Staged Road Construction in Very Weak Subgrade Using Polymeric Geocell

Arghya K Chatterjee, P.Eng.
Senior Project Engineer
Stratum Logics

Sanat K Pokharel, Ph.D., P.Eng.,
Principal Engineer
Stratum Logics

Marc Breault
President
Paradox Access Solution

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Abstract

The ongoing development of the energy industry in Canada, especially for pipeline-related structures, demands innovative ways of access construction. Most of these are at remote locations and under difficult geotechnical conditions making access a challenge. A 4.1km long unpaved access road leading to a proposed compressor station in Blainville, Quebec was planned for the construction of the station pad and future access. The road was expected to serve as a material haul road for the 200m x 250m gravel pad, regular compressor station construction loads, and future traffic. Construction of the pad was scheduled to start before the winter of 2020. The proposed road alignment had very soft to soft subgrade conditions with saturated peat. There were problems with limited right of way, a landslide-prone zone, a creek crossing, and overhead powerlines. The road geometry was to be designed such that there was enough clearance from the overhead powerlines and the slide-prone area and maintain the minimum turning radius required for the long and heavy trucks carrying compressor units. Additionally, there were constraints imposed in permits and other aspects of the project that left a short 6-week window for the construction of the road.

The existing subgrade was high water-bearing peat with depth varying from 0.6m to 2m. Removal of the peat and bringing engineered fill was not practical from cost, schedule, and environmental permit perspectives. A non-conventional design on top of a weak subgrade with geocell was deemed necessary.

The limited construction schedule did not allow for building the minimum reinforced structure necessary to support design loads, particularly the 65 Metric Ton compressor load. As an engineered solution, a road was initially designed for the design load limits and a maintenance plan for the operation. Taking advantage of the high-strength novel polymeric alloy (NPA) geocell load support mechanism, it was possible to avoid any material removal and yet build a minimum structure for initial construction traffic including some heavy haul traffic. Strict load restrictions were imposed on the temporary bridge. The initial design was done in a way to accommodate the final construction with minimum adjustments and without hindering continuous access to the pad. For low power lines and right of way, fill limits on the final design were further reduced with an additional layer of geocell. This paper describes in detail the design methodology and maintenance program that was implemented through the construction phases.

Introduction

Growing infrastructure development has an increasing demand to build roads across some challenging geotechnical conditions with minimal environmental footprint. Demand for innovation in road design and construction is therefore evident. A 4.1km long unpaved access road leading to a proposed compressor station in Blainville, Quebec was planned for the construction of the station pad and future access. The road was expected to serve as a material haul road for the 200m x 250m gravel pad (with fill thickness varying from 1.1m to 2.1m) and a valve pad (50m x 35m). It also needed to support the regular compressor station construction traffic and future traffic required for station operation. Construction of a pad was scheduled to start before the winter of 2020. The proposed road alignment had multiple challenges in design, especially the feasibility of construction and the schedule.

A struggle for infrastructure development on organic soil and available solution options were summarized by Yii et al. (2021). Considering all the options presented, for the given design use of high-strength novel polymeric geocell seemed to be the most suitable one, as it maximizes the total fill reduction for unpaved roads on the soft subgrade. Pokharel (2010) developed a design method for unpaved roads modifying the Giroud and Han (2004) method for planar geosynthetic reinforcement utilizing novel polymeric alloy (NPA) Geocell reinforcement. Han and Pokharel's design method (Han, 2015) for the design of unpaved roads with geocell has been validated through multiple applications around the world (Pokharel et al. 2013, Pokharel et al. 2015, Yii et al. 2021). Multiple successful performances of roads, built on muskeg soil having a California Bearing Ratio (CBR) less than one, with geocell reinforcement have been documented and the mentioned design method has been reported by Shenouda et al. (2021) and Pokharel et al. (2017). Norouzi et al. (2017 and 2019) showed the effectiveness of this technology in reducing environmental footprints. Based on the above-mentioned studies, it can be inferred that reinforcing soil with high-strength polymeric geocell provides three-dimensional confinement and acts like an infinite beam, which is essential for long-term better performance of load-bearing embankment structures on top of high water-bearing soft organic soil. The presence of geocell reinforcement increases the stiffness of the reinforcing layer and thus, distributes the vertical load over a wider footprint.

