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ON THE ANALYSIS AND DESIGN OF REINFORCED RAILWAY EMBANKMENTS IN COLD CLIMATE: A REVIEW

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Abstract: Railway embankments built in cold regions are exposed to particularly harsh environmental conditions. Railroad support structures must be designed to maintain adequate track alignment and geometry and ensure optimal riding quality for passing trains. However, railway embankments constructed in cold regions face additional challenges associated with the climate's effect on the components of their substructure. Avoiding frost action is of paramount importance since the phenomena it triggers, namely frost heave and thaw softening, have particularly detrimental impacts on the structural integrity of embankments, leading to undesirable and potentially dangerous track riding conditions. This paper provides an overview of the different strategies used to analyze and design railway embankments in cold regions and describes how soil reinforcement techniques may be used to mitigate the effects of cold temperatures on the performance and stability of railroad support structures.

1 INTRODUCTION

With 41,757 kilometers of track operated (Railway Association of Canada 2019), Canada has a large railway network that transported over 88 million passengers and 341 million tonnes of freight in 2018 (Railway Association of Canada 2019). Due to their geographical location, many of the railway lines built on Canadian soil are exposed to seasonally cold climates. Such climatic conditions pose significant challenges to the stability and integrity of ballasted railway embankments that must be designed to maintain minimum track roughness and ensure optimal riding quality and safety. Issues associated with railway embankments in seasonally cold regions arise from the occurrence of frost action, which unfolds as a two-step process that consists of frost heave and thaw subsidence. This paper first describes the structure of conventional ballasted railway embankments and the role of their components in resisting frost action. The mechanisms by which frost action affects railway embankments are then reviewed. Finally, the design strategies used to mitigate frost action are examined with a particular focus on the incorporation of geosynthetics as reinforcement in the substructure of railway embankments.

2 CONVENTIONAL BALLASTED RAILWAY EMBANKMENTS

Ballasted railway embankments consist of a superstructure and a substructure (see Figure 1). The superstructure is composed of the tracks, the fastening system and the ties. Its role is to guide the train and transfer the train wheel loads to the underlying substructure. The substructure is a multi-layer system made of a ballast layer, a subballast layer and a subgrade. The ballast layer consists of clean, coarse, angular unbound aggregates and is tasked with reducing the stresses coming from the superstructure down to a level that can be withstood by the subballast. Besides acting as a bearing platform for the superstructure, the ballast layer also provides drainage, resiliency, void space for the storage of fouling material and frost protection (Selig and Waters 1994, Alemu 2011, Li, Sussmann and Chrismer 2016, Alabbasi and Hussein 2019). Frost protection is achieved by providing a layer of ballast material which, by virtue of being composed of coarse granular material is non-frost susceptible and thick enough to prevent the frost penetration depth from reaching a potentially frost susceptible subgrade. However, the ballast material degrades over time under the combined action of cyclic traffic loading, maintenance operations and weathering, leading to an increased fines content in the ballast layer (Selig and Waters 1994, Kwan 2006). The fines content in heavily fouled ballast may increase its frost susceptibility and render it prone to suffering from frost heave (Nurmikolu 2012).

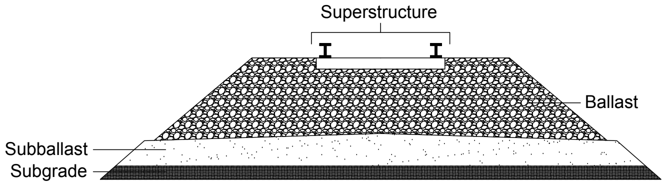

Figure 1: Typical Ballasted Railway Embankment

Below the ballast layer lies the subballast. It is made of non-frost susceptible broadly graded sand-gravel mixtures and acts as an extension of the ballast layer. It is used to reduce the required thickness of the expensive ballast material. Its core functions are to reduce the magnitude of the vertical stresses down to a safe level for the subgrade, separate the ballast and subgrade layers, allow for water drainage and extend the frost protection offered by the ballast layer (Selig and Waters 1994, Nurmikolu 2012). The frost protection offered by the subballast is akin to that of the ballast with the layer acting as an insulator preventing subfreezing temperatures from reaching a potentially frost susceptible subgrade (Selig and Waters 1994). Nurmikolu (2012) states than in Finland, the subballast is composed of two layers of non-frost susceptible material with one layer designed to reduce vertical stresses and act as a filter and separator while the second solely acts as an insulator for the underlying subgrade. In cold climates, the possibility of the subballast becoming frost susceptible due to fouling must be considered (Nurmikolu 2012).

