High Strength Polymeric Geocell-Reinforced Railway Line Repair in Degraded Permafrost Condition

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ABSTRACT

Permafrost degradation by human interventions and climate change has been a serious concern for infrastructure development in the pristine physiographic setting of Northern Canada. Several First Nation settlements spread over that region need permanent year-round access for uninterrupted supply of basic need items. The railway line built a century ago leading to Churchill in Manitoba crosses many stretches of permafrost. The flood in 2017 washed away sections of the railway line rendering the only on-land access to the town unusable. Repair was immediately needed to avoid airlifting the essential commodities for the residents, but it took two years to find an innovative way to do it. There was exposed permafrost at the washout sections, and as it was a linear project, access to the next location was possible only after repairing the damage preceding it. Limited access and construction material and harsh weather conditions were other obstacles. This paper discusses the rehabilitation work using high-strength novel polymeric alloy (NPA) geocell. The findings in this paper are supported by design basis and experience-based construction practice, photographs, and construction records. The two years of track operation has presented a promising technology for the future of transportation infrastructure in the permafrost region.

INTRODUCTION

Churchill is a port city located on Hudson Bay in Northern Manitoba at the mouth of Churchill River. The nearest road head is at the village of Gillam approximately 300km south. The history of the railway discussed in the paper dates back over a century. Hudson Bay Railway (HBR) was initiated in the early 1900s and completed in 1929 to serve as the only mode of land transport to Churchill. This single line railway track has served the northern port of Manitoba uninterrupted since then. It may have lived up to expectation but due to the lack of timely maintenance and upgrades it gets damaged putting extra burden on the maintenance budget and interruption in the services. The railway built on extremely soft ground crosses many stretches of permafrost. In recent years, permafrost deterioration caused by rising temperature and degradation caused by other forms of human intervention has impeded the smoothness of the rail ride and other serviceability features of this rail line. In the spring of 2017, the railway line was severely damaged by the flood in the streams crossing the rail line, some of the damage may have been further aggravated by the degrading permafrost. As the only mode of ground transport feeding the town was rendered unusable everything including the goods of daily need for the local population was air lifted causing further hardships to the remote town, where the daily mean temperature remains subzero for over 8 months in a year.

Even before this 2017 washout, in May 2016 a visit was arranged for the authors by the railway company with the track maintenance personnel to assess the impact of degrading permafrost on the railway track. Then some measures were also recommended to improve the track condition, especially geocell reinforcement to control the lateral spreading of ballast/sub-ballast material and to reduce the stress transferred to frozen subgrade. That time they were looking to improve the track condition to bring the train speed to 50km/hr throughout the entire length of the track up to Churchill. However, at this time, the intent was a quick and affordable solution to repair the damage caused by recent track washout and re-establish the access at the earliest possible time. Traditional ways of track repair had very high anticipated costs and a longer construction schedule due to the linear nature of the project. Strength requirement at the embankment substructure, erosion control and permafrost protection were other major issues that needed due attention. An innovative design was required to complete the job in 5 weeks duration and total cost was in the range of 20-25% of the over $100million as initially anticipated for the entire rehabilitation work.

For the railway embankment structure, authors had suggested the need for a robust structure to withstand the railway traffic while optimizing the construction costs and utilizing the available resources in that area. The general rule recommended by Pokharel et al. (2017) for other pavement structures applies to the railway tracks too. Hence, high strength Geocell reinforcement is an appropriate solution for the ballast or sub-ballast layer strengthening.

This paper discusses the design and the construction methodology applied using high-strength novel polymeric alloy (NPA) Geocell to complete the work in 5 weeks of Fall 2018 within the anticipated budget. The findings in this paper are supported by design basis and innovative construction practice, photographs, and construction reports. Attempts made to protect the permafrost under the rail line has also been explained. Based on over two years of operation of the railway line, this paper also recommends a viable method for the future of transportation infrastructure development in the permafrost region.

