Field Validation of Polyurethane Technology in Remediating Rail Substructure and Enhancing Rail Freight Capacity

CFIRE 09-14
December 2016

National Center for Freight & Infrastructure Research & Education
Department of Civil and Environmental Engineering
College of Engineering
University of Wisconsin–Madison

Authors: Abdullah H. Alsabhan, Benjamin J. Warren, Dante Fratta, James M. Tinjum and Tuncer B. Edil
University of Wisconsin–Madison

Principal Investigator: Tuncer B. Edil, Ph.D., P.E., Dist. M. ASCE
Professor Emeritus
Department of Civil and Environmental Engineering
University of Wisconsin–Madison

This page intentionally left blank

Technical Report Documentation

1. Report No. CFIRE 09-14	2. Government Accession No.	3. Recipient's Catalog No. **CFDA 20.701**

4. Title and Subtitle Field Validation of Polyurethane Technology in Remediating Rail Substructure and Enhancing Rail Freight Capacity	5. Report Date **October 2016** 6. Performing Organization Code
7. Author/s	8. Performing Organization Report No. **CFIRE 09-14**
9. Performing Organization Name and Address National Center for Freight and Infrastructure Research and Education (CFIRE) University of Wisconsin-Madison 1415 Engineering Drive, 2205 EH Madison, WI 53706	10. Work Unit No. (TRAIS) 11. Contract or Grant No. T002688
12. Sponsoring Organization Name and Address	13. Type of Report and Period Covered **Final Report 9/1/2014–6/1/2016** 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Railways are an important component of a multi-modal freight transport network. The structural integrity of rail substructure and problematic railway elements can be compromised leading to track instability and ultimately, train derailments. Because of this serious consequence, costly maintenance activities are routinely performed by railroads. An application of polyurethane void filling and particle bonding technology has been shown in the laboratory to mitigate impacts of ballast fouling and rail substructure deterioration and to enhance rail freight capacity. This study demonstrates its applicability and effectiveness in remediating rail substructure in the field. This study showed that polyurethane injection technology reduced settlements and increased track modulus significantly (i.e., at least one-fold). A life cycle cost analysis was conducted considering a period of over a ten-years. Polyurethane injection technology appears to be a superior improvement methodology to traditional maintenance resulting in a cost savings from $1000 - $20,000 depending on discount rate. In the life-cycle analysis, polyurethane injection technology results in reduced use of water and CO2 emissions i.e., 90% and 10% of traditional maintenance, respectively; however, it uses 25% more energy.

17. Keywords air voids, axle loads, ballast (railroads), freight trains, maintenance of way, multimodal transportation, railroad tracks, substructures	18. Distribution Statement **No restrictions. This report is available through the Transportation Research Information Services of the National Transportation Library.**

19. Security Classification (of this report) **Unclassified**	20. Security Classification (of this page) **Unclassified**	21. No. of Pages 63	22. Price **-0-**

Form DOT F 1700.7 (8-72) Reproduction of form and completed page is authorized.

DISCLAIMER

This research was funded by the National Center for Freight and Infrastructure Research and Education. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the US Department of Transportation, University Transportation Centers Program, in the interest of information exchange. The US Government assumes no liability for the contents or use thereof. The contents do not necessarily reflect the official views of the National Center for Freight and Infrastructure Research and Education, the University of Wisconsin–Madison, or the US DOT's RITA at the time of publication.

The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers names appear in this report only because they are considered essential to the object of the document.

Executive Summary

This project documents the results of a field study on the use of expanding rigid polyurethane (PUR) foam to remediate substructure deficiencies in a railroad track. The field site in Madison, Wisconsin consists of railway sidings owned by Wisconsin and Southern Railroad (WSOR). These sidings are no longer in service and the section used was constructed on a 3 m (10 ft) high embankment with a length of 80 m (263 ft). The railways on the embankment are of standard rail gauge (1.44 m or 4.7 ft), and 0.2 m shoulders. The siding area consists of three railway sidings. The ballast was of poor condition; multiple ballast types and fines were present.

To clarify what the contributing underlying problems are at the track field site, geotechnical and geophysical investigations were conducted that included ground penetrating radar, electrical resistivity tomography, dynamic cone penetrometer logging, elevation survey, and test pit and auger sampling. In addition, track modulus was measured to quantify the structural integrity of railway track before and PUR injection. The data from these different tests collectively indicated that railway siding 2 is considered to be in poor conditions. Furthermore, the mid-section of the middle railway siding, 50 m (165 ft) east of the frog, is seen to be softer than the section near the frog, 25 m (82 ft) east of the frog.

The investigation assisted in the design of two types of polyurethane injection: one to strengthen the railway substructure at depth 1.2 m (4 ft) and one to strengthen and stiffen soft subsurface material at depth 1.8 m (6 ft). URETEK ICR's background in polyurethane injection for infrastructure projects, including rail crossings, their expertise was necessary in designing a functional and economical injection package. The injection was proposed as a combination of subballast layer strengthening and URETEK Deep Injection (UDI) to strengthen and stiffen the subgrade. Due to imposed restrictions of the railroad, PUR could not be placed within 30 cm of the bottom of the tie. PUR injections took place in the soft area of railway siding 2 in which it start at 42.5 m (140 ft) east of the frog and extend about 14 m (46 ft) which comply with the influence zone of the 6-axle locomotive on the railway substructure.

PUR injections showed no significant effect on the geometry of the railway with or without loading. PUR injected areas showed a higher track modulus with average track rating, i.e., 15 or more based on u-values; whereas, non-injected areas exhibit a poor track rating, i.e., mostly less than 10. Furthermore, the control point P.4 shows a 90% increase in track modulus (increase from 8 MPa to15.2 MPa) after PUR injection.

The post-injection track substructure geophysical data were obtained. The ERT results showed the areas of the PUR injection as zone of increased electrical resistivity. In addition, GPR survey results showed some indication of the injection.

A life cycle cost analysis was conducted with inputs from URETEK ICR and Wisconsin and Southern Railroad considering a ten-year period. Over a 10-year period, PUR injection appears to be a superior improvement methodology to traditional maintenance resulting in cost savings from $1000 - $20,000 depending on discount rate. A life cycle assessment indicated that PUR injection results in reduction of water use and CO2 emissions, 82%, and 10% respectively, compared to conventional maintenance methods, however, it consumes an estimated 25% more energy compared to conventional maintenance methods.

Table of Contents

List of Figures

List of Tables

1. Introduction

Railways are an important component of multimodal freight transport networks that present a great potential for expansion. Ballast is a crucial material for structural support of rail tracks and trains and provides fast drainage during precipitation. The structural integrity of seriously fouled ballast (i.e., containing fine particles) and problematic railway elements (i.e., bolted rail joints, intersections, bridge approaches, track sections on soft subgrade, etc.) can be compromised leading to track instability and ultimately, train derailments. Because of this serious consequence, costly maintenance activities, such as ballast maintenance and track reconstruction, are routinely performed on railroads, particularly on tracks serving heavy axle loads. Despite numerous advancements in maintenance technology within the rail industry, railroads annually invest billions of dollars in maintenance activities.

This research involves a novel application of polyurethane (PUR) void filling and particle bonding technology in rail substructure management. Rigid-polyurethane foam (RPF) injection is a mature technology with numerous applications in natural soils; however, it has not been applied in ballast systems as envisioned herein. Prior to developing this novel concept of creating ballast reinforcement and protective barrier, experts of PUR void filling technology and technical experts of the rail industry were consulted to identify if there are any operational conflicts during construction, operation, and maintenance that may reduce or prevent the applicability of the envisioned application of this technology. Based on previous C-FIRE research, the feasibility of the technology has been demonstrated in the laboratory. Clean ballast, fouled ballast, and recycled ballast specimens were injected with PUR, and PUR materials appropriate for this application and injection methods were refined. It was found that RPF injections were still feasible for these materials. The mechanical properties of polyurethane-stabilized (PS) clean, fouled, and recycled ballast specimens were far greater than untreated clean, recycled, and fouled ballast (Keene 2012). In terms of elastic modulus, interestingly enough, PS-fouled ballast had a higher modulus than PS-clean ballast implying low potential for reduction of rail resiliency. Specimens subjected to freeze-thaw cycling exhibited final plastic strain and strain rates similar to that of duplicate specimens not subjected to freeze-thaw cycling (Warren 2015). From six samples subjected to 20 freeze-thaw cycles, there was no significant difference from specimens that were kept at room temperature. The effect of confined water in the polyurethane stabilized fouled ballast matrix did not affect the mechanical behavior. Constrained modulus testing found that no detectable internal degradation had occurred, which complements the cyclic triaxial tests. Long-term water absorbance of PUR foam was investigated by Warren (2015). Samples were submerged for 120 days then tested in unconfined compression. Minimal changes (approximately 3%) were observed from unsoaked PUR samples. The results from freeze-thaw cycling and water absorbance indicate that PUR will remain stable in field conditions.

The focus of this research is to explore the performance of a rail substructure when injected with PUR in the field. The objective is to validate the feasibility and effectiveness of remediation of ballast/track degradation by strategically placing PUR in the stabilizing rail substructure, thus reducing maintenance life cycle costs and increasing load capacity.

1.1 Track Background

Transportation systems are designed to provide a safe, efficient, and durable transit route for cargos and passengers. Ballasted railway track can provide a cost effective means of delivering the necessary functions. Ballasted railway tracks, similar to many other infrastructure systems, consist of a layered structure. The layered structure improves the performance and dissipates stresses to an acceptable level for natural soil.

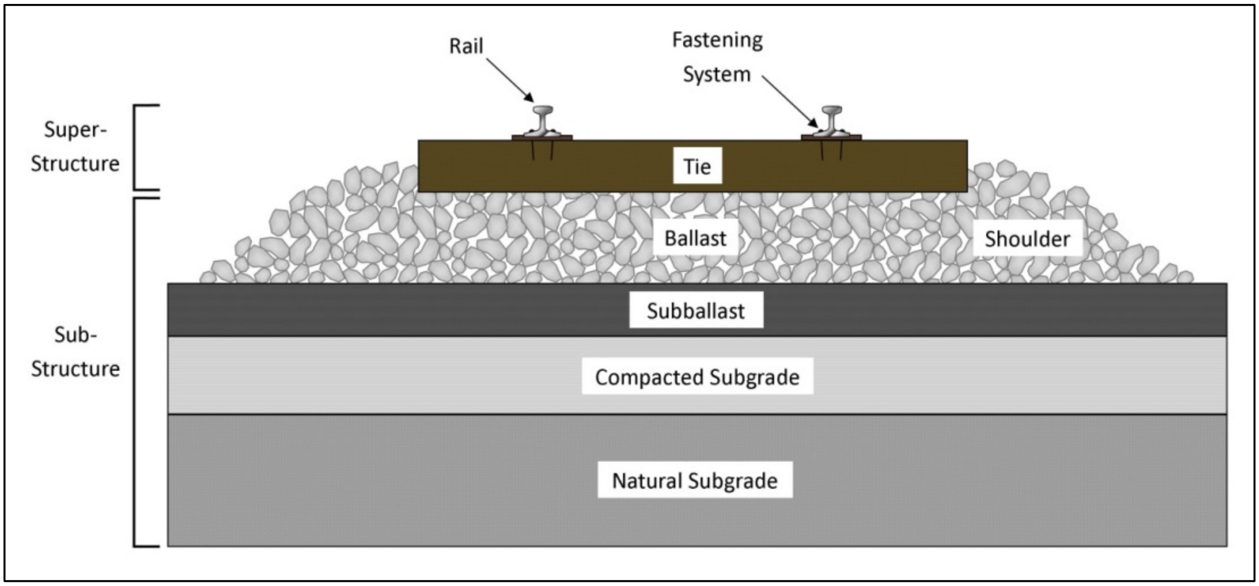


Figure 1.1: Railroad cross section

There are two distinct parts of a railway: the superstructure and the substructure, as shown in Figure 1.1. The superstructure consists of the rail, fastener, and tie. The substructure is composed of the ballast, subballast, and subgrade.