The subgrade is the bottommost layer of an embankment's substructure. It is typically made of the naturally existing soil or fill and acts as the bearing platform that supports the entire embankment. It plays a crucial role in maintaining satisfactory track performance. Subgrade problems are often the root cause of track failure or excessive maintenance needs (Li and Selig 1995). In cold climates, the temperature is of concern when it causes freezing and thawing cycles in a frost susceptible subgrade that has access to water because it creates an environment where frost heave and thaw softening are likely to occur (Li and Selig 1995).

3 IMPACTS OF COLD WEATHER ON BALLASTED RAILWAY EMBANKMENTS

Ballasted railway embankments located in seasonally cold regions are subjected to frost action, i.e., a phenomenon caused by the combined action of soil freezing and thawing. Frost action is detrimental to the integrity and stability of railway embankments due to the frost heaving and thaw softening that occur during freezing and thawing respectively (Jackson and Dhir 1996, Nurmikolu and Silvast 2013, Barker and Howard 2013, Akagawa, Hori and Sugawara 2017). Freezing triggers a phase change in the water present in soil, leading to the formation of ice followed by the flow of water from unfrozen to frozen soil that accumulates in ice lenses. Ice lenses significantly increase the volume of the soil in which they form and cause it to heave. Correspondingly, when temperatures increase, the ice present in the soil starts to melt from the top down, increasing the amount of water in the soil. However, the melt water is not able to drain downward through frozen soil and contributes to increasing the pore water pressure, resulting in decreased soil strength and increased subsidence. Three conditions must be concurrently satisfied for frost action to take place: 1) freezing temperature and sufficient frost depth, 2) access to water, 3) frost susceptible soil (Nurmikolu and Silvast 2013, Barker and Howard 2013).

Frost heave and thaw subsidence are particularly detrimental to railway embankments given that they significantly disturb the track geometry and are the source of differential settlement. Increased track roughness results in poor riding conditions that may warrant the reduction of traffic speed on the affected portions of the train tracks or create a need for maintenance operations to restore the track geometry (Nurmikolu 2012, Stenstorm, et al. 2012, Nurmikolu and Silvast 2013).

3.1 Frost Heave Mechanism

Frost heave is characterized by the expansion of soil caused by the formation of ice lenses. It occurs in frost susceptible soils located within the frost penetration depth with an access to water (Sheng, et al. 2014, Zhang, et al. 2015). The frost susceptibility of a given soil is determined by its capillary rise, permeability and fines content, with soils having more than 10% passing No. 200 sieve assumed to be frost-susceptible (Barker and Howard 2013). When a frost susceptible soil with access to water freezes, part of the water undergoes a phase change and solidifies. The remaining water then flows from the unfrozen part of the soil to the frozen one through capillary rise, accumulating around the existing ice and leading to the formation of ice lenses (Le Borgne, et al. 2019). The formation of ice lenses significantly increases the soil volume through the combined action of water accumulation at the freezing front and the expansion of water as it solidifies (Sheng, et al. 2014, Wang, et al. 2015, Zhang, et al. 2015, Akagawa, Hori and Sugawara 2017).

In a railway embankment, frost heave may occur as a result of the subgrade being frost susceptible, the ballast material being highly fouled and therefore prone to developing heave-causing ice, and issues with the subballast material such as the subballast aggregate becoming too fouled or being too thin to prevent the frost penetration depth from reaching a frost susceptible subgrade (Nurmikolu and Kolisoja 2005, Nurmikolu 2012, Nurmikolu and Silvast 2013, Zhang, et al. 2015, Akagawa, Hori and Sugawara 2017).