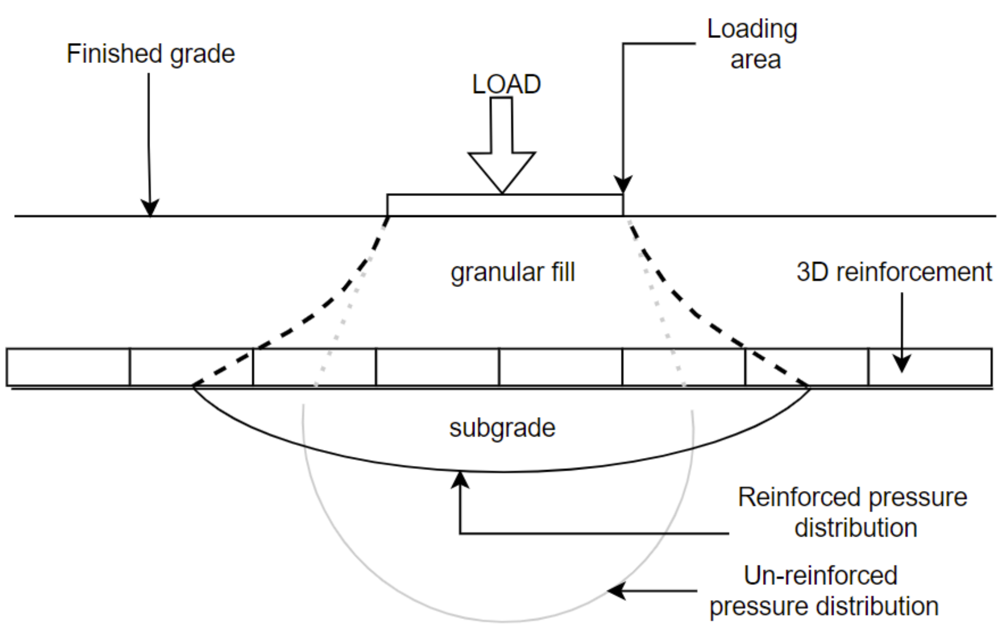


Figure 1: Schematic diagram for stress distribution under reinforced and un-reinforced soil

This effectively reduces the bearing capacity demand of underlying soils (**Figure 1**). However, given the entire spectrum of challenges, utilization of geocell design alone was not enough, some of the challenges with permits and schedule needed additional attention.

This paper discusses in detail the design methodology, and how a seemingly impossible schedule was achieved in collaboration between the design and the construction team without compromising on the quality. Available reinforcement technology was optimally used in the design and development of the maintenance plan. Construction methodology was dictated by design (at a macro level), for the successful elimination of potential risks. The objective of this paper is to establish a methodology for accelerated construction by phasing construction in different stages with respective load limits. This paper also suggests a guideline on the maintenance plan to refrain from overloading and perform local damage control through multi-stage construction.

Design Approach

Before looking for an engineered solution for infrastructure design, it is important to understand the challenges and the extent to which they can impact the design performance. The challenges in the current project under discussion have been grouped into three categories, namely design challenge, constructability challenge, and post-construction challenge.

Design Challenge

Design challenges are a summary of the information presented through geotechnical, hydrological, and topographical data that can pose failure risk for expected loads. The geotechnical report indicated that the boreholes were drilled parallel to the planned road profile, about 20m South on an existing ATV road. Drill holes identified 600mm engineered fill and thus, the natural soil profile at the current location of the load alignment remained unknown. This left a wide spectrum of uncertainty on subgrade strength. The Conservative assumption of the entire 600mm depth being organic peat seemed reasonable, based on the surrounding topography and the boreholes at the station pad. For the last 1km of the road, bore-holes were done on the actual road profile, and it identified peat depths exceeding 1.5m. The profile below the organic-peat cover was sensitive soft clay with undrained shear strength below 40kPa on average. From SPT (Standard Penetration Test) numbers, CBR was estimated to be less than 0.8% on the existing soil. Saturated subgrade with groundwater on the surface added to the challenges. Low pre-consolidation pressure also limited the total fill height to 1.5m. That added to the undulating surface made the geometric design challenging as the subgrade organic material removal was not permitted. To accommodate the total fill limit and existing surface profile, at crest locations, grade raise had to be restricted to 450mm on an average.

The road profile crossed a creek and an environmentally sensitive wetland area. To minimize the impact on the wetland the right of way had to be reduced without compromising the width of the top driving surface. To optimize the size of the bridge at the creek crossing and keep the bridge deck above the one in two-year high-water mark (as demanded by the environmental engineering team and hydrology report to avoid a trigger on fisheries act), the road profile demanded high slopes (about 7%). Around the creek, there was an identified unstable slope. Reducing the dead weight of fill in that area was essential. At the creek crossing and four sharp turn locations, the road embankment side slopes of existing ground and embankment were exceeding the natural stable slope, as identified in the geotechnical report. So, the same road embankment structure demanded slope protection, with minimum impact on cost and schedule for construction.

Constructability challenge

The construction team expressed multiple concerns in the early days of design. Environmental permits and schedules did not allow an opportunity for removing soft subgrade. Locally available fill material was MG112-sand (as per Quebec's BNQ 2560 - 114/2014) and the existing water level was on the surface. All these combined built the risk of equipment getting stuck. Thus, subgrade preparation (proof roll pass) was not feasible. Compacting the bottom lift (200mm thick) to the design requirement (92% Modified Proctor Dry Density) on top of saturated peat, just with a separation layer of geotextile was another challenge. Limited right of way for the toe of the embankment demanded steeper and naturally unstable side slopes. Thus, it was necessary to create a slope protection design for lateral stability of the road embankment.

