5%	ASTM D 6637	kN/m **lbs/ft**	21.5 **1,475**	21.5 **1,475**
Modulus				
Tensile modulus @ 1%*		kN/m **lbs/ft**	660 **45,300**	660 **45,300**
Tensile modulus @ 2%*		kN/m **lbs/ft**	500 **34,300**	500 **34,300**
Geometry* Aperture size*	Micrometer	mm **Inches**	32 **1.26**	32 **1.26**
Structural integrity				
Flexural rigidity*	ASTM D 1388	**mg-cm**	**500,000**	**500,000**
Junction strength*	GRI-GG2	kN/m **lbs/ft**	9 **617**	9 **617**
Aperture stability*	Kinney (COE)	**kg-cm/deg**	**11.4**	
Durability				
UV Resistance*	EN ISO 12224	%	95%	

4. Design and Construction Considerations

The entire construction industry has been faced with difficult grade construction scenarios for many years and as industrial development and other economic drivers push the need for access to challenging locations, so too has the engineering world been working towards sustainable solutions. It has been proven that separating materials into engineered layers and restricting the migration of weaker materials into these engineered zones allows for more effective construction over top of what is often termed as 'unsuitable material'. This can include silty and organic materials that would usually be removed to a minimum depth before building back up with 'suitable material'. As a general rule, the long-standing practice of removing these unsuitable materials and replacing with better soils is still the preferred solution, however numerous factors may provide incentive to consider alternatives that advancements in performance improvement products can offer.

When considering construction over muskeg, the depth of the muskeg should be measured as accurately as possible to determine whether it is practical to remove the unsuitable material and build up to final grade or to bridge over the muskeg with techniques developed through experience and enhanced by the advancements in the geotextile and geogrid industry.

When constructing over peat and muskeg, gradual, controlled and monitored placement of fill material layers is much more effective than rapid and less controlled bulk filling operations. Pre-loading the muskeg in predictable environmental conditions is one method that can also lead to success. This involves taking advantage of a key seasonal factor by placing a pre-determined thickness of lower-level fill material in frozen conditions. The winter season often allows for a good window of opportunity to place a depth of material sufficient to bridge over weak areas with minimal danger of degrading the peat and muskeg surface below. However, it is critical to understand that if the fill placement operation does cause a failure to the peat/muskeg layer, remediation measures are required to address the damage before proceeding further.

The weight of the embankment fill will create downward pressure on the muskeg and ground water will naturally rise in the path of least resistance. A good indicator of subsurface water changes that may occur when placing fill materials is to install water level monitors along the sides of the road (outside the work zone) and record changes as the fill progresses. Relatively consistent water level changes are desired along the length of the fill and a good indication of normal changes towards a sustainable equilibrium. However, if large fluctuations in water levels occur along the fill length, it is an indication of less predictable future performance or even a pending failure.

Assuming there are no failures once the initial fill placement is completed and water levels have stabilized, continued grading operations can resume. It is not uncommon for the pre-loading to occur in the winter followed by the remainder of the grade construction in the following spring or summer.

Experience shows that many types of failures can occur when building over weak soils and one of the most common is a rotational shear condition as shown in Figure 4.1. When weak fine-grained soils or peat/muskeg are the only thing available as the subbase and construction commences without the benefit of soil separation or reinforcement, there is a significant risk of rotational failure causing rotational movement of material resulting in severe cases of differential settlement. A problematic aspect of this type of failure is that the damage may extend down and through the subbase on a rotational arc where the shear forces meet the resisting forces. When performing a proper repair on this type of failure, the entire fault zone must be addressed which can often become more burdensome and costly than it would have been to build properly the first time. Figure 4.1 shows a rotational failure example on one half of a roadway. In extreme cases, rotational failures may occur on both sides of a linear fill area (roadway, railway, etc), creating an additional torsional shear concern along the center of the embankment.

Figure 4.1: No Material Separation or Reinforcement

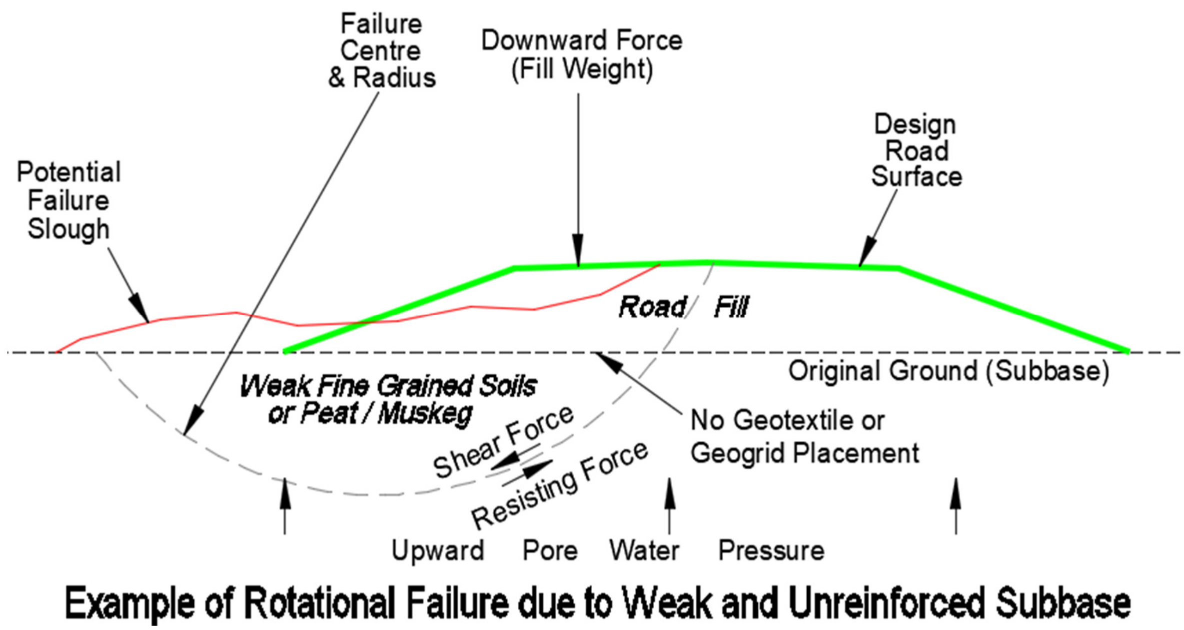


Figure 4.2 shows an alternative scenario where materials of different types are separated by the use of a geotextile layer and the subgrade fill material is reinforced with a structural geogrid layer. The downward forces caused by the weight of the road fill are now transferred more horizontally to distribute the weight over a larger area, resulting in decreases to the point load ground pressures and notably, no failure.