GEOCELLS ON RAILWAY APPLICATION

Geocells was originally developed by the US Army Corps of Engineers to increase the vehicular mobility over loose, sandy subgrade through confinement (Webster and Alford, 1978). Pokharel (2010) and Han et al. (2010) had identified three key mechanisms of geocell reinforcement as lateral and vertical confinement, wider stress distribution and the beam or slab effect. The higher stiffness of the geocell system reduces the stress applied to the subgrade due to bending stiffness of the mattress composite, similar to a slab (Pokharel et al., 2011). Giroud and Han (2016) clearly identified geosynthetics reinforcement to continue to contribute to the structural performance of pavement structures. On road pavement applications Norouzi et al. (2019) had discussed the state of the art of the pavement design method and emphasized the need for a robust structure that experiences repeated loading, recommending Geocell reinforcement as one of the reliable options. Railway embankments also undergo extensive cyclic loading and must be able to withstand the applied repeated load occurrences at the same time be economical to be sustainable in long term. The need for more robust embankment structure poses a huge challenge to the supply of granular material that are of the adequate quality and are affordable (Pokharel et al., 2017). Where a good quality material is not easily available, it requires a strong, high modulus and creep resistant geosynthetic reinforcing material at the substructure. Ability of geocells to use recycled, marginal or poorly graded granular material helps reduce the burden on environment and adds value to the design. In railway applications for the reinforcement of structural layers, Geocells can be used to reinforce the ballast or sub-ballast to improve the reinforced layer's modulus and reduce the stress transferred to the soft subgrades (Kief, 2016). NPA Geocell that was used in this project enables the use of inferior quality locally available granular material while improving the modulus ratio over the underlying surface by up to 7.6 times; the higher the strength and stiffness of the reinforcing geocell material the higher will be the improvement factor (Pokharel, 2010). This eliminates the need for hauling high quality granular material that is usually located far from the construction sites resulting in reduced CO_2 emission associated with the construction activities (Pokharel et al., 2016). This cost saving and environmental benefits of geocell reinforcement make them an attractive option from a sustainable development perspective.

Leshchinsky and Ling (2013) had found that the lateral spreading along the railroad substructure was greatly reduced with the ballast confinement with geocells. The prevention of lateral spreading is especially pronounced when the railway substructure overlies softer subgrades and weaker ballast material were used. The use of high strength Geocell confinement resists this spreading above the reinforcement through frictional resistance to the composite mattress and produces uniform stress distribution to the subgrade to a wider area significantly reducing magnitudes of stresses. Leshchinsky and Ling (2013) also reported that the confinement of the ballast using geocell was quite effective in reducing vertical deformations, especially when low-quality material was used. Palese et al. (2017) had conducted performance tests on Amtrak's Northeast corridor near Harve de Grace, MD, USA with NPA Geocell reinforcement in the track substructure. The material was selected due to its strength and creep resistance properties on the FRA (Federal Railway Administration) Class 7 track sees traffic from both highspeed trains (201km/hr) and higher speed regional trains (177km/hr). Palese et al. (2017) reported significant reduction in pressure at the ballast/subgrade interface on the order of 50% as well as a corresponding reduction in the rate of degradation on the order of a factor of 6+. Overall, the test based on the pressure data from load cells placed above the subbase directly beneath the rails and track geometry data had shown significant benefits associated with the installation of the NPA geocell material above and beyond that seen by more traditional rebuild and drainage improvement.

HBR TRACK REHABILITATION AND PERMAFROST CONSIDERATIONS

Designing Sustainable Infrastructure with limited engineering data is always a challenge and more so when it comes to where minimal interference to the environment is expected. Rehabilitation of HBR line had similar challenges as it passes through several stretches of permafrost. The rail line was damaged by flood that was triggered by melting snow and rain, that caused damages to the underlying permafrost as well. This, compounded with the harsh winter, shorter construction season and linear construction sequence, demanded a solution that could address all these issues and complete the work within reasonable time and budget. A design with NPA Geocell reinforcement for the railway embankment addressed issues like:

i) providing necessary structural strength for the railway traffic,
ii) protecting the underlying permafrost from further degradation,
iii) Controlling erosion at the embankment slopes against snow melt and creek flows,
iv) facilitating linear construction schedule to be completed within available time and budget significantly less than that estimated for conventional construction.

The pre-flood condition of the track in May 2016 and post flood condition in Spring of 2017 and 2018 are shown in Figures 1 through 3.