Safety concerns were raised regarding the presence of the electric poles, telephone lines, and low clearance for high tension power lines at multiple locations throughout the road. Maintaining a minimum 10m radius around the high-tension power line was necessary during the construction and later during operation. Relocation of any of those was out of the question for tight schedules and associated costs. The access road linked a compressor pad construction. The design of the station pad demanded the bottom layer be built before the ground freezes. This left a strict six-week window for the construction of the entire 4.1km road.

Post-construction challenge

The high-water table with limited fill height and design loads left a high risk for an early failure of the road embankment. This also exposed the risk of freeze-thaw degrading the long-term performance. Using high-performance reinforcement material that can sustain the reinforcing properties through construction and later years through operation was necessary. The client had high expectations of minimizing long-term maintenance costs.

Design Approach

Based on all the design, construction, and post-construction challenges and mechanisms for potential short and long-term failure were studied. Bearing capacity failure of the soft subgrade was one of the top considerations. Fines pumping into the granular fill during high water table and capillary action had to be considered. Vertical and lateral confinement failure over time or with water seeping inside and loss of inter-particle friction was expected to impact the long-term performance of the designed embankment. Slope stability for the limited right of way and settlement were other considerations.

All the above issues can be mitigated with proper reinforcement of base fill material. As indicated by Shenouda et al. (2021), the use of high-strength polymeric geocell was a viable solution to the challenge. High strength (highest yield strength and elastic modulus) was necessary to provide maximum stiffness to the compacted granular fill. Thus, spreading the load over a wider area and minimizing pressure on the subgrade, and minimizing the total fill thickness required. Polymeric alloy Geocell added the advantage of using sand as fill material, as the three-dimensional geometry of geocell improves the shear strength with the addition of apparent cohesion imparted by the geocell pocket, as presented by Amarnath et al. (2015). Properties of the high strength geocell selected are presented in **Table 1**. Based on Thakur et al. (2013), the selected material is also known for its better creep resistance and performance thereof. Creep performance implies that the material doesn't degrade with load cycles and being exposed to the environment. Thus, improving the long-term performance and reducing maintenance costs.

A geocell reinforced unpaved road structure is typically designed for serviceability criteria of rutting not exceeding 75mm, as per the Han and Pokharel design formula (Han, 2015) shown in **Equation 1**. Failure criteria in bearing of soil on given CBR and undrained shear strength for the entire depth and loss of long-term confinement with hoop stress limits were checked as well. Compaction of infill material is an important criterion for the geocell reinforcement to perform to its expectations. The use of poorly graded material is acceptable provided the desired compaction can be achieved. The three-dimensional geometry and high material strength provide good long-term confinement. This, help achieve the expected compaction even on top of weak subgrade and reduce the abrasion of the fill material. Abrasion shifts the particle gradation and introduces more fines. Fines eventually get washed and introduce voids leading to early failure of embankment structure. Confinement using 3D reinforcement minimizes this effect.

Table 1. Properties of Geocell

Characteristics	Type C	Type D
Material	Novel Polymeric Alloy	
Wide-width strength at yield	19 kN/m	22 kN/m
Cell height of geocell	150 mm	120 mm
Distance between weld seams	330 mm	330 mm
Coefficient of soil-cell friction efficiency	0.95	0.95
Coefficient of thermal expansion	<135 ppm/°C	<135 ppm/°C
Brittle temperature	<-70°C	<-70°C
Long term plastic deformation at 65°C (load 6.6 kN/m)	<3.0%	<3.0%
Dynamic (elastic stiffness) modulus at +30°C	>775 MPa	>800 MPa

$$h = \frac{0.868 + 0.52\left(\frac{r}{h}\right)^{1.5}\log(N)}{(1 + 0.204(R_E - 1))} * \left(\sqrt{\frac{P}{\pi r^2 m 5.14 c_u}} - 1\right) r \qquad \text{[Equation 1]}$$

where,
h= Required base course thickness (m)

r= Effective radius of tire contact area (m)
N= Number of wheel passes or equivalent single axle load (ESAL)
P = Wheel load (kN)
c_u = Undrained cohesion of the subgrade soil (kPa)
R_E = Modulus ratio of base course to subgrade soil
m = Bearing capacity mobilization factor

Using **Equation 1**, all cross-section passing criteria are set to passing the minimum rutting depth of 75mm for a maximum of (N=) 300,000 Equivalent Single Axle Loads (ESALs). The minimum fill height required (*h*), has been checked for multiple loads. Undrained shear strength for different cross-sections was taken from the geotechnical report.