Particular attention must be paid to the cyclic train loading applied on railway embankments. This dynamic load generates excess pore water pressure in the foundation soil of railway embankments that can lead to the upward flow of water and fine, also known as pumping, from the subgrade to the ballast. Sheng et al. (2014) defined pumping-enhanced heave as frost heave driven by the excess pore water pressure generated by cyclic train loads that becomes trapped below the frozen soil during the freezing period. The excess pore water being unable to dissipate then feeds the existing ice lenses and contributes to the existing heave (Sheng, et al. 2014). Using numerical modeling, Sheng et al. (2014) demonstrated that while the rate of frost heave increase stabilizes over time when there is no excess pore pressure, the rate of heave increase remains constant when excess pore pressure caused by dynamic train loads is generated, thereby indicating that pumping-enhanced frost heave occurs all winter long due to the frequent passage of trains on the tracks.

Frost heaving is a major contributor to the frost deterioration of ballasted railway embankments. The formation of ice lenses is not uniform in the substructure and leads to differential heave, thereby increasing track roughness (Lai, Zhang and Yu 2012). Frost heave is also responsible for the thaw subsidence and softening that occur during warmer seasons when the ice lenses that formed during the cold season start to melt.

3.2 Thaw Subsidence and Softening

During the warmer months of the year, when temperatures cease to be subfreezing, the ice lenses that formed during the colder months start melting from the top downwards (Jackson and Dhir 1996). While the ice thaws, the water escapes through the space initially occupied by the ice, leaving behind a weakened soil with a high void ratio (Graham and Au 1995, Jackson and Dhir 1996, Barker and Howard 2013). As thawing takes place, the soil can be divided into three zones, i.e., the thawed zone, the thawing zone, and the frozen zone (Zhdanova, et al. 2020). Given that thawing occurs from the top downwards, the melt water cannot initially drain because the soil below remains in a frozen state, resulting in an increased water content. This increased water content reduces the soil's strength and bearing capacity (Li and Selig 1995, Krzewinski, et al. 2006, Zhdanova, et al. 2020). This weakening of the soil creates conditions where railway embankments can easily get damaged by train traffic loads that generate additional pore pressure in the supporting soil, further weakening the soil and increasing settlement.

4 MITIGATING FROST-INDUCED DAMAGE

The frost heave and thaw softening of railway embankment materials caused by freezing and thawing cycles considerably increase settlement and create dangerous train riding conditions. Different approaches to tackle frost-induced damage have been described in the literature and involve either the insulation of frost susceptible material to prevent it from freezing, or the incorporation of reinforcement in the embankment structure to cope with the effects of freezing and thawing or a combination of the two approaches.

Based on an extensive survey of the railway network in Finland, Nurmikolu and Kolisoja (2005), Nurmikolu (2012) and Nurmikolu and Silvast (2013) emphasized on the importance of preventing frost susceptible material from freezing. To do so, attention must be paid to ensure the ballast and subballast material are not heavily fouled to avoid the presence of frost susceptible material in these two layers. The ballast and subballast layers must also have sufficient thickness to act as an insulating system for the underlying subgrade. Additionally, the subballast must be designed to act as a filter and separator to prevent the migration of frost susceptible materials within the embankment.

Geosynthetic reinforcements have been introduced in railway embankments built in cold regions to mitigate the effects of freezing and thawing. Various geosynthetics were used on the Qinghai-Tibet Railway to reduce the detrimental effects of cold weather on railway embankments. Geogrids were used as subgrade reinforcement to reduce settlement and increase bearing capacity, while seepage-proof geomembranes, insulation materials, geocells and geotextiles were used to prevent water infiltration and insulate the subgrade (Ge, et al. 2008). The geogrids successfully reduced differential settlement, improved stability and led to a more uniform embankment deformation compared to unreinforced sections (Ge, et al. 2008). Geogrids have more generally been used in ballast railway embankments wherever excessive settlement and lateral spreading are identified as issues. As such, geogrids can be used to mitigate the loss of bearing capacity and subsequent increased settlement experienced during spring thaw as the ice water melts and softens the subgrade (Petriaev, et al. 2020). Following the introduction of geogrids in embankments on the Qinghai-Tibet Railway, the use of geotextiles in combination with a crushed rock layer to prevent frost damage was investigated (Lai, Zhang and Yu 2012). It was reported that the assortment of geosynthetics and crushed rock successfully reduced the depth of frost penetration, prevented moisture migration and frost heave and resulted in smaller settlements (Lai, Zhang and Yu 2012).