Figure 4.2: Material Separation and Reinforced Subgrade

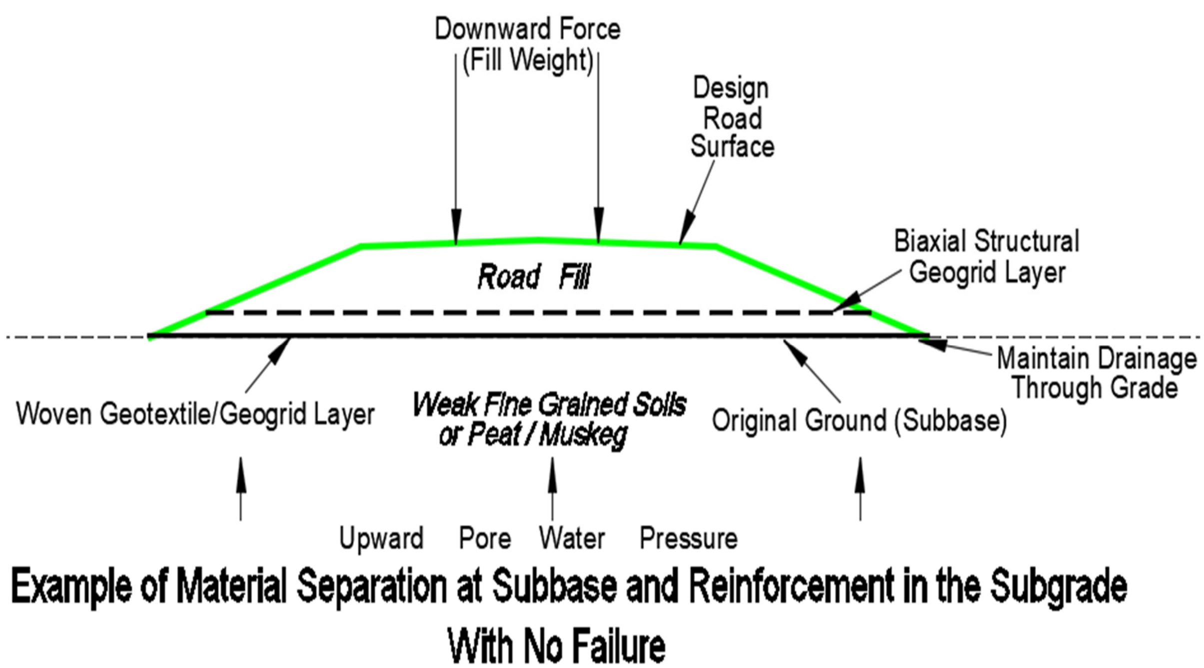
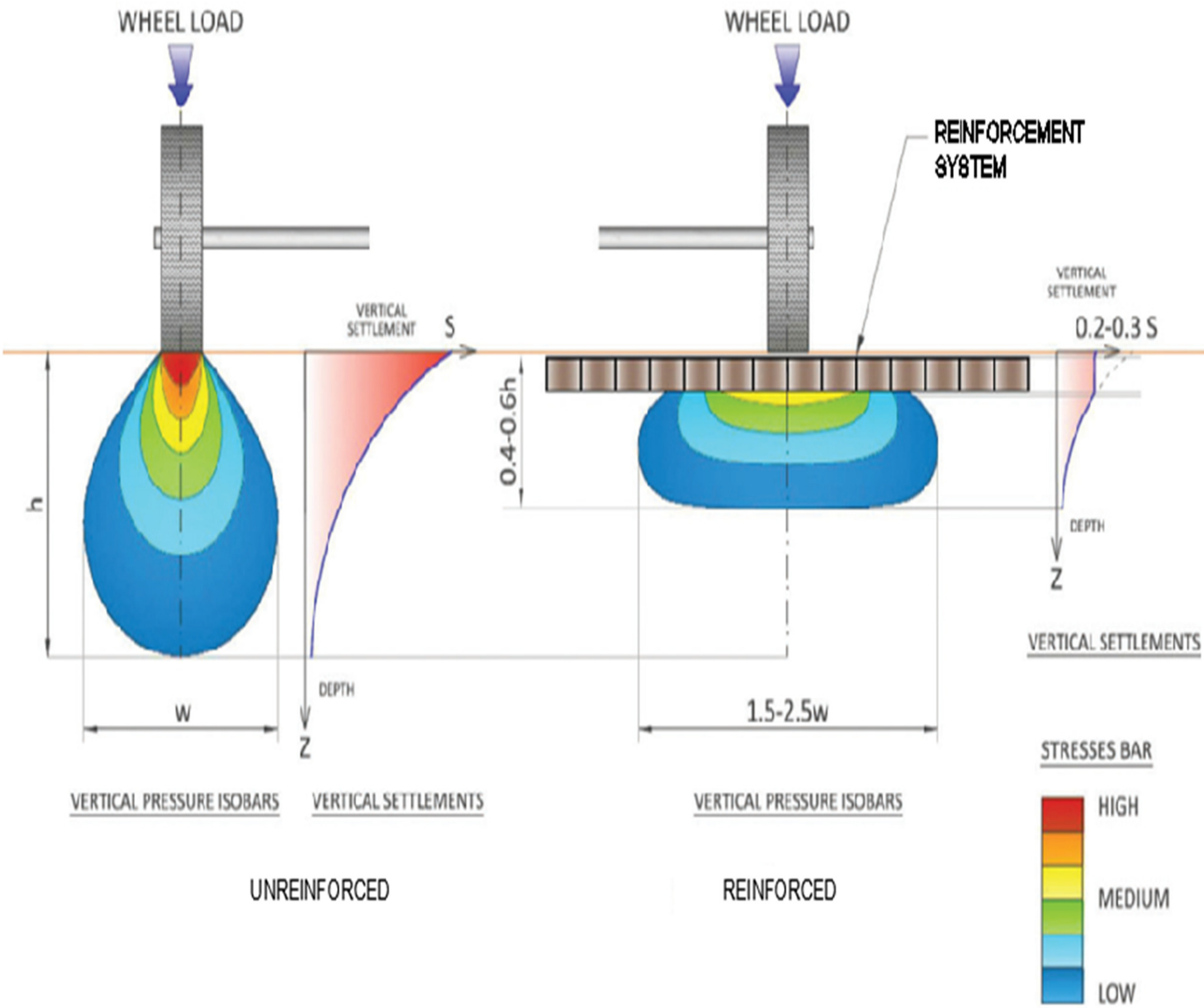