Superstructure

Rails

Rails provide the interface from the physical train to the railway track. Rails must be sufficiently strong (stiff) to handle the concentrated wheel loads from the train without much deflection (Selig and Waters 1994). The rail condition affects the function and longevity of the entire track structure. If there are defects in the rails such as cracks, impurities, poor welds, and jointed sections, these can cause stress rises that could increase stress and deformation. A properly functioning rail is integral to the durability of ballasted rail tracks.

Fasteners

Fasteners connect the rail to the tie. The fastener should resist vertical, lateral, longitudinal, and overturning movements of the rail (Selig and Waters 1994). Different fastening systems exist for both wood and concrete sleepers. Fasteners for wooden ties require a steel plate underneath the rail to dissipate the load on the tie. For concrete ties, a stiff rubber pad may be required to stop the degradation from repeated loads on a stiff surface, dampen vibrations, and insulate the rail.

Ties

Ties are the components of the track structure that are placed on top of the ballast layer perpendicular to the direction of the rail. The function of the tie is to receive the load from the bottom of the tie plate (or another fastening system) and distribute that load to the ballast structure (Indraratna et al. 2011). For this system to work effectively, each component must adequately handle the loads and stresses. Ties come in a variety of types and sizes, though the most common is the wood tie with dimensions of 2.59 m × 0.229 m × 0.178 m (9 ft × 9 in × 7 in) (L × W × H) (Selig and Waters 1994). Other types of ties include reinforced concrete, steel, recycled plastic, tropical hardwood, and composite ties (Indraratna et al. 2011). The target properties of an effective tie are long life, load-bearing capacity, and minimal defects. For majority of the freight industry and in most US climate regions, standard wood ties meet these requirements and are often the most cost effective (Webb et al. 2012).

Substructure

Ballast

Ballast is the top layer of the substructure consisting of a select crushed granular material (Selig and Waters 1994). The ballast should be composed of high quality rock, though this is often governed by location and economic considerations. No standards exist for ballast; however, the American Railway Engineering and Maintenance-of-Way Association (AREMA) offers suggestions for classifications of ballast. Regardless, ballast should perform many functions. The most important are

1. to resist vertical, lateral, and longitudinal forces applied to the sleepers through the track,
2. to provide some resiliency and energy absorption of traffic,
3. to provide immediate drainage of water, and
4. to reduce pressure in the tie bearing area to acceptable levels for the underlying layers (Selig and Waters 1994; Indraratna et al. 2011).

Subballast

The second layer in the substructure is the subballast. Typically a finer gradation than the ballast, the subballast performs three main tasks:

1. to reduce traffic stress at the bottom of the ballast layer to an acceptable level for the subgrade,
2. to extend the subgrade frost protection, and
3. to assist in draining water while preventing migration of ballast and/or subgrade into each other; the subballast acts as a filter between these two layers (Selig and Waters 1994; Hay 1981).

Subgrade

Subgrade refers to the natural soil of the area. When constructing sections of a track, the engineering properties of the subgrade must be known. Typically the top layer of the subgrade is compacted per specifications to increase the bearing capacity and shear strength. In areas where soft or weak soils are found, further design and remediation techniques may be applied to increase the soil strength to an acceptable level. As is true for the ballast and subballast, water drainage is a key factor when designing a track section. Drainage ditches, culverts, and vegetation management strategies need to be assessed, as any unwanted moisture retention can lead to track instability and major damage to track and train components (Hesse 2013).

Track structure can be modified by the use of geosynthetics to improve the performance of different aspects of the track.

Fouling

Selig and Waters (1994) defined fouling index (FI) as the sum of the percent mass of soil particles passing through a 4.75 mm (#4) sieve and a 0.075 mm (#200) sieve. Ballast exists in a wide range of fouling indices from clean (FI = 0) to heavily fouled (FI = 40).

$$\boldsymbol{FI = P4 + P200}$$

$$\begin{aligned}
&FI\ < 1\ - Clean\ Ballast \\
&1 \leq FI \leq 10 - Moderately\ Clean\ Ballast \\
&10 \leq FI \leq 20 - Moderately\ Fouled\ Ballast \\
&20 \leq FI \leq 40\ - Significantly\ Fouled\ Ballast \\
&FI \geq 40 - Highly\ Fouled
\end{aligned}$$

1.2 Track Maintenance Methods

Owing to static and cyclic loading on railroad tracks over time, permanent deformation occurs. Sections where this deformation occurs are deceptively small; however, they cause local stress raisers that result in a compounding effect and spreading of the deformation (Indraratna et al. 2011). To maintain operational speeds and ride quality, periodic maintenance must be conducted. Ballast is one of the few controllable variables in maintenance activities and is responsible for controlling the surface geometry (Indraratna et al. 2011). Considerable cost is incurred due to materials, labor, machine time, mobilization, contracting services, safety, permitting, and inspection and records when maintenance is conducted.

Typically, track/ballast maintenance activities consist of tamping, stone blowing, undercutting, and ballast addition. Ballast tamping involves a machine that clamps onto the rails, adjusts the tracks to the desired elevation/super elevation, and then uses vibratory probes to fill the created void spaces underneath. This is an effective method for adjusting the track geometry; however, vibratory squeezing has detrimental effects on the ballast. The ballast becomes loose in some areas (density change) and ballast particles are broken and rearranged (Indraratna et al. 2011). The ballast particles require readjustment after tamping to achieve the necessary interlock and resist further deformation.

Stone blowing is an automated technique that also lifts railway tracks to a desired elevation. Over time, voids form underneath the tie due to cyclic train loading. These voids are undesirable and cause decreased performance. Stone blowing is a pneumatic technique that lifts the rail track to a desired elevation, then injects ballast rocks into voids underneath the tie. This restores the geometry and decreases track deformation under cyclic loads (Indraratna et al. 2011).

Undercutting is a more aggressive approach to ballast maintenance. This technique is also used to remove and replace entire sections of fouled ballast with a new clean ballast. An undercutting removes ballast from underneath the track, removes the fines from the ballast, and returns the cleaned ballast underneath the track. Additional ballast is added, if necessary, and the track geometry is corrected possibly by tamping. The fines left over from sieving the ballast are either disposed of, or used to make new embankments or added to existing ones (Marsh 2015).

Additional types of maintenance or remedial techniques have been used to fix problematic sections of a track. The solutions include geosynthetics, stone columns, silicate grouts, lime slurry injections, and hot mix asphalt (HMA) layers (Indraratna 2011; Brill and Hussin 1992; Rose et al. 2000). Mixed reviews of the effectiveness of these techniques have been shown. In tangent tracks, geosynthetic usage as well as conventional soil grout injections have been effective (Indraratna 2011; Brill and Hussin 1992; Li and Davis 2005). At bridge approaches, the remedies intended to strengthen the subgrade may not be effective if they do not produce consistent track stiffness (Li and Davis 2005). Of the four sites investigated, most of the deformation at bridge approaches occurred from the ballast and subballast layers even with geogrid, cement stabilization, or HMA layers improving the stiffness (Li and Davis 2005).

The aforementioned maintenance techniques are costly and energy intensive. Track shutdowns and scheduling are required to conduct a maintenance event and install these remedial measures.

Interviews and Experience

Track design is often idealized and subpar material is used because there is no other choice. Information gathered through conversations with engineers and project managers working for railroads in Wisconsin and Illinois indicates that at times, standard track layer structure (ballast, subballast, and subgrade) is not attainable. Regional railroads have to invest more money in ties, bridges, and rails to keep operational speeds at a reasonable level. Ballast becomes a secondary issue and gains importance only during larger rehabilitation projects.

The initiative of returning abandoned railroad tracks back to service is a complex issue. Railroads in the past often did not include subballast and were frequently constructed on poor soils. This leads to a poorly draining track structure, which may have unacceptable tie conditions, poor rail, and multiple crossings that need to be replaced. When maintenance is required, undercutting is a common method to alleviate these problems. A common procedure to rehabilitate older tracks is as follows (Marsh and Schaalma 2015):

1. undercutting the ballast away from under the tie to gain access to the subgrade,
2. removing poor soils and/or placing a layer of geosynthetic/geomesh/filter fabric underneath (some tracks were not properly constructed on subballast),
3. re-establishing the ballast section, and
4. shoulder cutting these areas to allow previously trapped water to drain out of the ballast section.

1.3 Polyurethane (URETEK 486)

RPF is a closed-cell polymeric foam. The specific RPF used in this study was supplied by URETEK USA. URETEK USA provided 486STAR-4 BD, which is a two-component PUR resin system developed by Bayer Material Science in partnership with URETEK USA Inc.

There are two primary chemical components that are required prior to mixing and application of RPF. As defined in a technical data sheet from Bayer Material Science (2010), the liquid components are defined as “A” component and “B” component.

For synthesis of thermoset PUR-resin foams, the two components (polyester or polyether polyol and organic polyisocyanate) are proportionately mixed in the presence of a catalyst (Szycher 1999). The foam structure results from the formation of gas bubble during the PUR polymerization process known as *blowing*. Gas bubble formation is the result of introducing a *blowing agent* (Szycher 1999).

The cellular structure of the RPF is a closed-cell structure as defined by Szycher (1999). For closed-cell PURs, the percent of closed cells and open cells are determined per ASTM D6226, which was used in the technical data sheet produced by Bayer Material Science (2010). The 486STAR-4 BD possesses a closed-cell content of 90%. Further investigation and techniques are required for determining the closed-cell content of the RPF within the polyurethane stabilized ballast composite. Closed-cell content may provide further understanding of the overall RPF bonding properties and mechanical behavior. The higher the open-cell content (i.e., inverse of closed-cell content), the more the foam acts like semi-rigid (flexible) foam. In the case of rigid foam, where mechanical properties, such as high strength and stiffness are desired, high content closed-cell foam is ideal. However, the density of PUR is also important for the mechanical characteristics of the foam; as the density of the foam increases, the strength, hardness, and resistance to fatigue also increase (Randall and Lee 2002; Oertel and Abele 1985). Consequently, PUR may possess a density that would be sufficient in the case of rigid foam; however, high open-cell content would result in mechanical properties that are substandard for the intended design of rigid foam.

1.4 Polyurethane in Rails

Although PUR is a non-conventional maintenance approach, its use is increasing in rail infrastructure. PUR is attractive because of its rapid application and short curing time (Keene 2012). The advantage of this technology is that the geocomposite, which is the result of the combination of PUR and ballast; has a larger elastic regime than ballast, and increases the overall strength. This was proven beneficial in laboratory tests (Keene 2012; Woodward et al. 2014; Dolcek 2013; Dersch et al. 2010; Boler 2012).

In the study by Dersch et al. (2010) and Boler (2012), the material used for reinforcement is known as Elastrotrack®, which is a rigid-compact type of PUR used to coat the ballast particles. Using a direct-shear box test, the shear strength of the reinforced ballast was measured under varying confining stresses and PUR curing times (up to 14 days). In the study, the shear strength of the treated ballast specimen was 40–60% higher than uncoated clean ballast. After each of the direct shear test, a powdering test was conducted where the amount of breakage was measured by the percent of particles passing a 13 mm sieve; the treated ballast samples had 3–5% less breakage than untreated ballast. Therefore, Dersch et al. (2010) found that PUR treatment greatly increases the shear strength of ballast and reduces breakage of ballast particles under loading.