Grouping the entire set of challenges, the entire length of the road (**Figure 2**) was divided into four sections. For all the layers, a bottom layer of 1200N non-woven geotextile was used for separation. The heaviest load being 65 Metric Ton compressor and multiple transformers exceeding 45 Metric Ton exceeded the typical highway truck's axle load. It also demanded an additional turning radius (minimum of 27.5m).

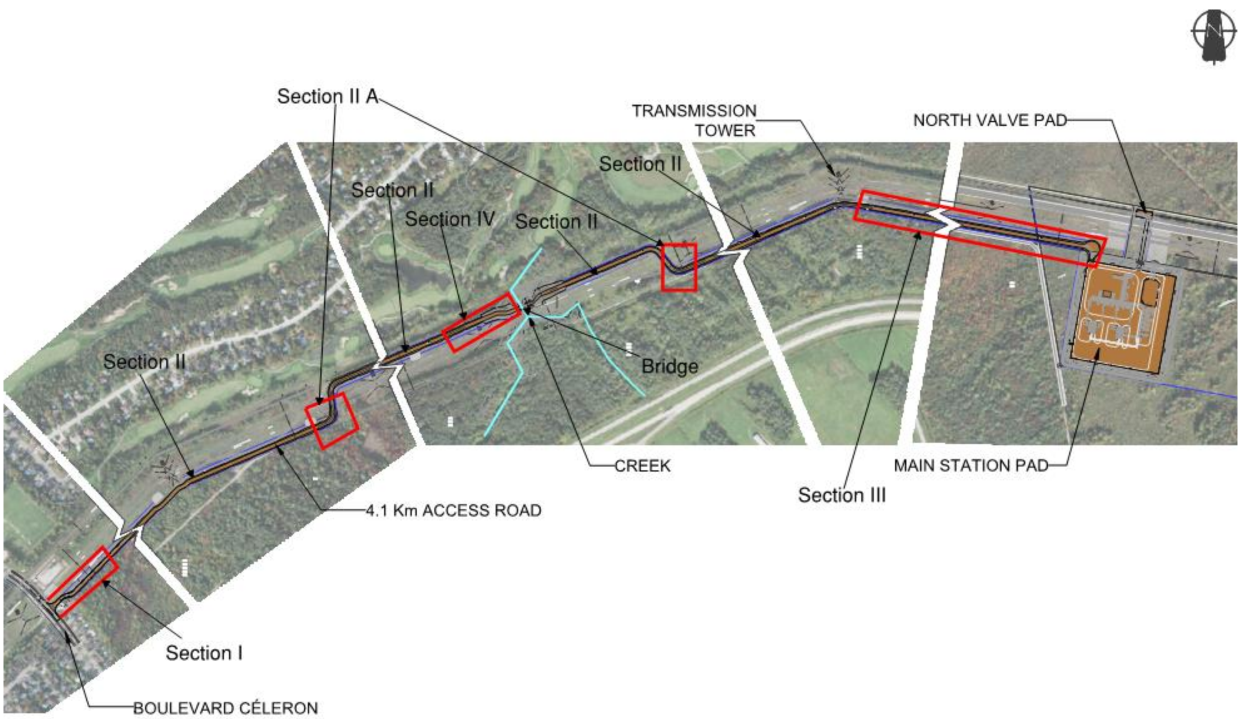


Figure 2: Plan of the road with different design sections

The first section (**Figure 3, Section I**) was for the initial 350m of road linking the municipal road. This is where a minimum of 325mm stripping was necessary to meet the clear elevation below the telecommunication lines. The subgrade condition in this stretch was the best as compared to the remaining road. So, subgrade preparation with proof roll (with loaded water truck having 110kN axle load) not exceeding 20mm deflection was recommended. The single layer of 120mm high Type D geocell (with perforation having optimal open pocket size 245mm x 210mm) was used right on top of the geotextile for long-term confinement and improved layer modulus. With loaded trucks end dumping throughout construction entering from here, this section was expected to have maximum equivalent single axle loads (ESALs). The fill material recommended was a minimum thickness of 300mm of MG56 (as per BNQ 2560 -114/2014) with top sealing gravel of 75mm thick of MG20 (as per BNQ 2560 -114/2014) for a smooth driving surface. For every 300,000 ESALs, minimum maintenance with grading and occasional capping of up to 25mm lifts was expected.

Following the first stretch, *Section II* (**Figure 3**) and *Section III* were a two-layer design with the bottom layer being 150mm high Type C for construction support on top of weak subgrade and the upper 300mm thick layer with 120mm high Type D geocell. *Section II* needed a minimum thickness of 650 mm and *Section III* needed a minimum thickness of 750mm for the varying subgrade strength conditions. A majority of the road was constructed as per *Section II* (**Figure 3**). Only at the last 0.5km, where observed organic thickness exceeded 1.5m, *Section III* was used. For sharp turn areas, where the side slopes were steepened by 1H:1V instead of a typical value of 2.8H:1V, an additional layer of 150mm high Type C geocell was used (**Figure 3, section IIA**) for embankment retaining and slope stability.