Photo 4.1: Muskeg area with geotextile and geogrid placement separated by fill material

On a road or driving pad surface, wheel load stresses are transferred through the surface structure (typically pavement, concrete or gravel) and subgrade materials and onto the subbase. The more this impact can be controlled, the better the road performance can be predicted. The optimal target is to keep the load stresses near the surface within the strongest part of the road structure and to minimize the vertical impacts throughout the subgrade and subbase. A critical factor is that engineered fill components should properly distribute the load to eliminate failures within the native materials in the subbase which can be very costly and time consuming to repair later. Figure 4.3 illustrates a geocell system near the surface and how it dramatically affects the way load stresses are transferred out and down from the point load. Similar stress bar configurations are apparent when structural geogrid is placed within subgrade construction. While the material separation layer (geotextile product) should typically be placed at the lowest level of the excavation, the geogrid is often placed at a higher level in order to assist with load distribution.

Figure 4.3: Load Stress Distribution With and Without Reinforcement

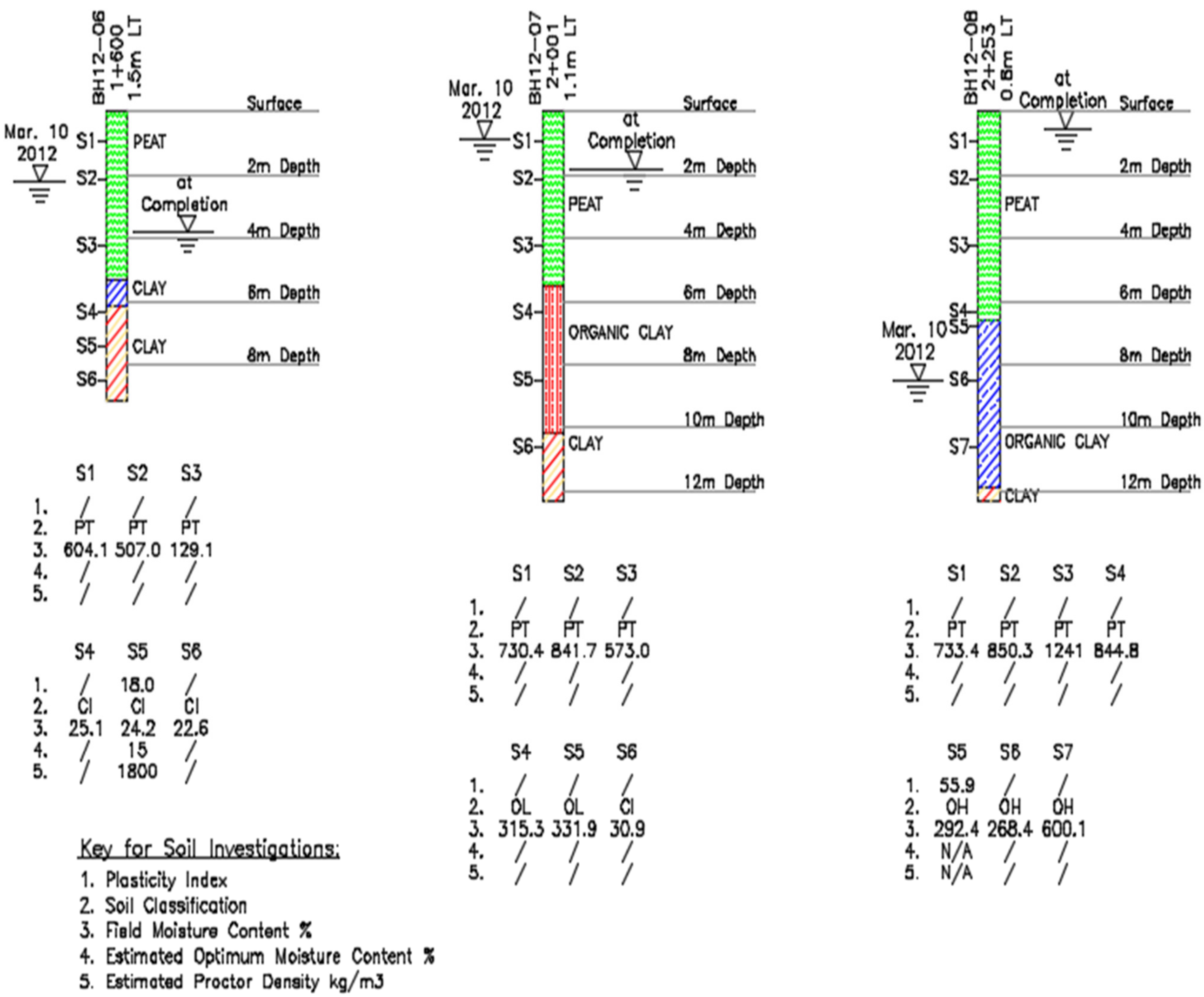


5. Case Study – Range Road 183 in Yellowhead County (Hwy 947)

A 6.4 km long section of Range Road 183 in Yellowhead County was constructed in an area with primarily fine-grained native soils but included a significant stretch of peat with challenging muskeg conditions. The project consisted of grading along the existing road and through virgin terrain, granular base course (GBC), asphalt concrete pavement (ACP) and other work. There were multiple pipeline crossings throughout the project with several in the muskeg region. In spite of these and other challenges, the Contractor was able to complete the work within an acceptable 17-month timeframe and about 3% over budget, due to issues discussed below.

The muskeg region required specific design considerations due to the very unstable conditions. The Soil Log information below demonstrates the degree of peat and moisture encountered in the pre-construction soils investigation.

Figure 5.1: Soil Logs for section of Range Road 183 within muskeg region



Due to the conditions noted above, specific design considerations were developed to spread out the weight of the road embankment and stabilize the base as much as possible.