The other commercially available product is XiTrack™, which is a flexible PUR material that contacts the ballast and creates a network of ballast particles and PUR composites. Kennedy et al. (2009) and Woodward et al. (2014) led a study where a full-scale model test was assembled and tested to determine the deformational characteristics of the ballast layer with and without PUR reinforcement. The full-scale model consisted of a superstructure system of several rails and ties and a substructure layer with a subgrade and a ballast layer. In their investigation, the accumulation of plastic strain in their full-scale model with over 500,000 loading repetitions was measured. The tests were conducted where loading repetitions applied to the full-scale model simulate railway traffic loading conditions on the substructure. Kennedy et al. (2009) found that the settlement of the ballast layer in the model was 95–98% less for the treated substructure than for the untreated substructure. It was also shown that the track modulus, a stiffness coefficient, was also improved over an untreated ballast section (Woodward et al. 2014).

Other trials of XiTrack™ have been conducted in laboratory and field settings, specifically in the United Kingdom, where XiTrack™ has been applied at junctions, tunnels, and tangent tracks (Woodward et al. 2012, 2014; Kennedy et al. 2013). Field verification of laboratory findings was crucial for a railroad contractor (Balfour Beatty Inc.) to adopt the technology and reduce maintenance costs; XiTrack™ has led to a three-time increase in the speed of deployment of repairs. The PUR grip reinforcement helps keep the train and track clearance issues in tunnels to a minimum. By creating a robust geocomposite, the clearance issues associated with ballast fouling and soft subgrade soil in a tunnel can be remediated (Woodward et al. 2012). In the study by Kennedy et al. (2013), the XiTrack™ polymer was applied to a switch and crossing on the West Coast Main Line in the United Kingdom. The polymer application lasted for 10 years until scheduled track rebuilding was completed. During those 10 years, no maintenance was conducted. Previously, maintenance was conducted 3–4 times per year. This implies a massive reduction in maintenance cycles and cost for this XiTrack™ treated section of rail (Kennedy et al. 2013).

An important concern with placement of PUR within a railroad structure is maintenance. Conventional maintenance equipment, such as tampers and undercutters may have a problem with stiff materials. In the study by Kennedy et al. (2013), the polymer was removed and no comments were made on whether it was problematic. In a previous laboratory work conducted at UW-Madison, the URETEK polymer was broken by a sledge hammer to observe bondings and interfaces.

1.5 URETEK Injection System

The patented URETEK PUR injection method is a proprietary process designed to enhance soil properties and remediate soil-related infrastructure problems. Once a problem is identified, URETEK conducts an investigation whether the PUR injection system is a viable solution. If PUR can be used to remediate the problem, an injection plan is devised. There are typically two methods used in the injection plan—URETEK deep injection (UDI) and a method that fills larger voids and cements soil grains.

The UDI process involves incremental vertical injections along the soil strata of interest (Figure 1.2). The first injection point is usually the highest elevation in the soil strata. This ensures that any interface between soil layers is sealed and further deeper injections do not vertically migrate to an unwanted location.

Figure 1.2: URETEK injection system (www.uretek.com)

Because of the expansive properties of the injected foam, surface elevations have to be monitored continuously while the injection is taking place. Expansion or lift, however, is controllable and this lends PUR injection itself to slab lifting/jacking.

Problematic soils, such as soft compressible silts, and clays can be remediated by PUR injection (Buzzi et al. 2010). The expanding PUR injection is similar to high pressure cementitious grouting. In compaction grouting using conventional slurries, soil is displaced and the volume of the soil voids is directly reduced (El-Kelesh et al. 2012). For conventional grouting methods, standard penetration test (SPT) and cone penetration test (CPT) are used prior to grouting and after curing of the cement grout to determine the soil strength improvement (El-Kelesh et al. 2012). PUR injection typically uses dynamic cone penetrometer (DCP) data to qualitatively and quantitatively measure soil resistance and penetration indices to determine ground improvement.

The other aspect of PUR injection is the bonding and cementing of soil particles. In soils where larger voids are found (e.g., gravel), the intrinsic permeability is higher, which results in the PUR injection infiltrating more soil (Buzzi et al. 2010). In unpublished tests conducted by Warren (2014), particle bonding has a high correlation with D_{10} with all other variables held constant. The quality of bonding between the PUR and the particles is a function of many variables (Szycher 1999); however, through many laboratory experiments (Keene 2012; Dolcek 2014), full permeation of ballast voids with PUR has increased the mechanical performance of the material.

2. Identification of Field Site

Identification of a field site for the project is the most critical step in this research and it proved to be the most difficult. The research team identified Illinois Railroad’s Ottawa Subdivision-MP north of Ottawa, IL near the town of Dayton, IL operated by OmniTRAX, Inc. The track is a single main railway running along the western bank of the Fox River and is primarily used to transport Ottawa sand for the fracking industry with nearly 100 cars, each weighing 100 t, at a frequency of 7–10 times a week. Because of rail distortion problems, the trains can travel only at a speed of 16 km/h (10 mph) in this area. The research team visited the site together with representatives of URETEK USA/ICR (our partners in this project) to determine if the problems at this site would be suitable for remediation as part of the project. The three chronic embankment problem locations were observed during our visit. These areas with problems all involve embankment slope failure and would confound the interpretation of results. The railmaster of Illinois Railway reported that four months ago, the track was raised 375 mm (15 in) and ballast was added (approximately 25 yd^3 or 20 m^3).

Considerable effort was spent in exploring the subsurface conditions using a variety of geophysical and geotechnical tools and developing a PUR injection strategy. The site investigation for OmniTRAX site can be found in the study by Warren (2015). However, after various delays, this site became unavailable for this project. A new search for other field sites was undertaken. Eventually, a field site consisting of two railway sidings located south of Parking Lot 44, on the corner of N. Park Street and W. Dayton Street at the University of Wisconsin–Madison owned by Wisconsin and Southern Railroad (WSOR) was identified. Permits and insurance issues were resolved and this site was used for the field validation of expanding RPF injection.

2.1 Overview and Location of Field Site

On June 13 and 14, 2016, UW-Madison researchers completed a geophysical investigation of two railway sidings in Madison, Wisconsin. The sidings are located south of parking lot 44, on the corner of N. Park St. and W. Dayton St. (Figure 2.1) just south of the University of Wisconsin-Madison campus. The railway sidings are owned by WSOR. These sidings are no longer in service and are used to store and unload coal for a nearby power plant. The investigated site is constructed on a 3 m (10 ft) high embankment and it has a length of 80 m (263 ft). The railways on the embankment are of standard rail gauge (1.44 m or 4.7 ft) and 0.2 m shoulders. The siding area (Figure 2.2) consists of three railway sidings. The railway sidings were named railway siding 1, railway siding 2, and railway siding 3. A 12,000 V utility line intersects railway siding 1 at 11 m and 40 m away from the east end. The ballast was of poor condition; multiple ballast types and fines were present.

Figure 2.1: Aerial view of the site location

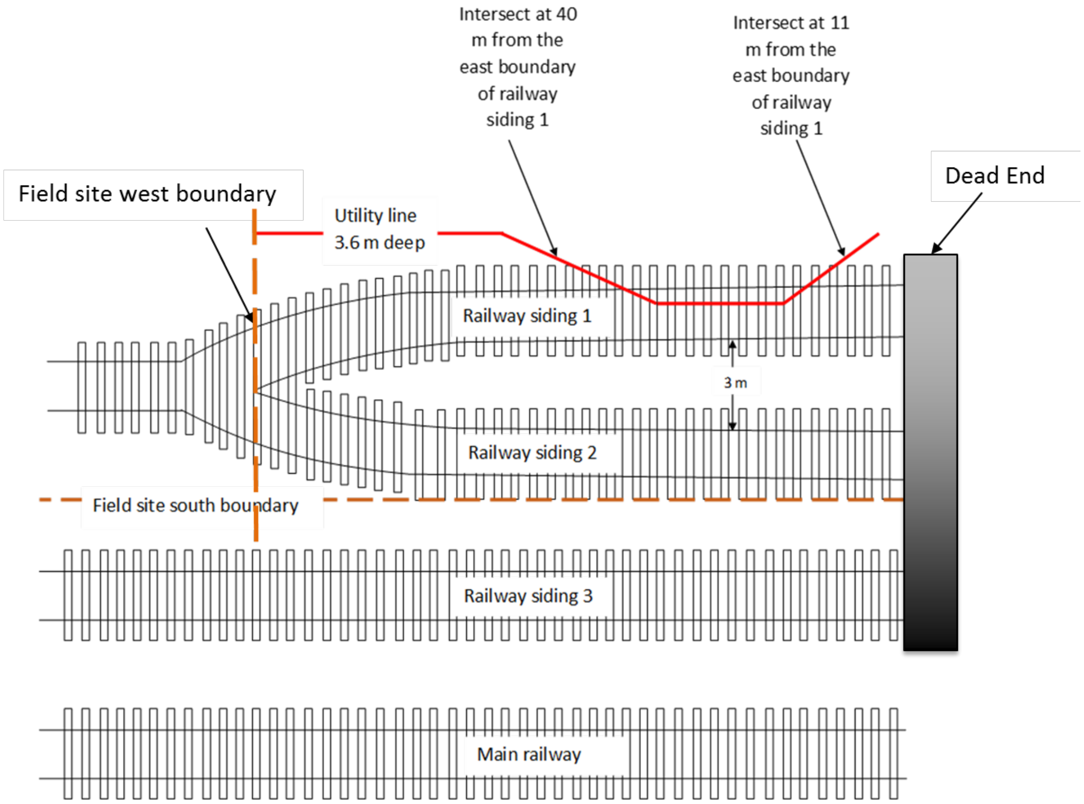


Figure 2.2: Simplified aerial view of the site showing siding aliases, site boundaries, and utility lines

2.2 Subsurface Exploration Program

The tests conducted were designed to identify the soil layer thickness and material type and to assess the extent of the rigid PUR injection at the site. Different survey lines were chosen for each test (Figure 2.3). The tests conducted are as follows:

- electrical resistivity tomography (ERT),
- ground-penetrating radar (GPR),
- dynamic cone penetrometer (DCP),
- elevation survey, and
- test pit and auger sampling to validate geophysical techniques.