Figure 1. The condition of railway line in May 2016.

Figure 2. The railway line during the flood in 2017, aerial view. (Global News, 2017)

Figure 3. The condition of railway line after the flood event pictures from 2018.

Very little has been done in dealing with the infrastructure development in permafrost region. Innovative design, construction methods with minimal interference to the surroundings and the protection of the permafrost below the structure is important both for the stability of the structures and to control the degradation of the permafrost. Global warming and other human interventions have led to permafrost degradation as shown by deepening of the active layer, thinning permafrost, rising ground temperatures, expanding taliks and the disappearance of permafrost patches (Jin et al., 2007). Climate change could be the real cause of permafrost degradation but the excessive and unwarranted human intervention to the pristine environment are other important causes that need to be addressed immediately with due diligence. Surface melt due to warm temperature causes permafrost degradation and at the same time as the subsurface is frozen impermeable medium entire melt becomes surface flow causing floods resulting in damage to the infrastructure and environment. Any design work in this region therefore is needed to avoid creating further problems upstream and downstream location of the creek crossings as well.

Several techniques have been implemented in Tibet (Wu et al., 1998, Wang et al. 2009, and Qi et al., 2012) to construct sustainable transportation infrastructure in Tibetan permafrost region most of them focusing on protecting the permafrost from degradation. One of the major technologies that could protect the underlying permafrost under the railway track is having a cover of geocell mattress that reduces the stress transferred to the subgrade and keeps the cover intact to protect the permafrost. The HBR track in Manitoba was facing severe problems caused by the lateral spreading of the ballast and sub-ballast material. There was erosion of the embankment material too. All these needed a reliable confinement and erosion control mechanism that could only come through a high strength and highly creep resistant geocell under the heavy dynamic loading coming on from the train movement.

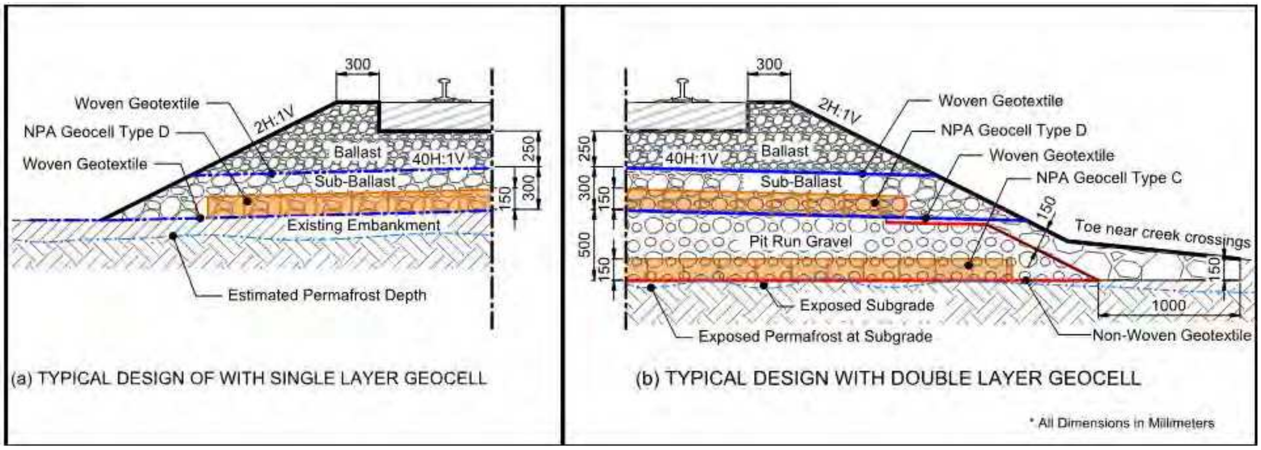
Twenty-six locations were identified along the 55km stretch of the track for immediate rehabilitation. The rehabilitation needed different levels of maintenance work and twelve of the major washout locations were designated to be repaired with Geocell reinforcement. All the twelve locations had degraded permafrost and needed culvert pipe installation as there were defined stream flow lines. The length of the washouts ranged from 70m to 210m. The repair work included, but was not limited to, reinforced embankment construction to support the structure from dynamic train loading, installing culverts, and erosion control at the slopes.