Section IV (cross-section is not shown, as it is similar to **Section I** in **Figure 3** with ditches on either side and varying stripping depth) was the approach side of the bridge. This section was on a steep slope (up to 7%, as in **Figure 4**) and had a minimum of 1.2m deep ditches on either side to account for the lower elevation relative to the surrounding area. It was similar to the first section with subgrade preparation but without any stripping. Only one layer of 120mm high Type D geocell (**Table 1**) with 1200N non-woven geotextile was used in this design. Minimum 400mm structure including 75mm of MG20 as wearing course was designed.

At no point throughout the design did the permanent footprint exceed 15m. A 6m wide temporary reclaim area was provided for construction. A minimum 5m spacing was maintained from telecommunication poles and a minimum clear vertical spacing of 3.8m was maintained from the restricted radius of transmission line wires. Concrete barriers were recommended as an additional measure for the protection of poles. As per the hydrological report detail, balancing culverts were provided at every 200m along the entire 4.1km road. 600mm diameter culverts were designed with a minimum 425mm cover on top with two layers of geocells. Towards the end of the road, hydrology demanded a 1200mm diameter twin culvert system. For that local raised area, smoothly transitioning into the remaining road profile, had to be created to get a minimum 450mm cover with two layers of geocell cover. As per the client’s specifications, the minimum elevation for the entire road respected the hydro-technical requirement of one in ten years event.

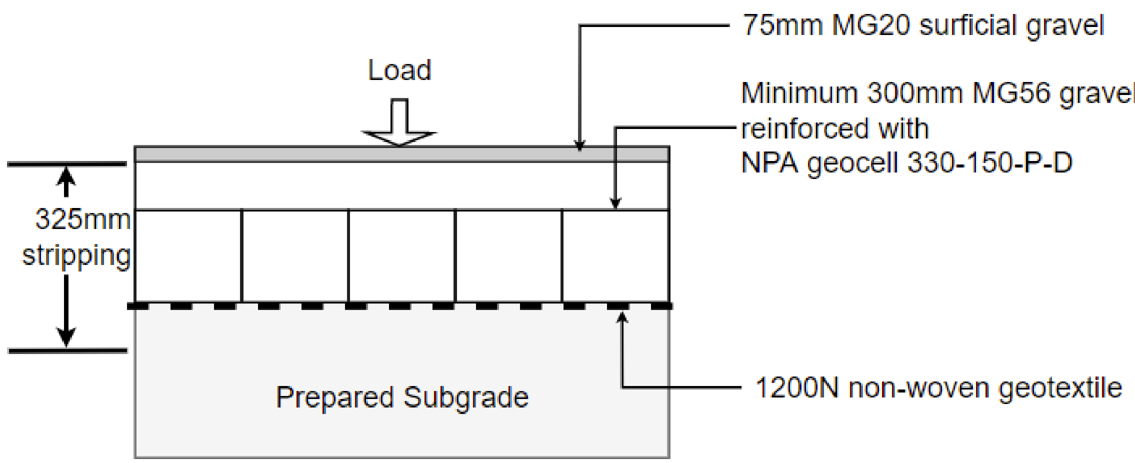
The bottom layer of geocell (extending up to the elevation right below the upper layer of geocell) was considered a ‘construction layer’. The primary purpose of this layer with Type C geocell was the confinement of fill and to allow compacting equipment to achieve the minimum 92% modified proctor density. The purpose of the top layer on the other hand was structural support and long-term performance of the embankment. For Section I and IV, the construction layer and the structural layer were the same. As the structural design criteria superseded the construction layer design criteria, the single-layer design was done considering bearing and rutting failures criteria for expected loads. Options with different lower strength geocell and two-dimensional structures were checked for top layer confinement. However, given the client's expectation of minimum long-term maintenance even with confinement loss, the peak loads and minimizing fill height (thus reduced right of way) high strength geocell (with the specified minimum of seam strength, dynamic elastic modulus, tensile strength) was found to be the most suitable solution. Using alternative reinforcement might have been acceptable if the minimum grade raise expected from the hydrological study was higher than the minimum fill height required using NPA geocell. MG112 (sand, as per BNQ 2560-114) for the bottom layer was replaced with MG56 (as per BNQ 2560-114) gravel for the sole reason of yielding under tires (**Figure 6**), which may lead to highway trucks getting stuck during construction or construction traffic.

Construction process

The construction process was laying the geotextile, stretching geocell, end dumping the infill material, and then spreading the fill with a dozer into the open stretched pockets of geocell. Then compact the granular fill with a vibratory drum compactor while maintaining a minimum cover of 75mm on top of the geocell, to avoid the risk of damaging the geocell. Originally, the road was designed for full load capacity with specified layers. However, to accommodate the challenging construction schedule, the entire structure was segmented into two phases, as described below.