5 GEOSYNTHETIC REINFORCEMENT

Railway embankments located in seasonally cold regions are exposed to freezing and thawing cycles and experience significant weather-induced deformations that have a detrimental impact on track roughness. Additionally, the degradation of the ballast and subballast layers must be avoided such that they do not become frost susceptible and further contribute to frost heave and thaw subsidence. The cold weather-induced deformations and degradation of the unbound aggregate layers can be mitigated through the incorporation of geosynthetic reinforcement materials in railway embankments (Han and Jiang 2013, Bonthron and Jonsson 2017). The uses and functions of geogrids, geotextiles and geogrid composites are discussed in the following subsections and summarized in Table 1.

Table 1: Functions of Geogrids, Geotextiles and Geogrid Composites

	Geogrid	Geotextile	Geogrid Composite
Reinforcement	✓		✓
Separation		✓	✓
Filtration		✓	✓

5.1 Geogrids

Geogrids are geosynthetic materials composed of large openings called apertures bordered by longitudinal and transverse ribs that are used as reinforcement materials in railway tracks (Koerner 2005, Kwan 2006, Das 2016). As shown in Figure 2, geogrids may typically be placed within the ballast layer, at the interface between the ballast layer or at the interface between the subballast and subgrade (Raymond and Ismail 2003, Das 2016, Hussaini and Sweta 2020). The reinforcing action of geogrids hinges of their ability to develop a strong mechanical interlocking with the soil they are placed in (Kwan 2006). A geogrid's apertures allow for the surrounding aggregate or soil to strike through the plane of the geogrid, thereby reinforcing the soil or unbound aggregate layer by confining it laterally, increasing its stiffness and modulus and reducing the magnitude of stresses transferred to underlying strata (Gobel, Weisemann and Kirschner 1994, Indraratna, Hussaini and Vinod 2013, Hussaini and Sweta 2020, Gedela and Karpurapu 2021). By providing additional lateral confining to the ballast material, geogrids reduce the lateral spreading and vertical settlement that would normally occur in the ballast layer, reduce breakage of the ballast aggregate and diminishes the magnitude of the vertical stresses transferred to the subgrade (Indraratna, Hussaini and Vinod 2013).

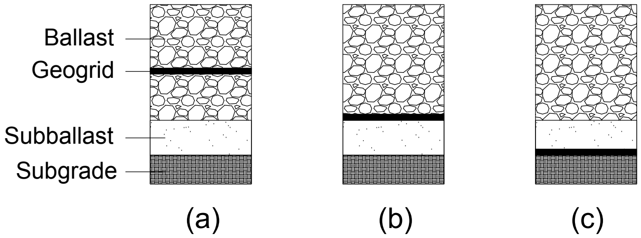

Figure 2: Geogrid Placed: (a) In the Ballast, (b) Between the Ballast/Subballast, (c) Between the Subballast/Subgrade

In the context of railway embankments located in cold regions, geogrids can help reduce the rate of degradation of ballast material under regular service loads and prevent the increase in the content of fine particles in the voids between the ballast material that could render the layer susceptible to frost heave (Raymond 1986). Geogrids may also lessen the magnitude of the deformations experienced by the embankment as a result of freeze/thaw cycles (Ge, et al. 2008, Lai, Zhang and Yu 2012). The depth of placement and the aperture size of a geogrid have a significant impact on its ability to perform its functions. These two parameters are discussed in the following subsections.