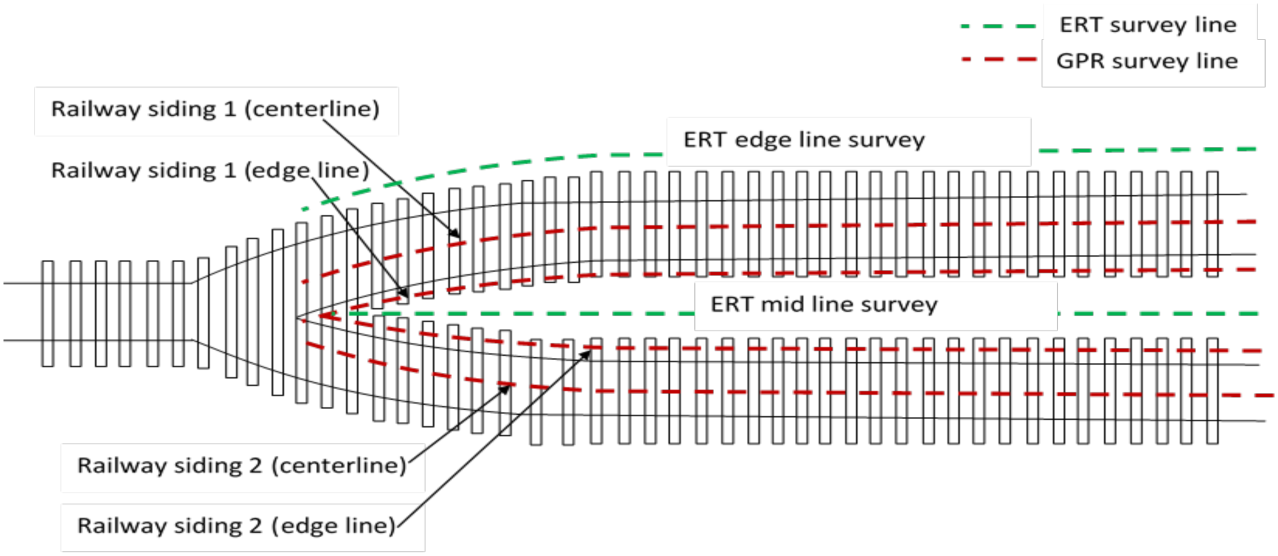


Figure 2.3: Geophysical survey line locations on siding 1 and 2

Description of Tests

GPR is a geophysical technique that uses a source at the surface to generate electromagnetic (EM) waves that travel down through the subsurface until it reaches a boundary between materials with contrasting electromagnetic properties (Figure 2.4). When the EM wave reaches such an interface, some of the wave energy reflects back while some of the energy is transmitted. The reflected energy travels back to a receiver at the surface where its arrival time and amplitude are captured.

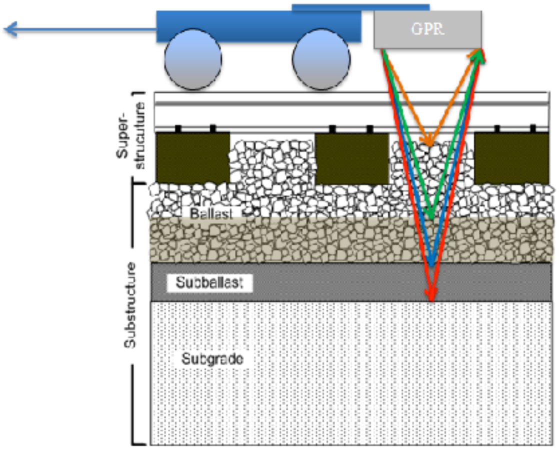


Figure 2.4: Ground-penetrating radar (GPR) survey technique

GPR data were collected using a pulse EKKO PRO system with 100 MHz and 200 MHz antennas for the two sidings of the track—railway siding 1 and railway siding 2. To interpret these data, a set of processing steps were implemented—time-zero correction, mean spatial filter, median spatial filter, and gain control function.

The ERT survey, which is another geophysical technique, was also used to obtain images of the subsurface. Imaging relies on the electrical resistance of the soil materials. Different resistances correlate with different geomaterials (Figure 2.5). The apparent resistivity is measured through the applied current/voltage at the surface to electrodes embedded in the soil. Changes in apparent resistivity imply changing conditions in the underlying soil. Different features can be imaged using this technique—water table, underlying strata, voids, and other objects.

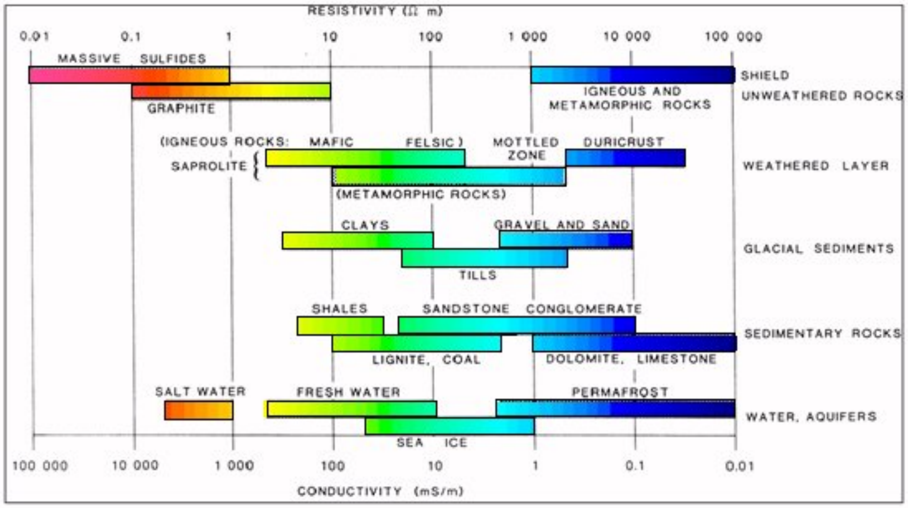


Figure 2.5: Geological resistivity ranges (Sharma 1997)

SYSCAL KID Switch-24 by IRIS Instruments was used to conduct the electrical resistivity surveys. A spacing of 3 m (10 ft) was chosen depending on site geometry and 24 electrodes were embedded in the soil at each site. RES2DINV software was used to invert the data and obtain images of the subsurface.

Soil sampling techniques were also utilized to collect soil samples and to determine the soil stratification for ground truth verification of the geophysical survey results. Mass samples of in situ ballast from within the ties and shoulder ballast were taken. These samples are disturbed; however, they are highly valuable for engineering property characterization using various techniques such as grain size distribution and particle characterization.

DCP was conducted at multiple locations (presented later in this report) to ground truth the geophysical data. The DCP system penetrated to depths of up to 5 m during this field test. DCP tests provide an indirect measurement of the shear strength in the underlying soil strata without the need for excavation. A weight of known mass is dropped from a distance; the force that is created drives a cylindrical cone into the underlying soil strata. The depth of penetration per blow (mm/blow) provides a measure of the inverse of the shear strength of the soil. Thus, using these data, DCP profiles can be used to estimate the depth of the different subsurface layers (Herrick and Jones 2002).

A detailed elevation survey was conducted to monitor long-term changes in the track geometry. Berntsen RSAK130 adapter with smart-angle-retro-reflective survey targets was installed on the rail webs and ties using epoxy construction adhesive. Reflectors were installed prior to PUR injections and an initial reading was conducted.

2.3 Subsurface Conditions

2.3.1 Ground-Penetrating Radar Results

Please refer to Appendix A for further information on the processed GPR radargram figures.

Railway Siding 1 (Centerline)

Both 100 MHz and 200 MHz processed GPR data of the centerline of railway siding 1 indicated four-layer interfaces corresponding to a ballast layer, subballast layer, subgrade layer 1, and subgrade layer 2. In addition, the 100 MHz processed data showed a deeper reflection taking place at 2 m (6.5 ft) depth and descending to 3 m (10 ft), which may correspond to the natural soil of the subgrade beneath the embankment. Minor intrusion of the subballast layer into the subgrade layer at 30 m (100 ft) and 40 m (130 ft) horizontal locations was observed. Figure 2.6 shows the stratigraphical interpretation of the GPR data.

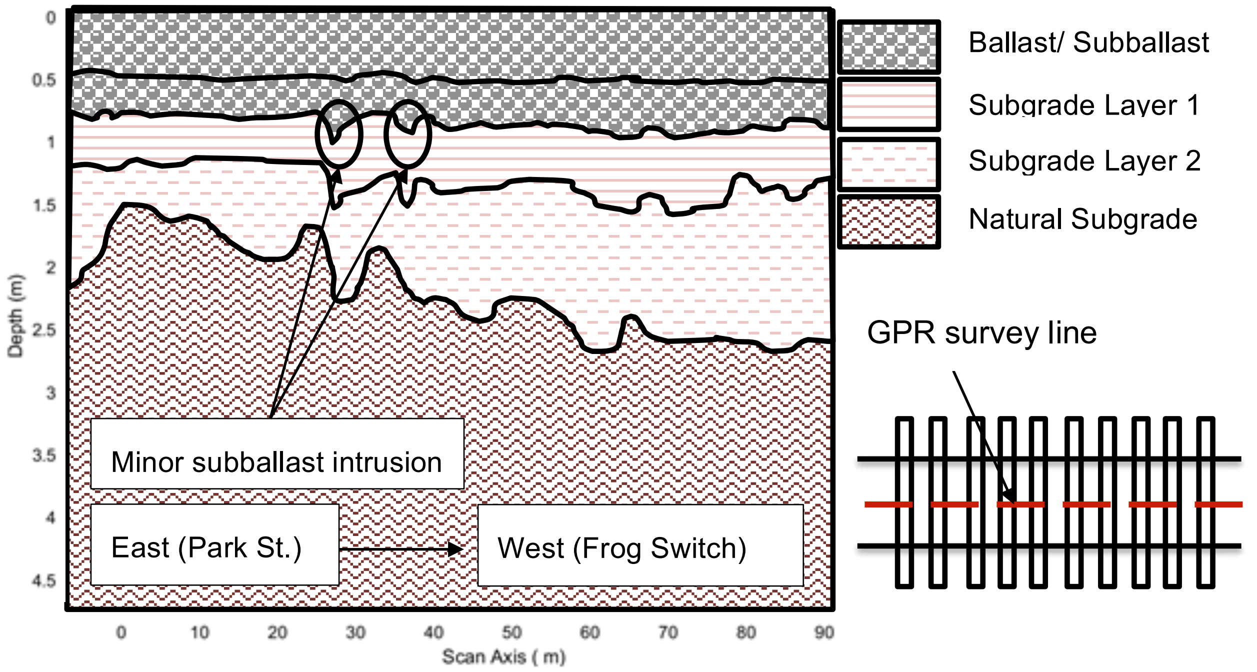


Figure 2.6: Railway siding 1 (centerline) stratigraphical interpretation based on GPR processed radargrams

Railway Siding 1 (Shoulder line)

Similar results with those of the centerline of railway siding 1 were observed for the 100 MHz and 200 MHz processed GPR data of the shoulder line of railway siding 1. The results indicated four-layer interfaces corresponding to a ballast layer, subballast layer, subgrade layer 1, subgrade layer 2, and a deeper reflection taking place at 2 m (6.5 ft) depth and descending to 2.7 m (8.9 ft), which may correspond to the natural soil of the subgrade beneath the embankment. Figure 2.7 shows the stratigraphical interpretation of the GPR data.