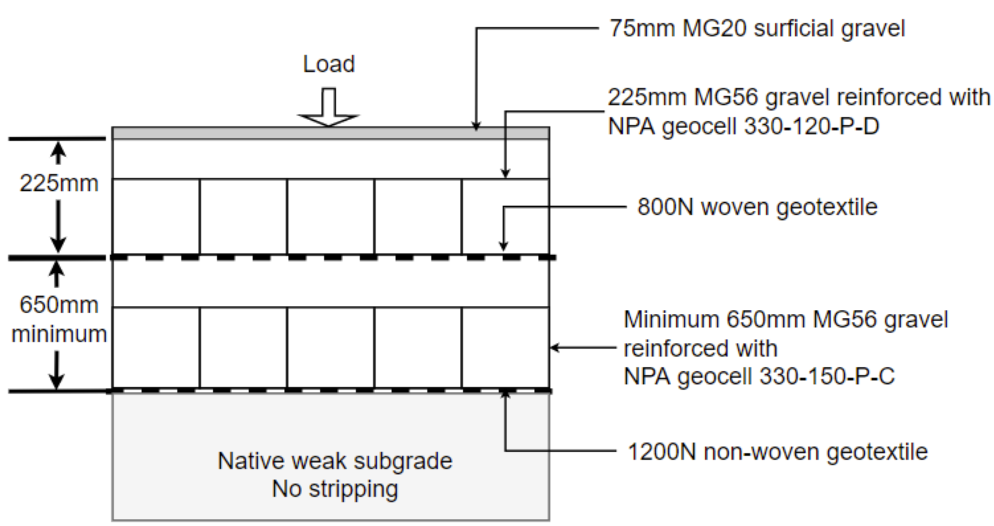
The first phase was the construction of the bottom layer of the geocell (construction layer) prepared to design specifications. For Sections I and IV, since it was a single-layer design, phase one construction included the entire structure without the top MG20. This construction layer was only good for 100,000 ESALs, slower traffic (less than 30km/hr), and lighter construction load. Peak loads with compressors were not allowed at this stage. If the design limits were to, a maintenance plan would be necessary and was suggested. The maintenance plan stated the minimum serviceability criteria as 75mm rut depth. Exceeding that risked structural damage and subgrade degradation beyond normal repair. Thus, continuous observation was a mandatory quality control requirement during road operation. The site engineer was assigned the responsibility to continually assess the rut depths and stop vehicles (and operations) as necessary until remediation approved by the design engineer was in place. The expected remediation was grading and compacting the top surface. However, in extreme cases for local soft areas, provision for using temporary access mats on top of the construction layer would have been a potential solution. The maintenance scope included maintaining the rough grade (top of construction layer) with additional gravel material if required. Additionally, the road edges needed some grading work for positive surface runoff and not overloading or risking damage to exposed geocells. A temporary pre-assembled bridge was used with similar load restrictions at the creek crossing.

Since the road was not built in this phase to design grade, the necessary cover on top of culverts was not met. Not installing culverts in the first phase was considered a risk for the possibility of flooding during spring. Pumping of water from one end to the other would have needed additional permits and thus affected the schedule negatively. Thus, equalizing culverts were installed through phase one. For most culverts, a locally raised ground was created with another layer of geocell, and some needed additional protection with an access mat laid on top. Whether a temporary mat was required or not depends on the amount of coverage that could be built with a local hump and the loading cycles.



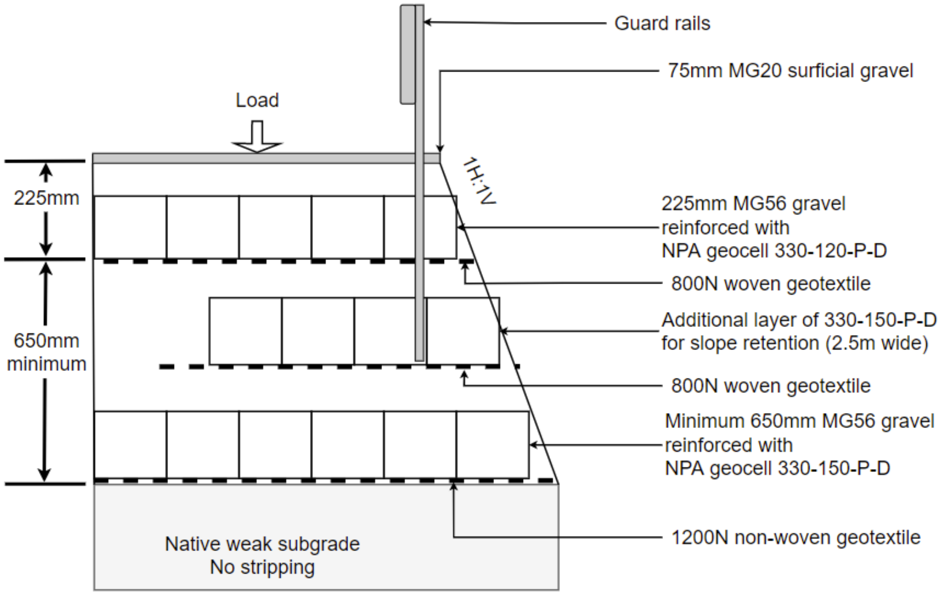
Schematic of single layer design

a. **<u>Section I (same as Section IV – except IV had side ditches and 300mm stripping)</u>**