5.1.1 Depth of Placement

Various recommendations exist on the desirable depth of placement of geogrid reinforcement in the ballast layer of a railway embankment. Bathurst and Raymond (1986) and Raymond and Ismail (2003) indicated that geogrids placed between 50mm to 100mm below the bottom of the ties are the most effective at reducing settlement but that for practical reasons, a depth of placement of 200mm below the depth of the ties is appropriate. The depth of reinforcement placement to tie width ratio (D_r/B) was defined to characterize the depth of placement of geogrids in the ballast layer and acceptable values for the ratio were given as $0.2<D_r/B<0.4$ (Bathurst and Raymond 1987). Indraratna et al. (2013) indicated that the effects of a geogrid are maximum in its immediate vicinity and quickly decrease with increasing vertical distance from the geogrid and concluded that there exists a threshold distance beyond which a geogrid loses its ability to restrain the lateral deflection of the ballast. The optimum depth of geogrid placement was found to be 130mm above the subballast, but the recommended geogrid placement depth was set to 65mm above the subballast due to practical considerations (Indraratna, Hussaini and Vinod 2013). Similar findings were reported by Hussaini et al. (2016) who determined that the geogrid placement depth that resulted in the maximum decrease in ballast particle damage was 130mm above the subgrade but that the recommended placement depth was 65mm due to practical considerations (Hussaini, Indraratna and Vinod 2016). Additionally, Gedela and Karpurapu (2021) reported that geogrids placed 125mm below the ties were most effective at reducing vertical settlement.

5.1.2 Aperture Size

The reinforcing mechanism of a geogrid relies on the strong mechanical interlock between the geogrid and the soil that surrounds it. The effectiveness of the interlock is itself a function of the relative size of the geogrid apertures with respect to the average particle size of the surrounding soil. An extensive study conducted at the University of Nottingham comprising of a numerical modeling campaign (McDowell, et al. 2006) and laboratory experiments (Brown, Kwan and Thom 2007)on the geogrid reinforcement of railway ballast that an optimum ratio of aperture size to ballast particle diameter of 1.4 was needed to achieve maximum resistance, mobilize the greatest interlock and obtain the smallest displacement in the ballast layer when it is subjected to loads (McDowell, et al. 2006). Laboratory experiments echoed the results of the numerical study, showing that for aggregates with a nominal size of 50mm, a geogrid with an aperture size of 65mm were very effective at reducing settlement while a geogrid with an aperture size of 38mm yielded no improvements compared to the unreinforced case due to a lack of interlock with the surrounding aggregate (Brown, Kwan and Thom 2007). The ratio of the geogrid aperture size (A) to average particle diameter (D_{50}) was related to the effectiveness of the mechanical interlock between the geogrid and the surrounding particles by Indraratna et al. (2012). The ratio A/D_{50} was divided into three zones: the feeble interlock zone where $A/D_{50}<0.95$, the optimum interlock zone where $0.95<A/D_{50}<1.20$, and the diminishing interlock zone where $A/D_{50}>1.20$ (Indraratna, Hussaini and Vinod 2012). The relevance of these categories was validated by Indraratna et al. (2013) who demonstrated that a geogrid’s ability to reduce the lateral spread of ballast increases when A/D_{50} increases from 0.60 to 1.20, but that a geogrid became less effective at reducing lateral spread when A/D_{50} exceeds 1.20. Similar findings were reported by Hussaini and Sweta (2020) who showed that a geogrid is increasingly successful at preventing ballast material from spreading as its A/D_{50} ratio increases from 0.63 to 0.93 and described the existence of a threshold value for the A/D_{50} ratio beyond which a geogrid became unable to restrain ballast lateral displacement due to the free movement of ballast particles in its aperture. Gedela and Karpurapu (2021) described direct shear and pull-out tests on geogrid-reinforced aggregates which indicated that the aperture size played a central role in a geogrid’s ability to reinforce soil and that the range of aperture sizes to obtain an optimal reinforcing action is $0.9D_{50}$ to $2.5D_{50}$.

5.2 Geotextiles

Geotextiles are a type of geosynthetics that are made of non-woven, woven or knitted polymeric textile. In railroad applications, geotextiles are usually used to perform three functions: separation, filtration and reinforcement, with the third function being a consequence of the first two (Raymond 1999, Indraratna and Nimbalkar 2013, Gedela and Karpurapu, 2021). Geotextiles are typically installed at the interface between the ballast and subballast layers, within the subballast or between the subballast and the subgrade to act as a barrier against the migration of particles from one layer to another, improve drainage conditions and provide some degree of reinforcement. (Raymond 1999). A geotextile acts as a separator when placed over a layer of fine and soft materials (e.g., subgrade) and under a layer of coarser materials (e.g., subballast) by preventing the upward migration of fine particles into the voids of the coarse materials (R.