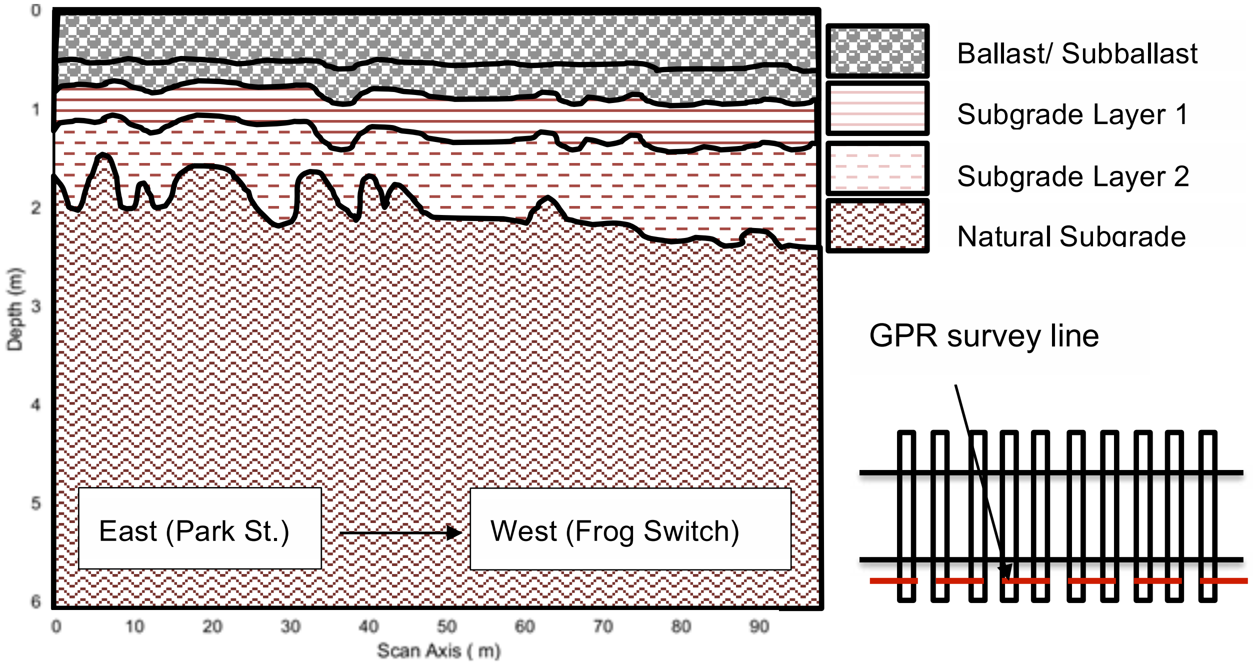


Figure 2.7: Railway siding 1 (shoulder line) stratigraphical interpretation based on GPR processed radargrams

Railway Siding 2 (Centerline)

The GPR survey data of the centerline of railway siding 2 were only valid for the 200 MHz antenna frequency, whereas the 100 MHz survey did not yield good data due to an error while running the survey. The results of the 200 MHz antenna survey indicated the presence four-layer interfaces corresponding to a ballast layer, subballast layer, subgrade layer 1, and subgrade layer 2. No information was found on a deeper reflection that corresponds to the natural subgrade layer considering that the 100 MHz survey did not yield good data. Figure 2.8 shows the stratigraphical interpretation of the GPR data.

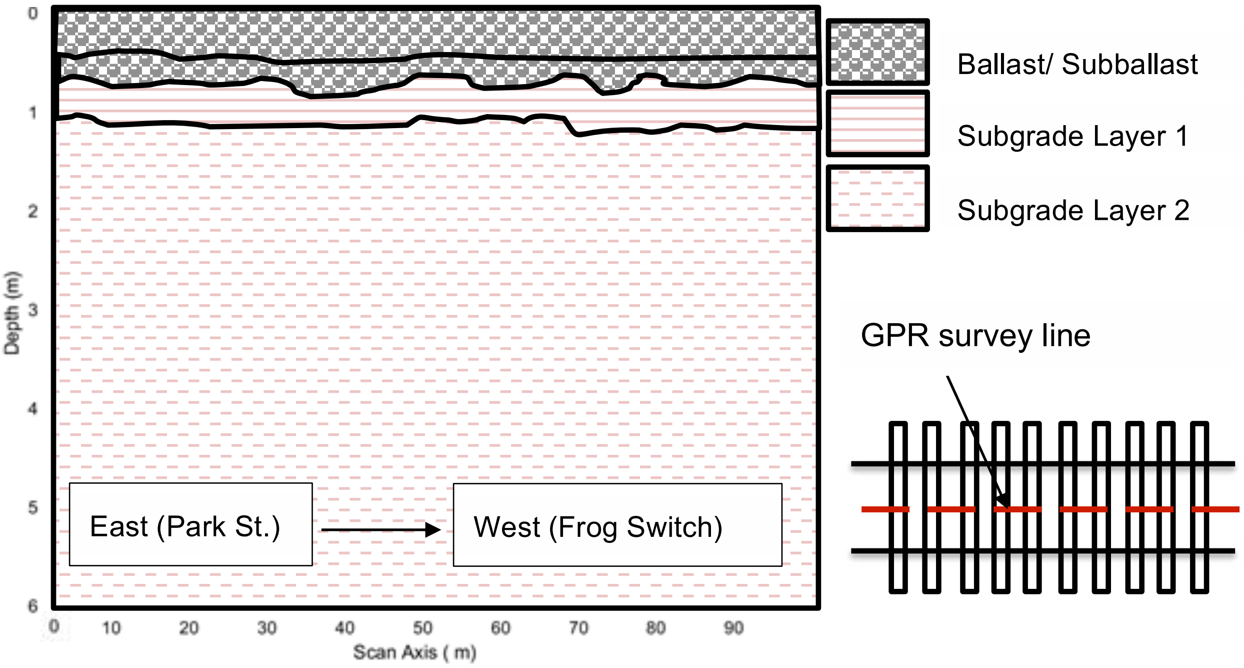


Figure 2.8: Railway siding 2 (centerline) stratigraphical interpretation based on GPR processed radargrams

Railway Siding 2 (shoulder line)

Both 100 MHz and 200 MHz processed GPR data of the shoulder line of railway siding 2 indicated four-layer interfaces corresponding to a ballast layer, subballast layer, subgrade layer 1, and subgrade layer 2. In addition, the 100 MHz processed data showed a deeper reflection taking place at 2 m (6.5 ft) depth and descending to 3 m (10 ft), which may correspond to the natural soil of the subgrade beneath the embankment. Major dipping zones of subgrade layer 1 at 20 m (65 ft) and 50 m (165 ft) horizontal location were observed, which coincide with the local settlement observed in the geometric elevation results. Figure 2.9 shows the stratigraphical interpretation of the GPR data.

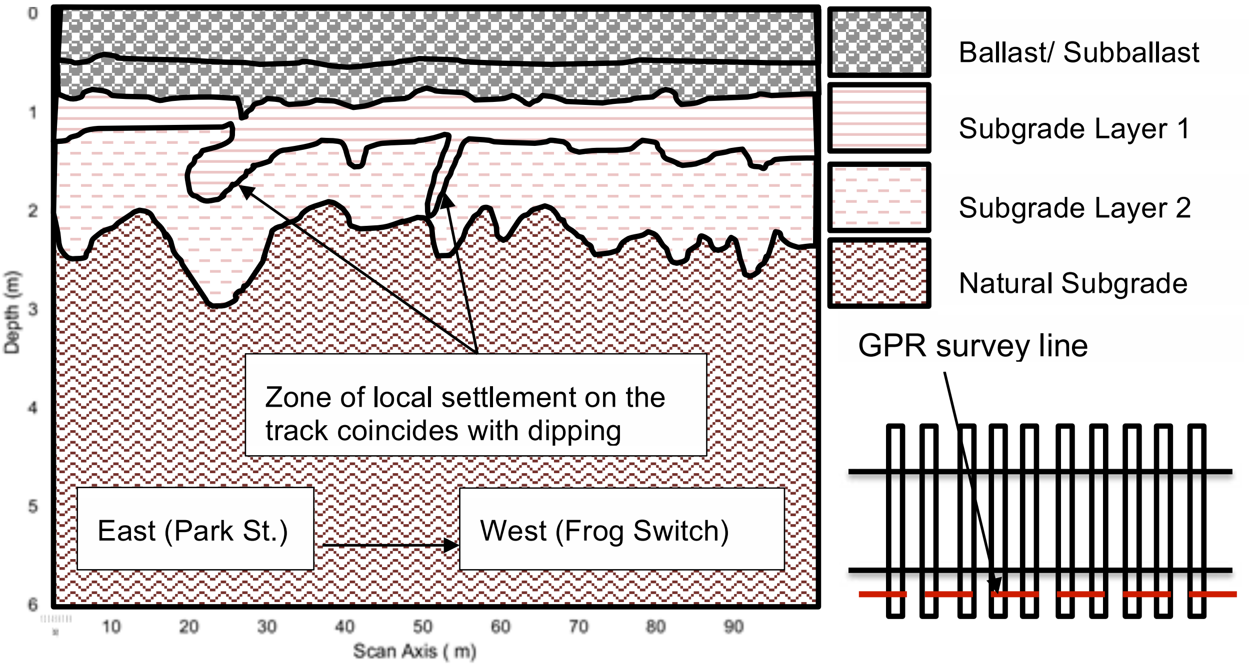


Figure 2.9: Railway siding 2 (shoulder line) stratigraphical interpretation based on GPR processed radargrams

2.3.2 Electrical Resistivity Tomography Test Results

ERT was conducted using a dipole–dipole array at 3 m (9 ft) electrode spacing. The electrodes were placed at two locations, i.e., shoulder line of railway siding 1 and the mid area between railway siding 1 and 2, to increase ground coupling and to enhance resolution of the subsoils.

Railway Siding 1

The results from the north shoulder line of railway siding 1 (Figure 2.10) do not exhibit the expected resistivity behavior of the underlying soil. This might be due to an error while running the ERT survey.

Railway Siding 2

The results from the mid area between railway siding 1 and 2 (Figure 2.11) show a zone of low resistivity (blue) close to the west end of the survey that correlates to increased moisture content and/or a clayey soil. In general, resistivity values range from medium to high indicating the presence of granulated materials, which is consistent with typical fill materials used in embankment construction.

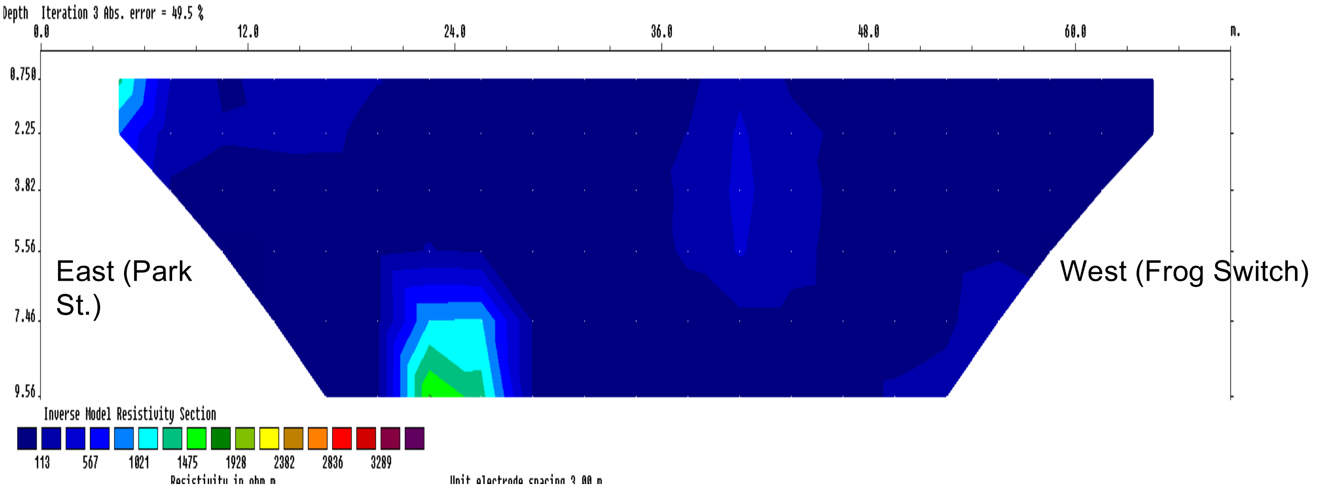


Figure 2.10: Electrical resistivity tomography (ERT) section for railway siding 1