THE DESIGN CONCEPTS

The design of transportation infrastructure in the Tibetan permafrost area has brought some light on how they should be sustainably designed. Citing 35 years of experience, Wu et al. (1998) had indicated that the height of embankment over 0.8m maintains a steady state on the permafrost. Based on an overall analysis on the change in permafrost table under the embankment and after considering the fact that the permafrost in the area is degrading and the requirement of the deformation of the road surface is of high quality, it was suggested that 1.6m height of embankment for the gravel road as optimal. Wang et al. (2009) emphasized the need to control the width of embankment as the increase in width was found to increase the gross heat absorption that could lead to permafrost degradation by 1.0m width increase and can bring the permafrost table down by 0.11m. Qi et al. (2012) suggested that in the initial operation years the degree of thaw consolidation of permafrost increases. However, it tends to decrease after the increase in the characteristic drainage length and decrease in the effective consolidation time. But it would take some residual consolidation time to dissipate causing settlement of embankment as an ongoing process. It was important to have minimum cover at the same time avoiding the unnecessary fill to avoid residual consolidation.

The HBR track was not in a good shape especially as it has lost the smoothness of ride because of the undulation in the track. The reason of that rough ride was because of permafrost degradation causing vertical deformations at some locations and at many places the lateral spreading of ballast and the sub-ballast material ultimately unevenly causing the track to settle. The aim this time was to bring it to its running condition as it was before the damaging flood event. The major mode of failure was washout which has exposed the permafrost and the erosion control at almost all the stream crossings. The pictures in Figures 2 and 3 show the extent of devastation. The design for rehabilitating this railway line needed to address multiple issues that included structural strength, erosion control, protecting the already degraded permafrost from further degradation and most importantly, utilizing the washed-out material deposited at and around the washout locations. If the material was not enough it would have needed to bring virgin aggregate but still it would have been a low quality 75mm minus pit run gravel from Gillam (about 200km to 250km south). It should be noted here that the only access to the site was the railway line itself. Given the timeline of 6 weeks which seemed impossible for any other options thought of at the time because there were more than 26 damage locations along 150km stretch in series.

AREMA and CN railway design principles were checked to confirm the structural requirement of the geocell reinforced structure. The mechanism of load distribution via the slab effect to protect the weaker region within the permafrost was anticipated by transferring the load to a wider and competent area. The design had attempted to make only 5% of the applied stress to be transfered to the subgrade. The lateral and vertical confinement and friction between the geocell wall and infill material were the major factors helping create the stress reduction. Boussinesq's method of stress distribution and stress reduction due to the Geocell reinforcement at different layers were used to calculate the stress transferred to the underlying layers. The geocell reinforcement was designed to increase the modulus of the unreinforced gravel by 3.5 to 4 times. In the design the thickness of geocell plus 25mm was assumed as the reinforced thickness for stress transfer calculations as recommended by Pokharel (2010). The geocell-reinforced typical design cross sections are shown in Figure 4.



(a) TYPICAL DESIGN OF WITH SINGLE LAYER GEOCELL

(b) TYPICAL DESIGN WITH DOUBLE LAYER GEOCELL

* All Dimensions in Millimeters

Figure 4. Typical design sections, requiring single and double layers of Geocell

The original plan of the design was to reinforce the ballast section too with perforated NPA geocells to maintain required drainage and provide confinement and control on lateral spreading of the ballast material but, due to the construction constraints and available tamping equipment at the site option to reinforce the ballast was abandoned. The ballast regulators are the common equipment used in railway maintenance which use spikes of about 150mm to 200mm deep to shape and place ballast under the track ties. It turned out that reinforcing the ballast would have increased the ballast thickness by 150mm thus avoiding mechanical damage to the geocells during tamping operations. To save the costly ballast material this concept was abandoned. Only the sub-ballast layer was reinforced, and a layer of reinforcement required was decided by the fill height. To avoid further damage to the existing surface and protecting permafrost from further degradation nothing was removed from the existing subgrade and construction started right on top of it.