Figure 5.2: showing typical section in standard muskeg region

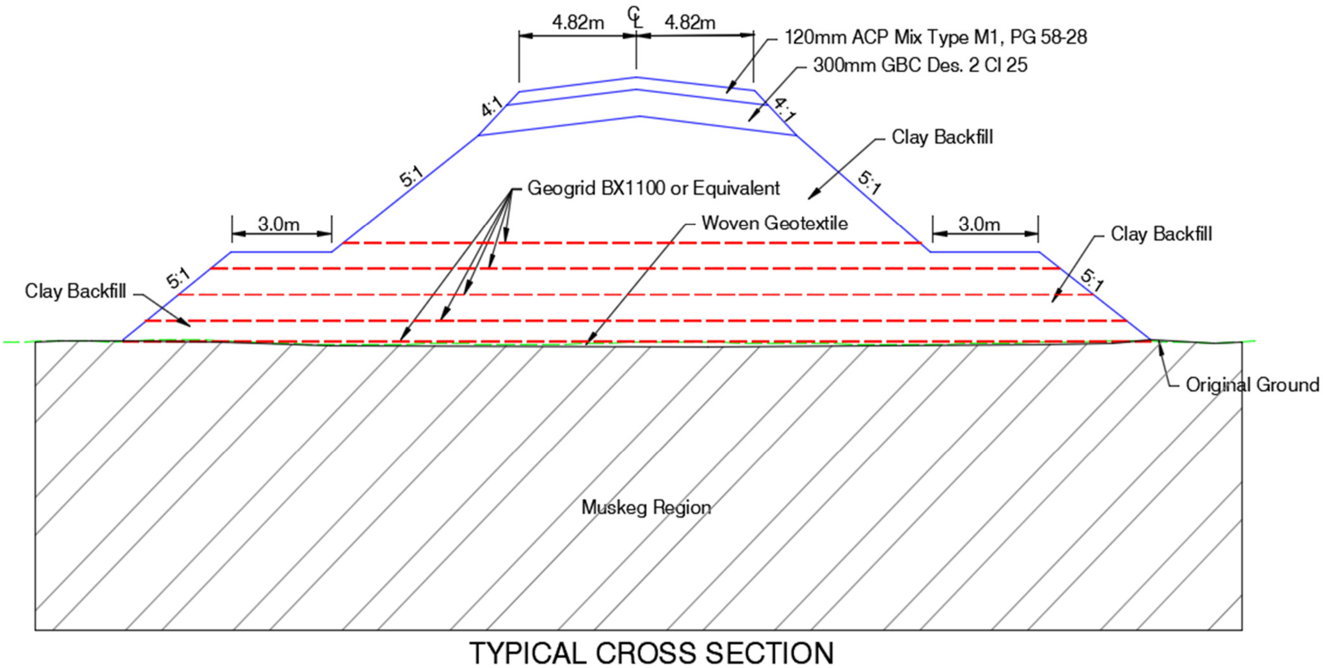
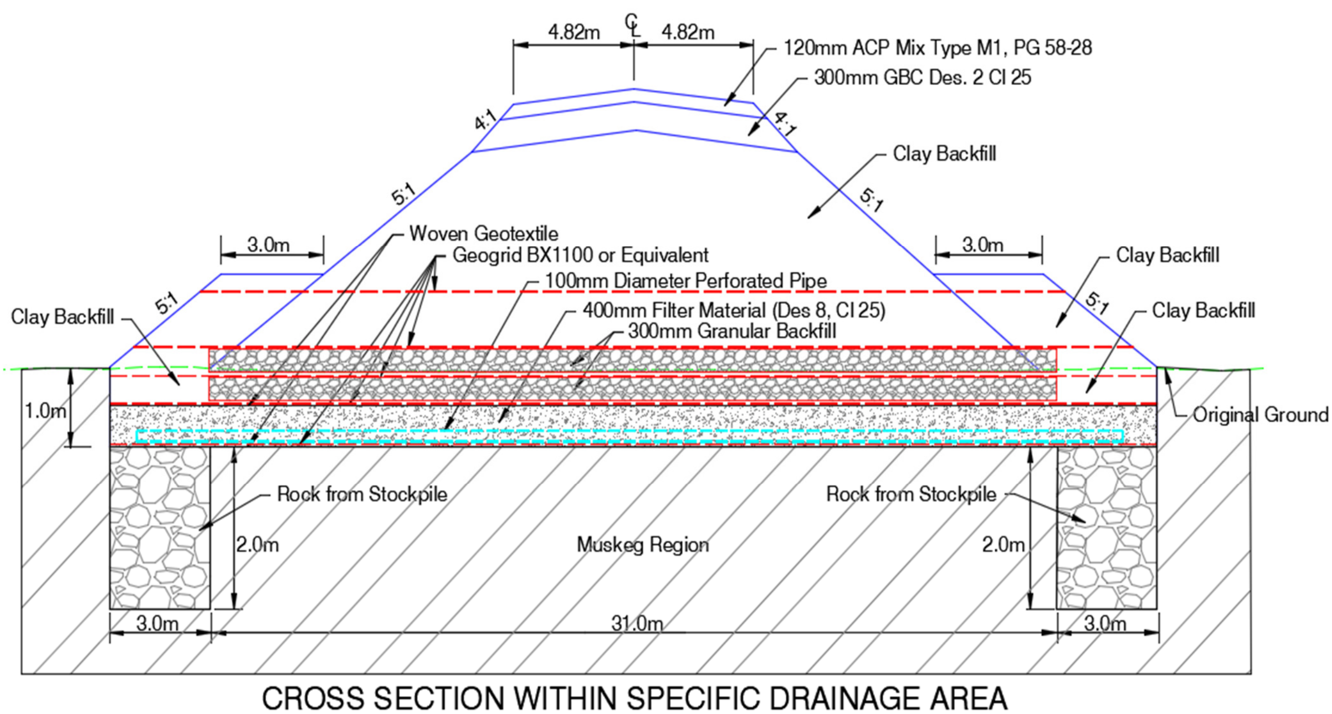


Figure 5.3: showing typical section in specific drainage area with high flows



Construction activities were staged to allow for tree clearing operations within the appropriate migratory bird window and to gain access to the muskeg region in winter months when the ground was frozen. The muskeg extended for approximately 1600m through the middle section of the project and was padded over with geotextile, geogrid and an initial lift of embankment pre-load during the frozen winter season. Tracked machines in cold conditions were used to apply downward forces and get the frost deeper into the muskeg in order to achieve maximum strength.