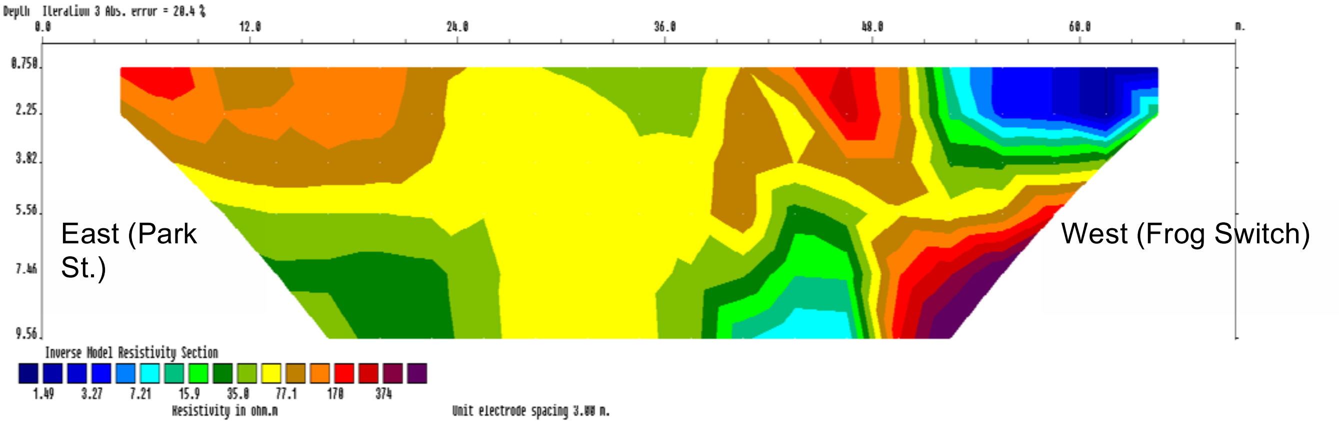


Figure 2.11: ERT section for railway siding 2

2.3.3 Dynamic Cone Penetrometer Results

DCP tests were conducted by URETEK USA/ICR at the locations shown in Figure 3.3. The results are shown in Figure 2.12. The DCP profile exhibits a strong ballast layer followed by a weak layer with a depth of approximately 1 m (3.3 ft). Beyond the depth of 1.8 m (6 ft), the soil profile exhibits loss of resistance to penetration (N = 0) depths of up to 3 m (10 ft). The DCP results correlate well with the GPR stratum thicknesses and sampling conducted at this location.

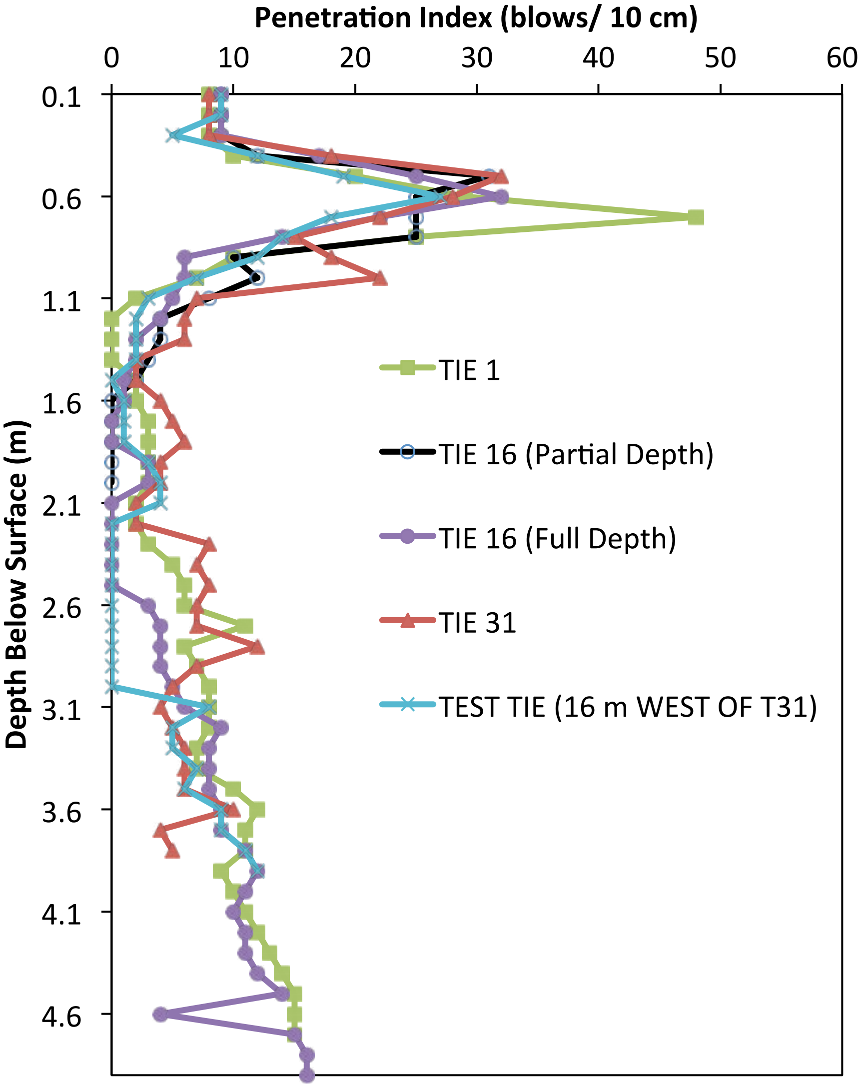


Figure 2.12: Dynamic cone penetrometer (DCP) results

2.3.4 Elevation Survey Results

A detailed elevation survey was conducted using a total station at railway sidings 1 and 2. Generally, railway siding 2 showed a higher elevation than railway siding 1 with a local settlement between the horizontal locations of 15 m to 45 m. Railway siding 1 showed a descended slope between the horizontal locations of 50 m to 70 m that corresponds to the presence of the railway frog switch, which causes a differential stiffness and differential static force at the location of railway joints, leading to a local settlement problem. The geometric elevations of railway sidings 1 and 2 are shown in Figure 2.13.

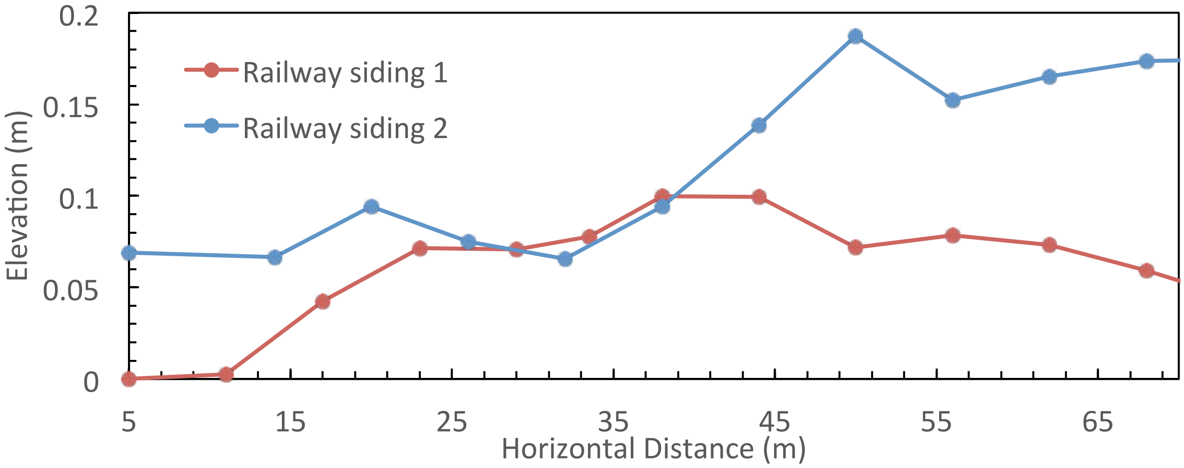


Figure 2.13: Geometric elevations of railway siding 1 and 2

2.3.5 Laboratory Analysis of Samples Collected

Multiple ballast samples were collected during the site visit. Ballast samples were taken from the top of ballast layer up to 5 cm (2 in) below the tie. These samples were oven dried, then a sieve analysis was conducted in accordance to ASTM D422 (Figure 2.14). The ballast sampled has a range from moderately clean ballast to moderately fouled ballast (Table 2.1).

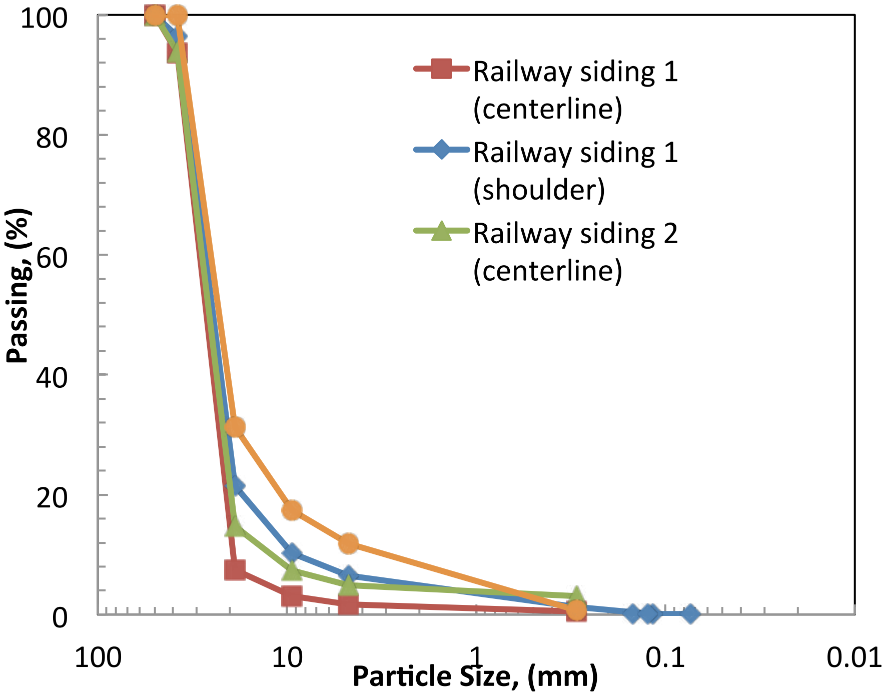


Figure 2.14: Grain size distribution

Table 2.2.1: Summary table for ballast condition

Sample Location	**Fouling Index**	**Comment**
Railway siding 1 (centerline)	1.73	Moderately clean ballast
Railway siding 1 (shoulder)	6.54	Moderately clean ballast
Railway siding 2 (centerline)	4.90	Moderately clean ballast
Railway siding 2 (shoulder)	11.80	Moderately fouled ballast

Note: Fouling index (FI) classification

$FI\ < 1\ - Clean\ Ballast$
$1 \leq FI \leq 10 - Moderately\ Clean\ Ballast$
$10 \leq FI \leq 20 - Moderately\ Fouled\ Ballast$
$20 \leq FI \leq 40\ \ - Significantly\ Fouled\ Ballast$
$FI \geq 40 - Highly\ Fouled$

3. Field Instrumentation and Load Tests

To determine whether the PUR injections have been effective or not, a measurement technique was employed. With loading using a locomotive, the results were expressed in terms of the track modulus. Short-term (elastic settlement) measurements were used in this study as the tested tracks were out of service and long-term (plastic settlement) measurements were not applicable. These measurements provide insight whether the PUR injection has improved the railroad track section.

3.1 Railway Deformation Response

Winkler's model is the generally accepted analytical model for track design (Kerr 2003). This model is based on the assumption that each rail acts as a continuously supported beam, which is governed by the differential equation for the bending theory of an elastic beam:

$$EI\frac{d^4y}{dx^4} + uy\,(x) = 0 \tag{1}$$

where EI is the vertical flexural stiffness, u is the track modulus, and y(x) is the vertical deformation of the rail at distance x.