At some locations beaver dams were also found to block the stream flow and at many locations the culvert pipes were found to have settled rendering them useless. The new design raised the culvert beds to the existing stream bed level and provided a semirigid NPA geocell-reinforced mat at the culverts to avoid any such situation in the newly installed culverts. Some of the washout locations needed relocating the culvert location as the stream channel made its own course during the flooding and weaker easily erodible areas were washed away first. For erosion control at the toe of the embankment at and near the stream bank rip rap was provided.

MATERIALS USED

The geosynthetic materials used in this project was woven and non-woven geotextiles and high strength polymeric geocells. Salvaged washed away granular material was used wherever possible. Granular infill material with less than 12% was desired but the site engineer and contractor had to use the washed out granular material deposited at the downstream side to save the construction time and cost in bringing similar material which was available at a gravel deposit near Gillam (200km far). From visual observation and experience-based qualification of the 75mm minus pit run gravel designers approved the material fit for infill in the geocell. The granular fill chosen was the only option available at the site as it had been previously used at the sub-ballast layer, so it was approved. Riprap used was 150mm to 300mm size.

Two different types of NPA Geocell was used for reinforcement. NPA geocell was chosen for the design as it has higher tensile strength, modulus, and creep resistance than other available geocell material. The top layer of sub-ballast just below the ballast was reinforced with Type D geocell and layers below were reinforced with Type C geocell. Both geocells were perforated, 150mm high and had 330mm between seams. Type D, the higher grade geocell of the two was used immediately below the ballast and Type C was used at lower layer where lesser applied stress was expected. The properties Geocells used are given in Table 1.

Table 1. Properties of Geocell used in the design

Properties	Type C Geocell	Type D Geocell
Material	Polymeric nano composite alloy	
Wide-width strength at yield	19 kN/m	22 kN/m
Cell height of geocell	150mm	150mm
Distance between weld seams	330mm	330mm
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

Both the woven and non-woven geotextiles were used as separation, the non-woven geotextiles used had a grab tensile strength 911N and 1330N with 50% elongation on grab. The woven geotextile had a grab tensile strength of 890N. As the exposed degraded material at the subgrade surface was very soft that could compress further non-woven geotextile was used for the bottom layer.

CONSTRUCTION METHODS

The pictures and videos of damaged area were made available for the design. There was no survey of other engineering data available. The designers conducted aerial survey to assess the extent of damage to determine whether repair work at the washout locations will be good enough to get the rail traffic back. During this it was clear that this project would be a linear construction and ground access to next location would be available only after completing work at the preceding location. The author also reached the first damaged site on highrail and walked to next few location on foot to access the damage and check the suitability of the design plus construction methods. The construction crew also needed to be extra careful as there were protected wild animals including polar bears in the area. As the access was limited the work needed to be completed with limited number of construction equipment or whatever could be transported to the site by available means. Even daily commute for the construction crew from nearest available camp in Gilam on highrail or caboose was not easy. The travel time alone was in the order of 6 hours two way per day.

There was very limited space to work in those locations as the construction team was instructed not to touch/damage any area outside of the railway right of way. Transporting heavy compactor and heavy equipment except for whatever could be accommodated within the width of railway line was out of question. The geosynthetic installation procedures were followed as per the manufacturer's installation guide and experience-based compaction methodology was applied for compacting the granular fill at the sub-ballast and layers below. The lower layer of the gravel fill was compacted to the possible extent only so that the permafrost layer at the subgrade was not damaged. As there was no facility to do compaction testing, ruts developed by the 4-ton compactor were used as an indication of the required degree of compaction. At each location as the construction moved to the upper layers, a maximum rut of 12.5mm under the roller wheel was taken as equivalent to 95% compaction and was used for the entire construction. Twelve passes of the compactor were used as the minimum compaction criteria at the site at every point. The picture in Figures 5 through 8 show the construction sequence of the repair work in order from track cutting and removal, geocell installation, gravel compaction, and reinstalled rail track.

Geocell was stretched and installed at the site with guide stakes. The requirement of more than one layer of the Geocell was decided at the site wherever there was more than 750mm fill required between two layers. The railway track was cut and placed aside to allow the installation of geocell and construct the embankment. When the embankment was ready it was lifted back to the position and connected.