Photo 5.1: showing tree and bush clearing over muskeg areas

Geotextile materials were placed directly over the muskeg after clearing operations were completed and a zone of engineered fill was placed to an approximate depth of 500mm. At this level, a layer of structural geogrid was placed over the prepared surface and followed by additional layers of compacted fill.

Photo 5.2: showing geotextile fabric placement and initial layers of embankment

Photo 5.3: showing machine tracking to force frost deeper into the muskeg

Photo 5.4: showing upper-level grade construction over geotextile and geogrid layers

Even with the pre-loading and product placement as described above, there were a couple of failure areas within the muskeg region that needed to be dealt with during construction.

During a night shift operation while placing the first lift of embankment, the muskeg sheared longitudinally along the grade and parallel to the road centerline. The zone of influence was within close proximity to a pipeline right of way with two high pressure pipelines crossing perpendicular to the roadway. The pipeline owner had decommissioned the lines in advance of the road construction work however, they were an asset that was planned for future use and needed to be adequately protected from further stresses.

Photo 5.5: shear failure within muskeg zone during placement of initial fill lift

After consultation with the pipeline owner and other stakeholders, it was determined that an extra measure would be necessary to satisfy concerns about the integrity of the pipelines. A proposal was put forward to install a layer of swamp mats prior to advancing any further grade construction which was agreed to. The previously placed materials were leveled off and another layer of geotextile was installed in preparation for swamp mat placement.

Photo 5.6: swamp mat placement over geotextile as extra layer of protection

Photo 5.7: additional layers of geogrid used within subgrade layer above failure area

This configuration was successful in stabilizing the area for continued grade construction over the two pipelines. It is worth noting that a layer or two of geocells may have worked adequately in lieu of the swamp mats, however the matting option was viewed as the clear favorite by the affected stakeholders in this situation due to the sensitivity of the pipelines.

A second area within the muskeg zoned experienced a shear failure that was noticed during the winter season. Localized activities were completed by the Contractor to try and contain the spread of the failure. After a couple of attempts at remediating the issue, it was decided to let it settle out for the rest of the winter season and to re-evaluate the area in the spring.

The primary area of concern was about 50m in length. In the spring, shear cracks were visible parallel to the road centerline and up to 600mm in width. After negotiation with the stakeholders including the Contractor, the following methodology was successfully completed:

1. Removal of the embankment and native material for the full length and width of the failure zone and to a depth of approximately 1.0m below original muskeg surface elevation.
2. A trench was excavated along both the left and right proposed toe of slope. These two trenches were approximately 3.0m in width and 1.5m in depth below the above noted 1.0m cut below original muskeg.
3. Large rock, from a project stockpile were placed in the two trenches with selected materials removed from the trench being used to fill voids between the large rocks.
4. Before placing the large rock material, geotextile fabric and geogrid were placed at the bottom of the trench excavation. The fabric was extended up the sides with sufficient material being available to wrap over top as well. The result was to have the filter material fully encased by the geotextile fabric.
5. Two rows of 100mm diameter perforated pipe were installed for the full length of the trenches, one row along the inside sidewall of each trench.
6. Filter material was placed above the geotextile and geogrid layer at the bottom of the trench, covering the perforated pipe.
7. Geotextile fabric was wrapped around the surface of the filter material resulting in the filter material being fully encased by fabric.
8. A second layer of geogrid was placed above the geotextile fabric covering the surface of filter material.
9. A 300mm thickness of granular backfill material was placed above the geogrid in the previous step for the full width of the excavation by the full length of the excavation less 3.0m at either end. The end 3.0m received a 0.3m thickness of clay to act as a seal.
10. A third layer of geogrid was placed above the granular backfill material and clay from the previous step for the full width and length of the excavation.
11. A 300mm thickness of granular backfill material was placed above the geogrid in the previous step for the full width of the excavation by the full length of the excavation less 3.0m at either end. The end 3.0m received a 0.3m thickness of clay to act as a seal.
12. A fourth layer of geogrid was placed above the granular backfill material and clay from the previous set for the full width and length of the excavation.

13. Select embankment materials removed in the first step were then used to bring the grade up to 600mm above the original muskeg surface elevation.
14. A fifth layer of geogrid was placed above the embankment material installed in the previous step for the full area and keyed into the start and end of the excavation.
15. Regular subgrade grade construction was resumed from this level up to the top of the design subgrade followed by the GBC and ACP operations.

Photo 5.8: showing fabric, geogrid and perforated pipe placement within the failure area