Koerner 2016). Filtration is a necessary complement of a geotextile's separation ability. In the presence of water in the track structure and under repeated loading generated by the passage of trains, high pore pressures are induced in the track roadbed and may force fine particles from the subgrade and sub-ballast to migrate upwards into the ballast layer (Raymond, 1999). A geotextile placed at the bottom of the ballast layer prevents the mixing of fines with the ballast materials by retaining the fine particles while allowing water to pass through it (Raymond, 1999).

In seasonally cold regions, a geotextile's ability to improve the internal drainage conditions of the track support structure and to separate its various components are of particular interest. During the spring, thaw occurs from top to bottom in a frozen track embankment, with the bottom frozen soil preventing the downward dissipation of the melt water which then becomes trapped in the embankment, creating conditions where high pore water pressure may arise under train traffic loading (Raymond 1999). A geotextile's filtration ability may help drain the melt water away from the track support structure and into the side ditches. A geotextile may also act as a barrier to prevent capillary rise and reduce frost heave during the winter (Han and Jiang 2013). Additionally, a geotextile may mitigate the extent of ballast fouling by separating it from the underlying subgrade and/or subballast which contain smaller particles, thereby preventing potentially frost-susceptible materials from reaching the ballast layer (Raymond 1986, Christopher 2016).

5.3 Geogrid Composites

The reinforcing property of geogrids can be combined with the separation and filtration properties of geotextiles with a geosynthetic product called a geogrid composite. A geogrid composite consists of a geogrid bonded to a geotextile that acts as a separator, filter and reinforcement. This type of geosynthetic has been used in the construction of railway embankments in Canada (Bhat and Thomas 2015, Bhat and Thomas 2017) over weak saturated subgrades. The use of geogrid composites rolled over the subgrade improved drainage conditions and allowed excess pore pressures generated by train traffic to be dissipated while also separating the subgrade soil from the rest of the embankment and reinforcing the entire track support structure (Bhat and Thomas 2015).

6 CONCLUSION

Seasonally cold regions akin to those found in Canada impose harsh environmental conditions on railway embankments. The subfreezing temperatures that characterize the coldest months of the year can adversely impact the geometry of railway tracks through frost heave. Frost heave occurs when frost susceptible materials found in the subgrade and fouled subballast/ballast layers of a railway embankment are exposed to subfreezing temperatures and have access to water, leading to the formation of ice lenses that significantly increase the volume of the soil and results in the heaving of the embankment's surface. Frost heaving is following by thaw softening and subsidence that take place during warmer months. As the ice lenses start to melt from the top down, melt water becomes trapped in the embankment substructure, being unable to drain downward through the frozen soil, and causes a reduction in the soil's strength, leaving it vulnerable to damages caused by ongoing train traffic. Several approaches are used to either prevent frost action from occurring in a railway embankment through the use of sufficiently thick, non-frost susceptible ballast and subballast layers, or to reduce the deformations caused by frost action through the incorporation of geosynthetic reinforcement in the embankment substructure. Commonly used geosynthetic reinforcements include geogrids, geotextiles and geogrid composites. Geogrids are typically placed within or at the bottom of the ballast layer and reinforce it by developing a strong mechanical interlock with the ballast aggregates, thereby reducing ballast breakage, deformation and the magnitude of stresses transferred to underlying layers. Geogrids help reduce the frost action-induced deformations and prevent the ballast from becoming frost susceptible by reducing its fouling. Geotextiles are primarily used for their separation and filtration functions. They inhibit the upward migration of frost susceptible fine soil particles coming from the subgrade into the subballast and ballast layers and drain water away from the embankment's substructure. Finally, geogrid composites combine the properties of both geogrids and geotextiles and effectively reinforce an embankment while providing filtration and separation.

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