Figure 5. The track removal for the repair works

Figure 6. Geocell installation and compaction

Figure 7. Geocell for sub-ballast reinforcement and section ready for ballast fill

DISCUSSION

Sustainable construction can be achieved by appropriately choosing the technology and using innovative ideas. Reusing the washed-out material can save the environment, cost, and time. As pointed out in the preceding sections the design in this rehabilitation project did not only consider the strength requirement but it also gave due consideration to the environment. The design had to balance among protecting the permafrost, controlling the lateral spreading and embankment side erosion, or strengthening the sub-ballast structure to bear the railway traffic load. The use of available aggregate from the washed-out locations reduced about 50% of the virgin aggregate extraction and reduced the hauling and stock piling burdens. Geocell provided the required shear strength by confinement of poorly graded granular material. However, a traditional design approach would not have used the washed-out material and achieved the required structural strength. It saved the huge amount of virgin aggregate extraction and carbon emission that would have happened due hauling and mining virgin aggregate from far off location. This was made possible using geocell as reinforcement.

Figure 8. Completed rail re-installation at MP 427 and near switch at MP 414

This project also showed that knowledge and experience of the construction crew to work on the harsh climate and difficult situation plays a very important role especially those who have prior experience working in similar settings and materials. The project was completed in effective 33 working days at a cost about 20% of initially anticipated for conventional rehabilitation work. The saving was primarily because of the reduced construction time, use of the washout material, and working right on top of the existing subgrade without removing the degraded subgrade material. The construction equipment available was limited so a coordinated approach between the geocell installers, culvert pipe installers and earth work crew were of utmost importance to getting the job done in timely fashion.

Unless a ballast tamping method that does not damage the reinforcing geocell at the ballast layer is found out, the ballast layer cannot be reinforced so the loss of ballast material by lateral spreading in this railway line is expected. So, there is a need to find a different technique in the remote area to do the tamping that allows ballast reinforcement as well to control the loss of ballast material by lateral spreading.

All possible precautions were made to cause minimal or no damage to the unspoiled surrounding ground. Better pre planning on construction activities involving all the sub-contractors can improve overall productivity of a project. At times prime contractor and client's engineers understanding of geocell technology, led to some misunderstanding. However, as the work progressed, the work went smoothly.

The damage to this railway infrastructure was contributed in part by the melting permafrost, unmanaged cross drainage structures and erosion prone embankment slopes. The permafrost degradation along the railway track is evident by the uneven settlement along the railway length and subsidence of the existing culvert pipes. Lateral spreading of ballast was another problem. The railway line is in operation but about 150km stretch of the railway line North of Gillam is still in need of repair. Once those areas are also repaired the rail line can be run at 50km/hr as designed. There are many locations where the ballast and sub-ballast material are seen scattered and spreading laterally. A confinement technique such as high strength geocell reinforcement can control that and reduce the maintenance cost in long run.

This rehabilitation work was completed just when daytime temperature started falling to subzero in that region. The access was reestablished on the last day of October 2018 after the track was inspected and approved for operation by Transportation Safety Board of Canada. The Railway has been in operation for two full seasons after the rehabilitation without any major concerns. This proves the effectiveness of NPA geocell reinforced railway structure. Figure 9 shows the first train arrival in Churchill after the rehabilitation work.

Figure 9. First train arrival October 31st, 2018 in Churchill in almost two years

CONCLUSION

The NPA geocell-reinforced design of the railway embankment proved to be a successful solution for maintaining and strengthening the railway structure. In this project it allowed the railway that was un-operational for almost two years to operate in a short time after the rehabilitation work started. The time required for construction was enough to repair the washout location because about half of the granular infill material was taken from the washout location itself which was made possible by the geocell reinforcement. The geocell reinforcement helped in controlling lateral movement of sub-ballast that was a very poorly graded sandy pit run gravel and controlled the settlement and damage to the permafrost. It also controlled the erosion of the embankment slopes. The design also saved the construction time and budget. Based on over two years of operation of the railway line, this paper also recommends this design as a viable method for the future transportation infrastructure development in the permafrost region and other similar areas.

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