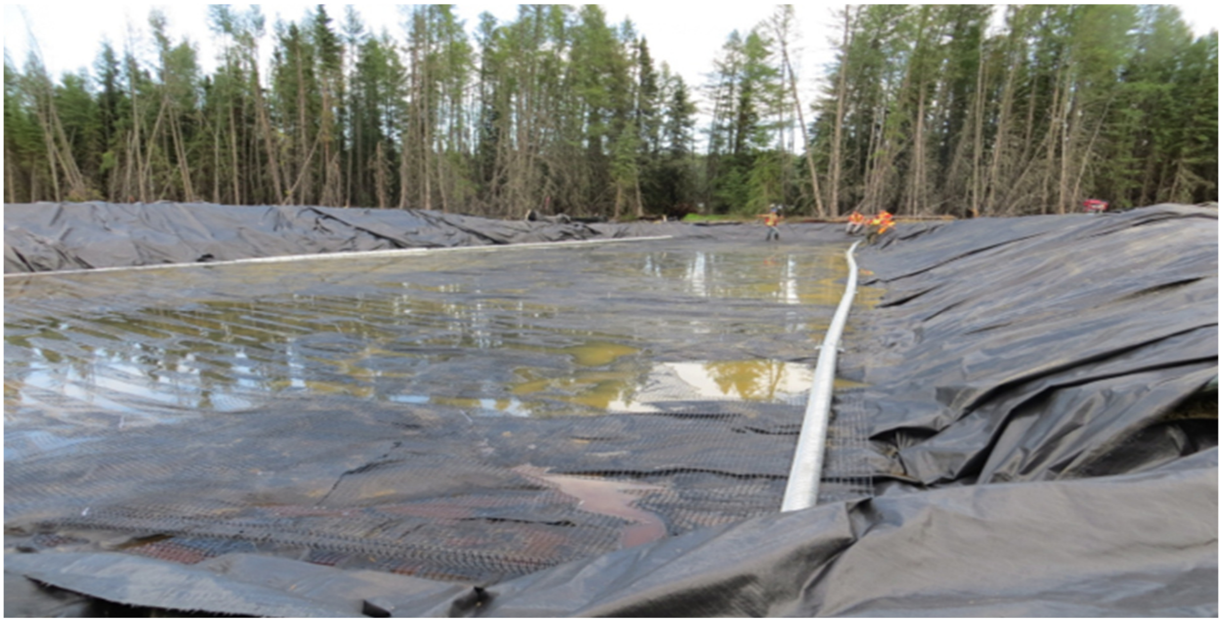


Photo 5.9: showing the fourth level of geogrid placement above the failure area

Post Construction Monitoring has been carried out to determine how the section through the muskeg region is performing and to see if/when settlement concerns have stabilized. Centerline profile surveys have been conducted at intervals since the construction was completed with varying degrees of settlement throughout the region as predicted. Once settlement trends stabilize, it is proposed to conduct a leveling course followed by application of the final pavement lift.

Comparisons have been made to determine how annual precipitation levels may be affecting road settlement through this region. The following figures represent the vertical profile with four points identified for settlement monitoring and comparison to rainfall level.