Schematic of double layer design

b. **<u>Section II (2-layer reinforced cross-section of the road)</u>**



Schematic of double layer with side retention design

c. <u>**Section IIA (only at locations where ROW limited the side slopes)**</u>

Figure 3: Different designs section

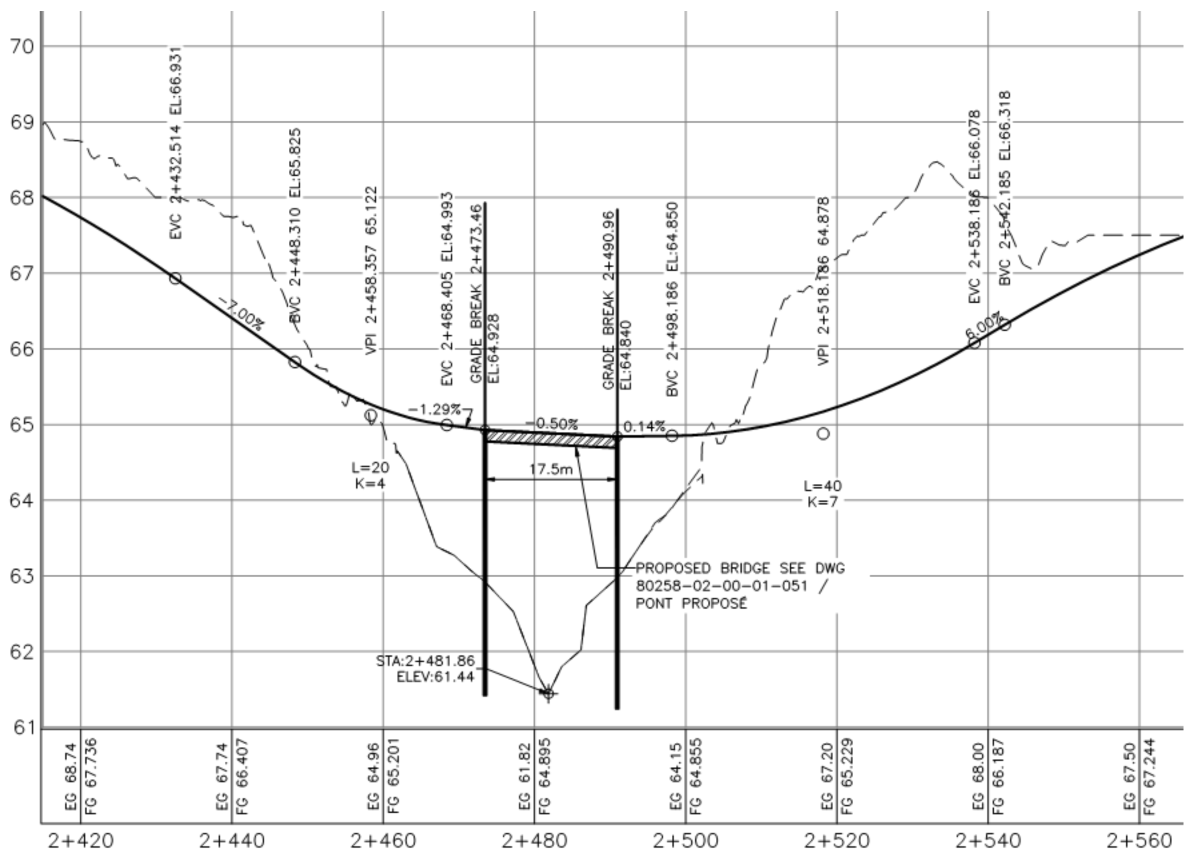


Figure 4: Profile of road in the bridge area

The risk of overloading the construction layer was controlled by continuously monitoring the project and communicating actively with the design engineer. Pumping of fines and capillary action compromising the strength of the construction layer was eliminated with the strategy presented by Leshchinsky (2011), where a layer of woven geotextile is used under geocell. A significant portion of the top grade of phase one construction stayed below the minimum elevation necessary for one in ten years event. This was deemed acceptable given that the approaching season was winter. The first phase was completed within six weeks.

The second phase of construction started once the ground started to thaw (**Figure 8**) in the Spring. In areas with sensitive subgrade, having more than 0.6m depth of organic soil, proof rolling was performed before grading and laying the top layer of geocell. Full design loading and allowed design speed were accepted only after compaction of the final grade.