Considering that Winkler's model is a linear model, superposition of multiple axle loads is commonly used in the interpretation of results. The 6-axle locomotive used for loading in the field site is modeled to represent the influence of its loading on the substructure. Figure 3.1 shows a railway track deflection caused by the 6-axle locomotive. The maximum deflection is located near the heaviest wheel (the back wheel was found to be the heaviest based on field measurements). The deflection profile extends to approximately 28 m (91 ft), exhibiting two zones of deflections. Each zone corresponds to a set of 3 axles that extends to approximately 13 m (42 ft). The corresponding bending strains are shown in Figure 3.2. The maximum bending strain in the rail is located underneath the heaviest loading point. The bending strain diagram exhibits positive values underneath the loading points; however, the bending strains are negative elsewhere.

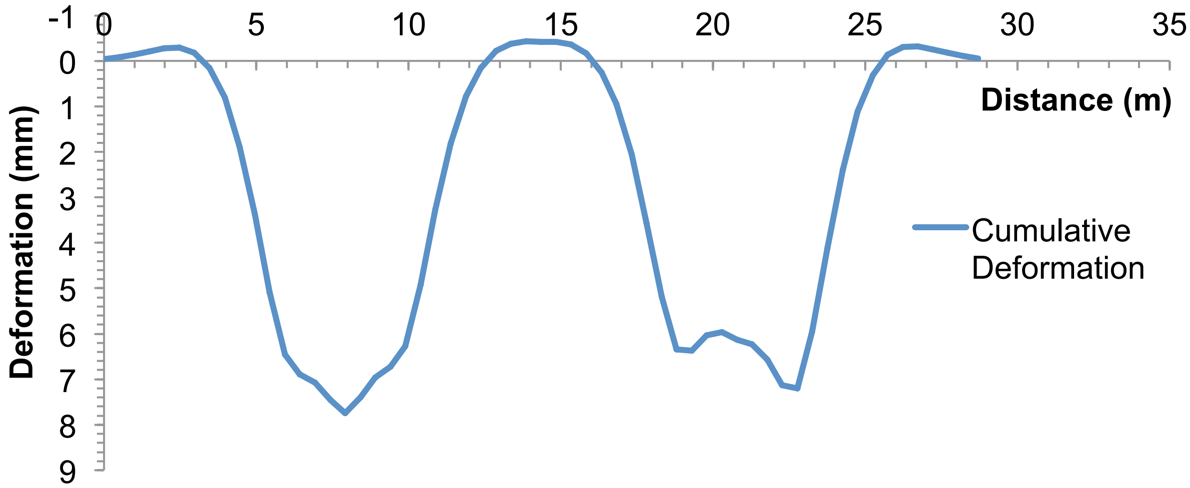


Figure 3.1: Rail deflection for 6-axle locomotive

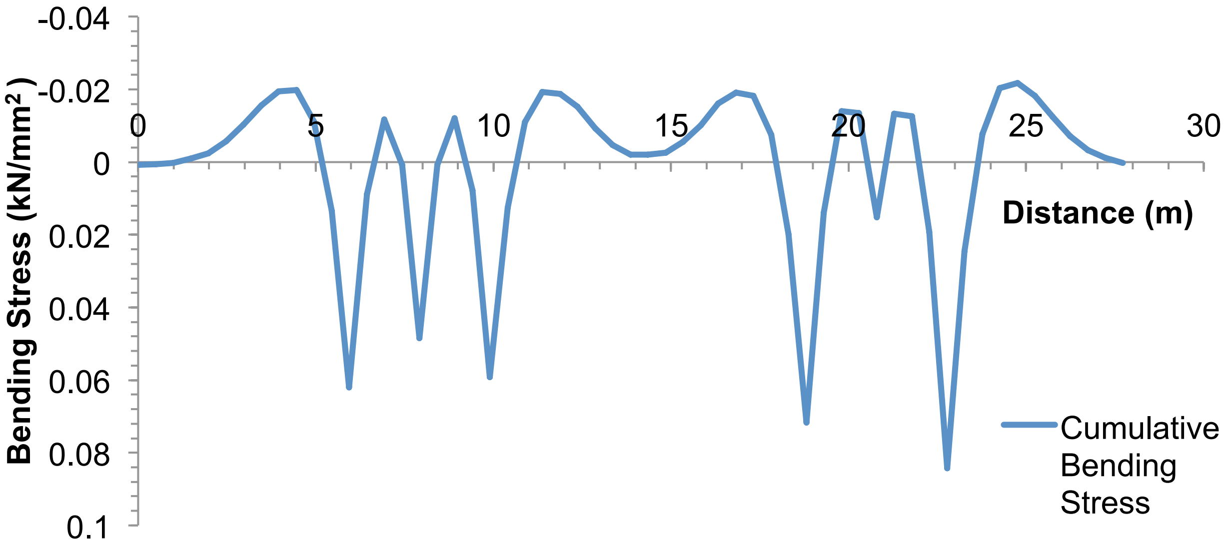


Figure 3.2: Bending strain for 6-axle locomotive

3.2 Track Modulus

Field testing for measuring in situ strength of railroad beds differ from measuring the entire track response or measuring individual soil layers. Measuring the railroad track total response to a load is referred to as the track modulus. Track modulus is considered as a representative parameter to quantify the structural integrity of a railway track (Selig and Li 1994; Kerr 2003; Lichtberger 2005). Selig and Li (1994) described it as a measure of the vertical stiffness of the rail foundation. The track modulus is essentially a spring constant [F/(L·L)]. The higher the track modulus, the larger the force required to vertically displace the railroad track. The track modulus should be in the range of 14–69 MPa and it should neither be extremely high nor extremely low (Selig and Li 1994). A modulus that is extremely low is a safety concern, while a modulus that is considerably high sacrifices ride quality.

Furthermore, Selig and Li (1994) used a mathematical model based on the theory of continuous beam on elastic foundations to define track modulus as the supporting force per unit length of the rail, q, per unit vertical deflection of the rail, y.

$$u = -\frac{q}{y} \tag{2}$$

By equating the maximum measured rail deflection at one point with the corresponding analytical expression of the differential equation for the bending theory of an elastic beam (equation 1), equation (2) can be rewritten as

$$u = \frac{k^{\frac{4}{3}}}{(64EI)^{\frac{1}{3}}} \tag{3}$$

where E is the rail modulus of elasticity, I is the rail moment of inertia, and k is the track stiffness, which can be calculated as

$$k = \frac{P}{y_m} \tag{4}$$

where P is the wheel load, and y_{m} is the maximum rail settlement. Researchers have adopted these parameters in evaluating railway track conditions (Cai et al. 1994; Read et al. 1994; Norman et al. 2004; Priest and Powire 2009).

3.3 Instrumentation and Field Monitoring Procedure

To monitor short-term settlements, strain gauges and a high-resolution camera were used, and a detailed standard survey was conducted. The track moduli were measured using the Kerr method by means of multiple-axle vehicle load test (Kerr 2003).

The procedure to determine the track modulus is as follows:

1- Measure the wheel distances of the train locomotive that was used as a loading device for the field test.
2- Determine the wheel loads of each axle by placing each axle exactly on the point instrumented with a strain gauge for weighing.
3- Then, move the locomotive near the rail at the track location of interest. When the front/back wheel of the locomotive reaches the point above the point of interest, record the vertical rail deflection.
4- Measure the deformation using a total station and a high-resolution camera placed approximately 10 m (30 ft) from the rail.
5- To determine the u value at another location, move the locomotive to the new location and repeat steps 2 to 5.

3.4 Pre-injection Track Modulus Measurements

On July 8, the UW-Madison team obtained pre-injection track substructure condition measurements. Four measurement points (P.1, P.4, P.1”, and P.4”) were selected to obtain the track modulus (u). Figure 3.3 shows the location of each of these points. Bending strain measurements showed that the locomotive back wheel is the heaviest and, thus, all deflection measurements were tracked based on the placing of the back wheel of the locomotive on the point above the point of interest. Vertical deflection was successfully measured using the high-resolution camera and total station surveying (Figure 3.4). Variation in the measurements between total station and the high-resolution camera is due to the uncontrolled vibration of the high-resolution camera that was caused by winds at the site. Overall, the maximum difference between the two measurement techniques is minimal: approximately 2 mm (0.08 in). Track modulus, u, values were calculated and are shown in Figure 3.5. In general, railway siding 2 was considered to be of poor condition based on u values. Furthermore, the middle of railway siding 2, P.4, was observed to be softer than P.1, which is the section near the frog.