Figure 5.4: showing road profile through the muskeg region

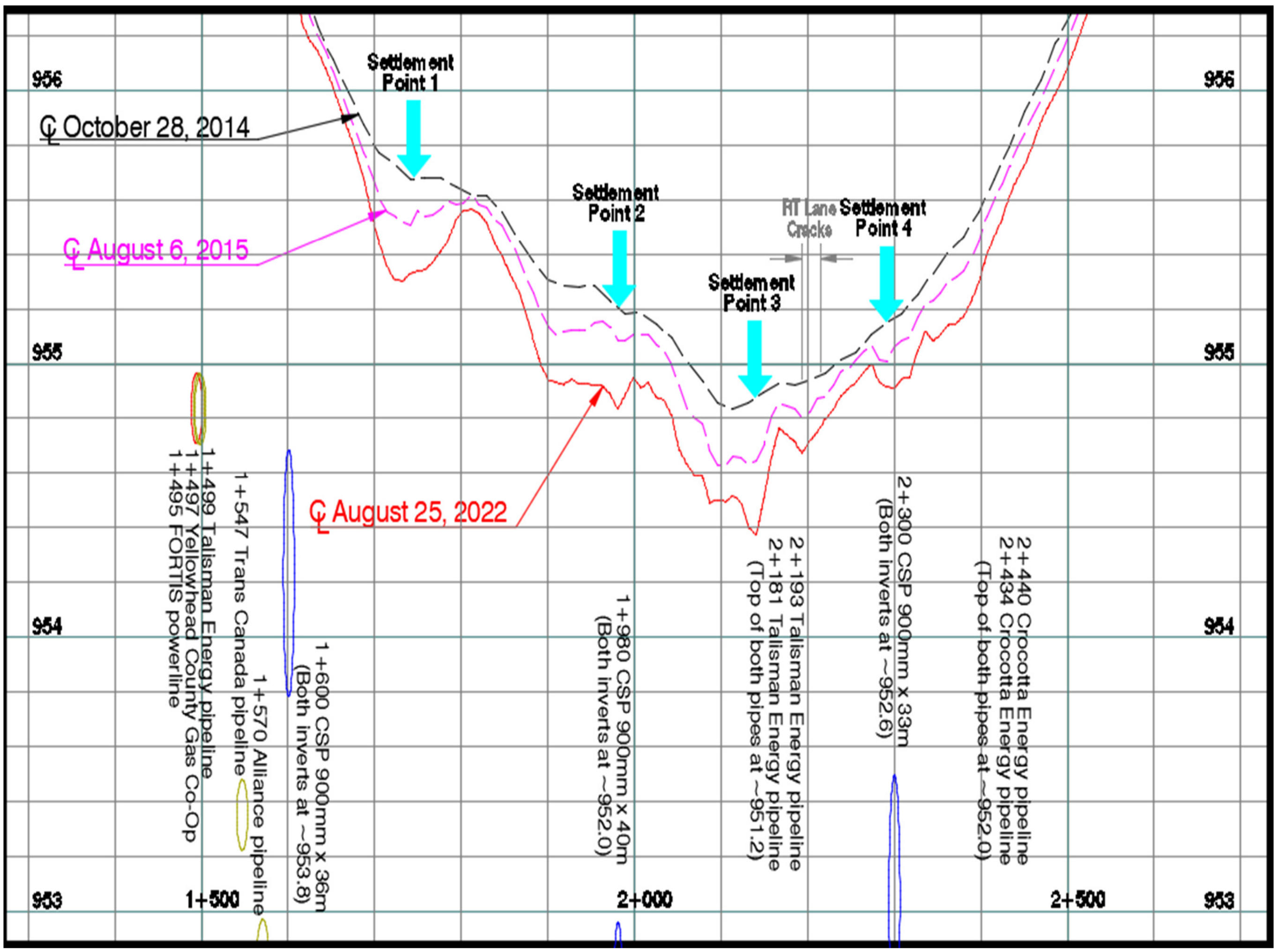


Figure 5.5: comparing annual rainfall effect on settlement at settlement point 1

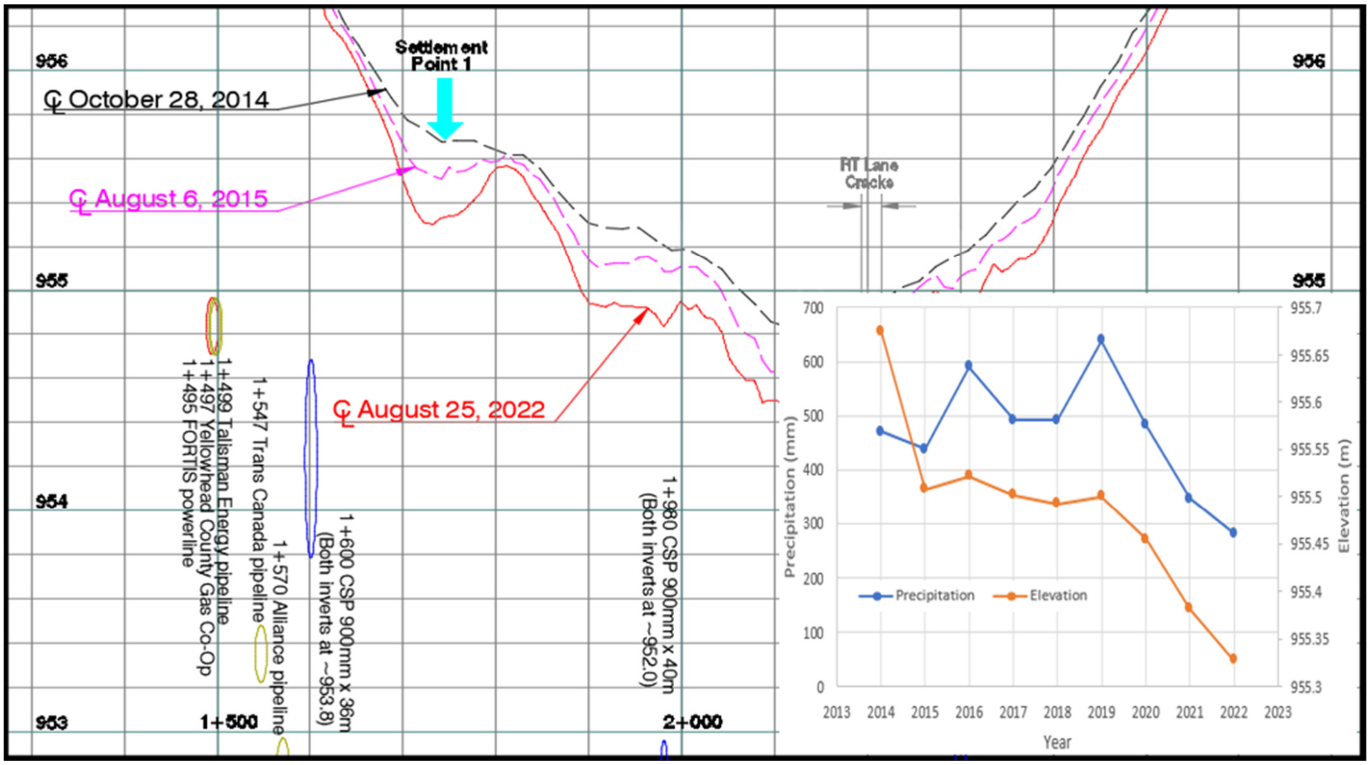


Figure 5.6: comparing annual rainfall effect on settlement at settlement point 2