Guard rails were provided for safe driving at sharp turns and around the bridge approach. Top-soil cover and riprap were the main elements for erosion protection. Particularly the side ditches approaching the creek had to be protected with hand-placed riprap. Ramps were built with relevant safety signage for ATV crossings. By limiting the grade raise of the road embankment, the risk of construction equipment stretching into the safety perimeter around powerlines was eliminated.

Results and Discussion

The crew size for building the road includes a couple of laborers, supervisors, and equipment operators. The construction area being close to a residential area, work hours were limited to single shift 6 days a week. During construction, there were 4 workdays due to bad weather. Even with all those limitations, it was only 6 weeks from initial crew mobilization to construction vehicles reaching the compressor station pad area. Achieving designed compaction on top of weak subgrade in saturated conditions (**Figure 5 and Figure 6**), was achievable. Undercuts were done only at culvert locations to match designed invert elevations (**Figure 7**). The construction method with the inclusion of geocell reinforcement made this possible.

Grade elevation was noted by survey, upon completion of the first phase of construction and before starting the second phase of construction (after the ground thawed). Some local deflections were observed not exceeding 35mm. In some places, 3% positive grade from road crown to edge was found to be reduced to around 2%. This was expected as the peat and clay below were likely to compress with the dead weight of the fill. The performance of phase one construction exceeded the expectations of the client, as no re-work with excavation or another failure was necessary and maintenance was only grading once every 5 working days (roughly, until the entire ground froze). Theoretically, maintenance was expected between 3 to 10 working days based on load frequency. No access mat support was needed (other than two culvert locations to protect the culverts) during operation on the construction layer, as originally expected while planning the maintenance program.

As per the maintenance plan, regrading and compaction were carried out on top of the construction layer before laying the second layer of geocell (**Figure 8**). The geotechnical report expected a 75mm long-term settlement for the clay and an additional short-term settlement of 800mm from compression of the top organic layer. The total settlement of the road was not measured (initial compression of peat remained unknown) but based on rough grade, final grade survey, and the design thickness of the structural layer, no noticeable settlement was observed. Thus, adding the dead weight of the structural layer had no further compression of peat. It is expected that the reduced deflection was a direct outcome of reduced bearing load on the subgrade for the beam/slab effect of geocell.

More than 5500 loaded trucks carried sand and granular material for the station pad through the road. With an effective surface maintenance plan in phase one, more than 70% of those loads were delivered successfully prior to the completion of the structural layer. Added to this, there were construction vehicles, and trucks carrying mechanical equipment. The total equivalent single axle load (ESALs) reached almost three times the design value (excluding traffic on frozen months) of 300,000 ESALs. However, with minimum grading on the top surface, the road surface showed no signs of any failure. For both construction phases, the design allowed less than 10% of the load transferred into the subgrade.

Visual observations upon completion of construction and a year later showed no mentionable failures (**Figure 10**). That is expected because of the confinement provided by the three-dimensional pocket geometry. Thus, it can be said that the design approach and construction method with maintenance was successfully implemented throughout the project.

With the elimination of subgrade removal and subgrade preparation, using high strength geocell reinforcement, the construction schedule and cost improved significantly. With fill height reduction ranging from 22% (for a single layer at the beginning of the road) to 65% (at the deep organic areas) using geocell as compared to an equivalent conventional design, issues like limited right of way, a safe clearance below power lines were successfully mitigated. Thus, lesser material to haul and lesser hours of construction. Considering an approximate cost of compacted gravel at $26/ Metric Ton, the current geocell-reinforced design resulted in minimum savings on the gravel of around 13,500 Metric Ton. Roughly 430 fewer trucks hauling gravel and an additional 7000 fewer loads of hauling out subgrade material (considering minimum 600mm peat thickness and 30 Metric Ton per truckload). At the turnarounds, where the Right of Way was further limited, narrowing down the top drive surface was not required because 1H:1V side slopes could be achieved using geocell embankment retaining structure design.

Figure 5: Stapling geocell on non-woven geotextile (above the existing ground)

Figure 6: Existing water level and filing bottom layer of reinforced structure

Figure 7: Stretched bottom of Type C geocell and local dip at culvert location

Figure 8: Top layer reinforcement getting built

Figure 9: Aerial view of a portion of road under construction


Figure 10: Road surface a year later

Conclusion

The current design and construction techniques expressed through the Blainville project, not only show a combined effort of the engineering and construction team to overcome a challenging performance-constructability situation but also reduced environmental footprint by a significant amount. Saving subgrade removal and reducing the amount of material that needs to be imported into the project site are significant savings in terms of cost, schedule, and environment. High-strength polymeric geocell owing to its high material strength has the unique advantage of adding confinement and heavy load-bearing properties into the design. Thus, extending a temporary design into a permanent long-lasting structure with minimum adjustments. This staged construction approach with soil reinforcement can be an added layer of insurance when the critical path of construction faces challenges.

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