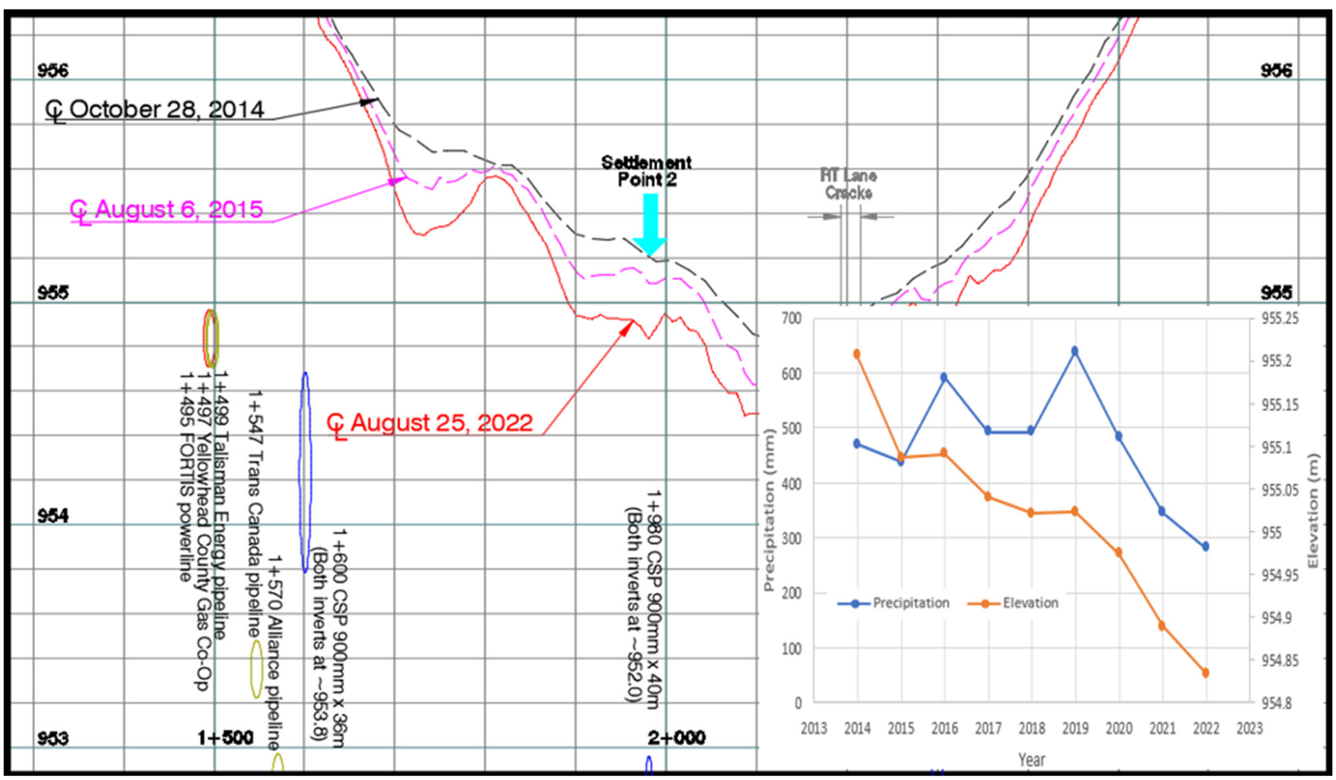


Figure 5.7: comparing annual rainfall effect on settlement at settlement point 3

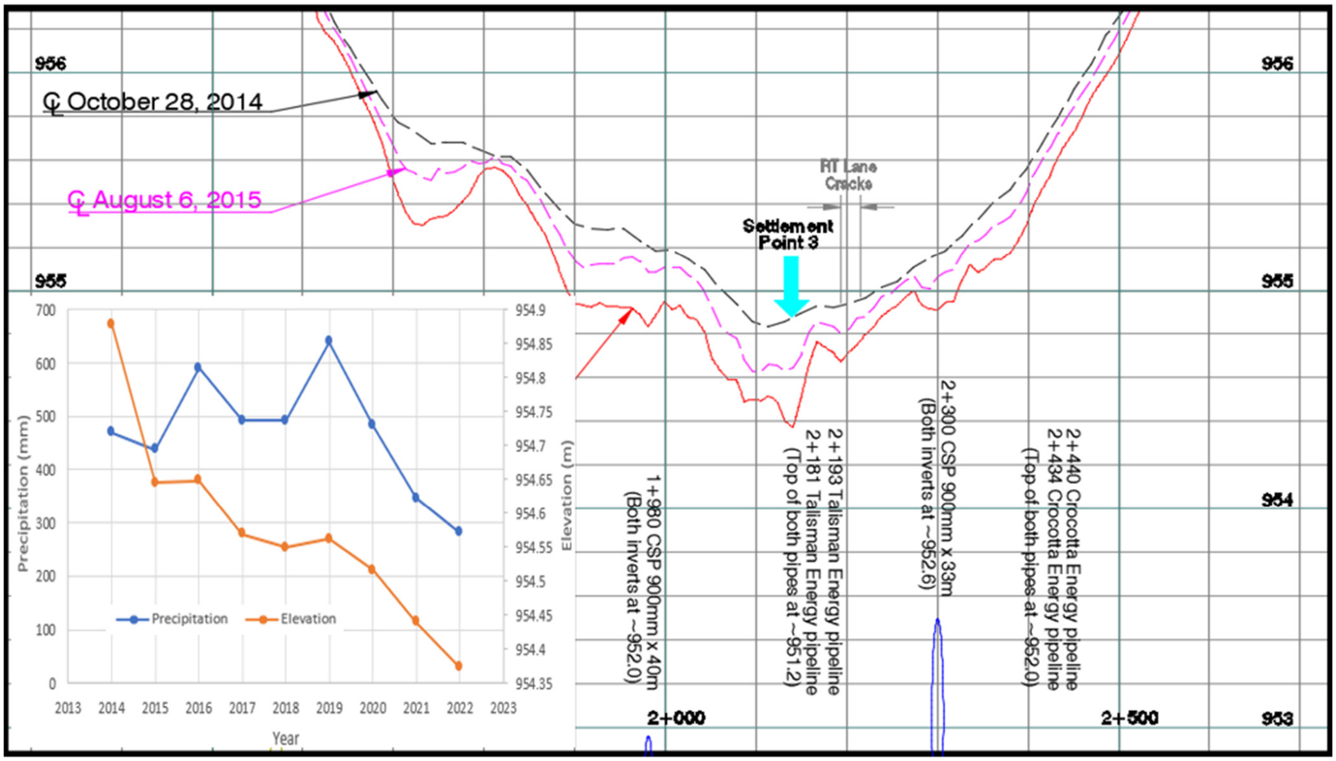
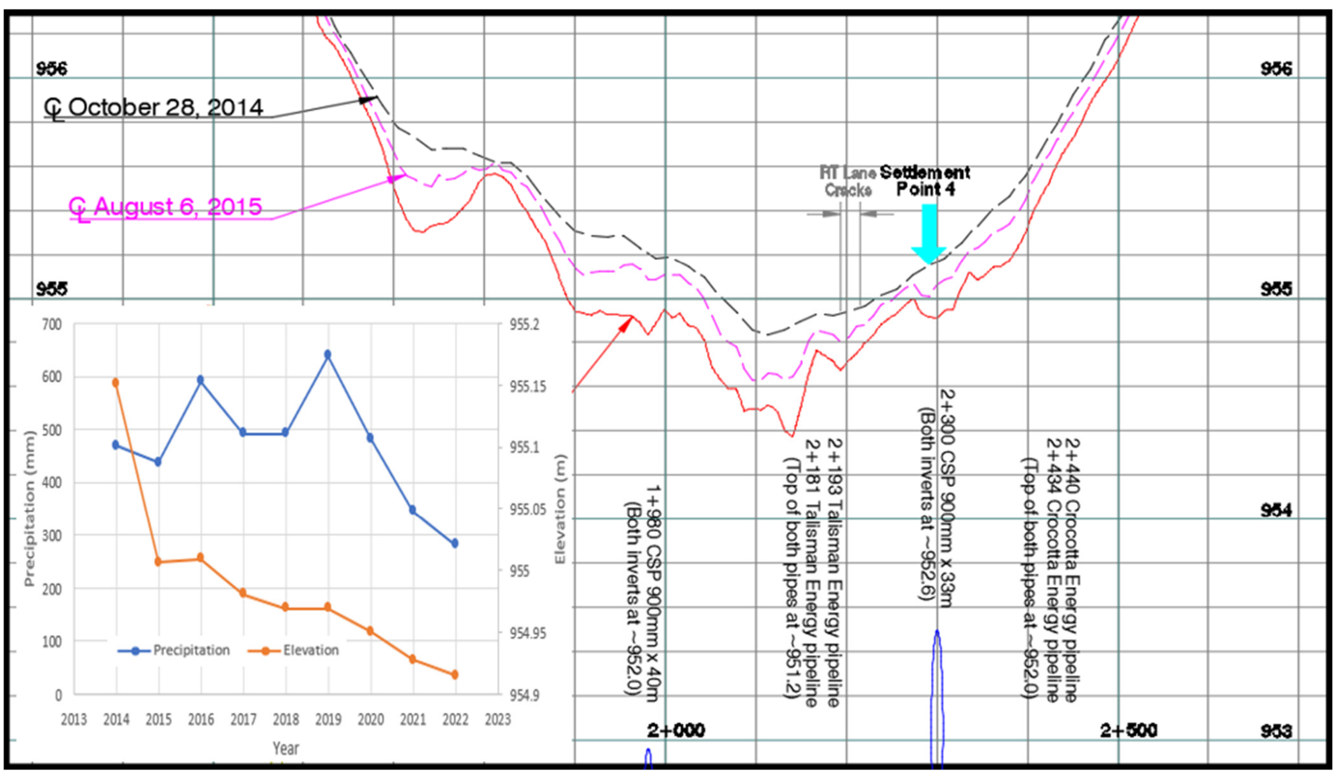


Figure 5.8: comparing annual rainfall effect on settlement at settlement point 4



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