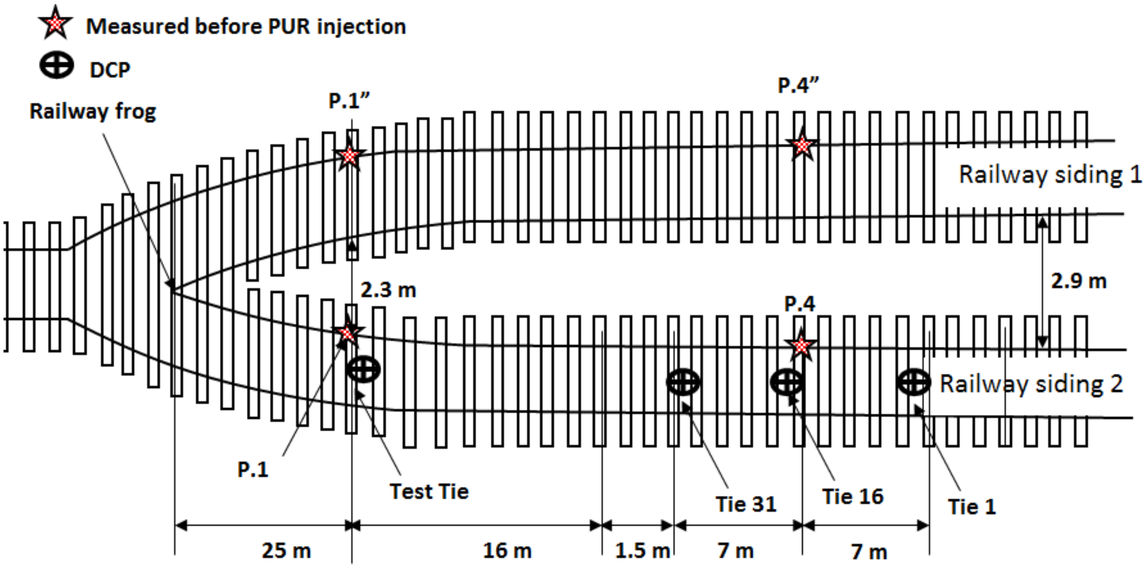


Figure 3.3: Pre-injection measurement point locations

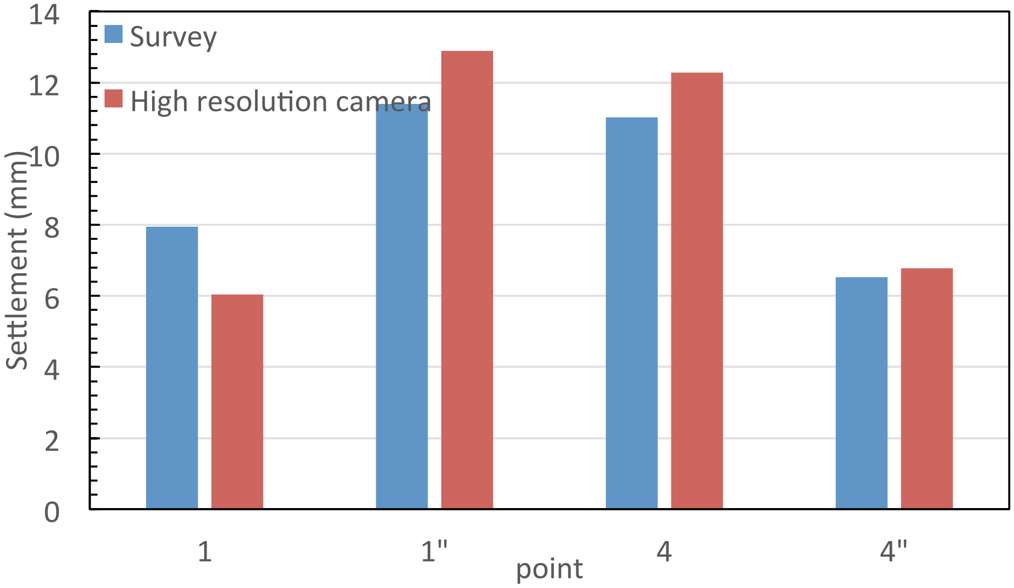


Figure 3.4: Pre-injection deflection measurements for all points

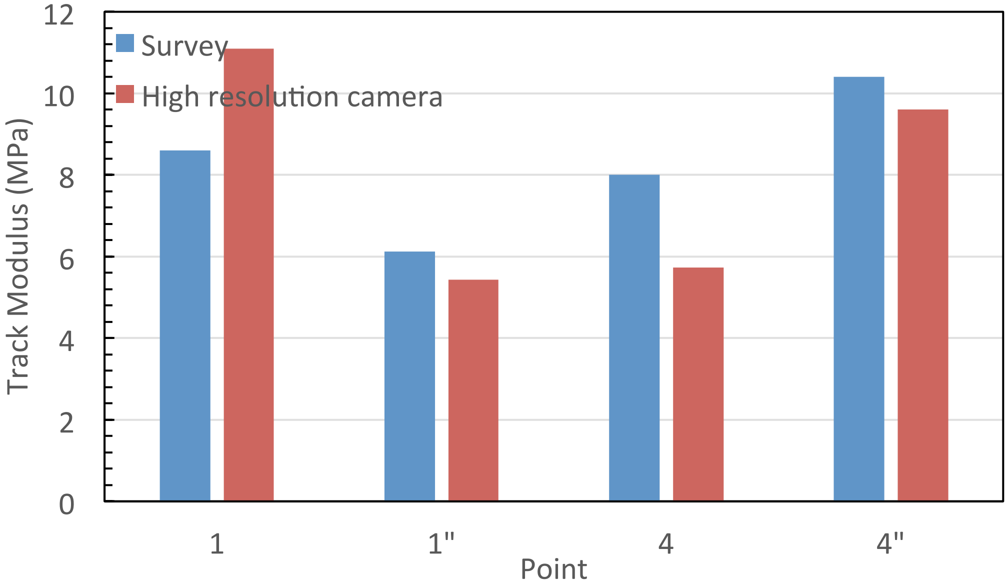


Figure 3.5: Pre-injection track modulus measurements for railway siding 2

3.5 Polyurethane Injection Plan

Injection Location

Geophysical (electromagnetic) surveys indicated major dipping zones in the middle of railway siding 2 at subgrade layer 1 within the horizontal location of 20 m (65 ft) and 50 m (165 ft), which coincide with the local settlement that has been observed in the geometric elevation results. The DCP results confirmed the presence of a soft layer (wet silty sand) at depths of 1.2 m (4 ft) and 1.8 m (6 ft). In addition, track modulus (u) values (as described below) at the midsection of railway siding 2, which was 50 m (165 ft) east of the frog, were observed to be softer than the section near the frog switch, which is 25 m (82 ft) east of the frog. Therefore, PUR injections were proposed to be applied in the soft area of the track that starts at 42.5 m (140 ft) east of the frog and extends to approximately 14 m (46 ft) (Figure 3.6), which complied with the influence zone of the 6-axle locomotive on the railway substructure. Extra deformation measurement points (P.2, P.3, P.5, and P.6) were used to study the transition zones between the injected areas and non-injected areas.

Injection Strategy

The PUR injection strategy was designed by URETEK USA/ICR with input from UW-Madison. UW-Madison provided the goals it would like to accomplish with the field site. The goals included

1. stabilizing the ballast, and
2. stabilizing the subballast and subgrade soils.

The two goals stated above were established to investigate the effect of PUR placement throughout the substructure of a railroad track. URETEK USA/ICR specializes in chemical grouting techniques. The progression of construction includes the following steps:

1. Utilities were marked by an independent party.
2. DCP results verified the length and depth of the treatable area to be at depths of 1.2 m (4 ft) and 1.8 m (6 ft) to stiffen the soft layers detected in the substructure survey.
3. Hollow steel tubes/probes were driven in the designed injection pattern. Injection of PUR started at this point.
4. The injections were conducted starting from the shallowest to the deepest elevation.
5. Probes were extracted out of the subsurface.
6. The area was cleared of all debris and remnants.

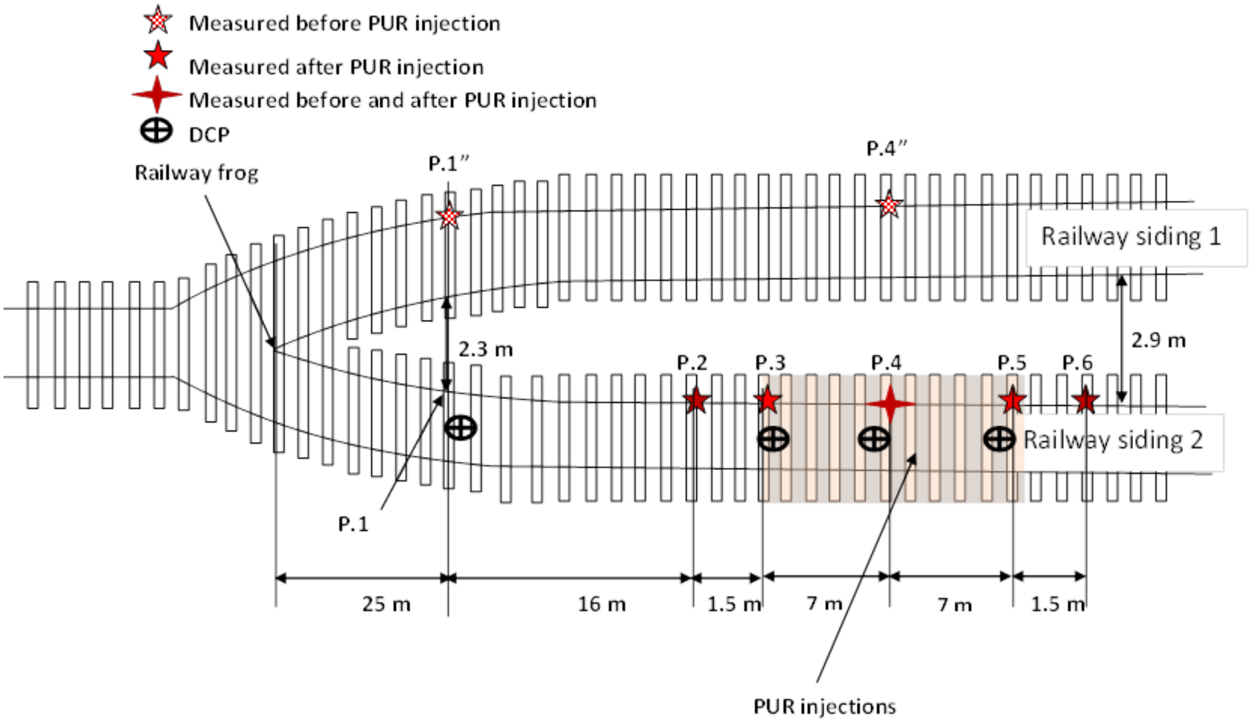


Figure 3.6: Injection area

3.6 Post-injection Track Modulus Measurements

On July 11, the UW-Madison team obtained post-injection track substructure condition measurements. Six measurement points (P.1, P.2, P.3, P.4, P.5, and P.6) were selected to obtain the track modulus (u). Figure 3.6 shows the exact location of each point. Bending strain measurements showed that the locomotive back wheel is the heaviest and, thus, all deflection measurements were tracked based on placing of the back wheel of the locomotive on the point above the point of interest. Vertical deflection was successfully measured using a high-resolution camera and total station and both measurements showed good agreement.

A detailed survey was conducted using a total station to monitor the effect of PUR injections on the overall geometry of the railway. Figure 3.7 shows that the PUR-injected area does not exhibit a rise in elevation compared with the results of the pre-injection area. Furthermore, PUR injections showed no significant effect on the geometry of the railway with or without loading.

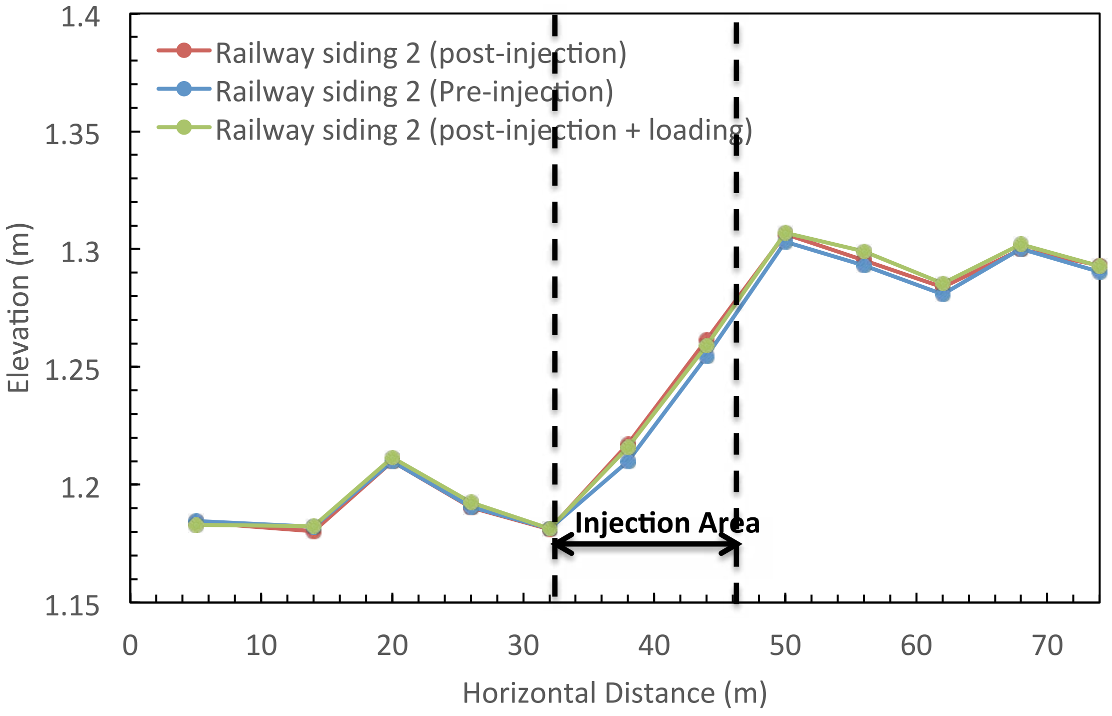


Figure 3.7: Geometric elevation of railway siding 2

Figure 3.8 shows the different settlement values of each point, in which P.4 provides a direct illustration of the effect of PUR injections. In essence, P.4 showed a reduction in the settlement values from 11 mm to 6 mm after PUR injections. Transition zones at P.2, P.3, and P.5 did not show any significant gap in the settlement between the PUR-injected areas and the non-injected areas.

Track modulus values are shown in Figure 3.9. The PUR-injected areas showed a higher track modulus with a track rating of average based on u values, whereas, the non-injected areas exhibited a poor track rating (Ahlf 1975). Furthermore, control point P.4 showed a 90% increase in track modulus (increase from 8 MPa to 15.2 MPa) after PUR injection.

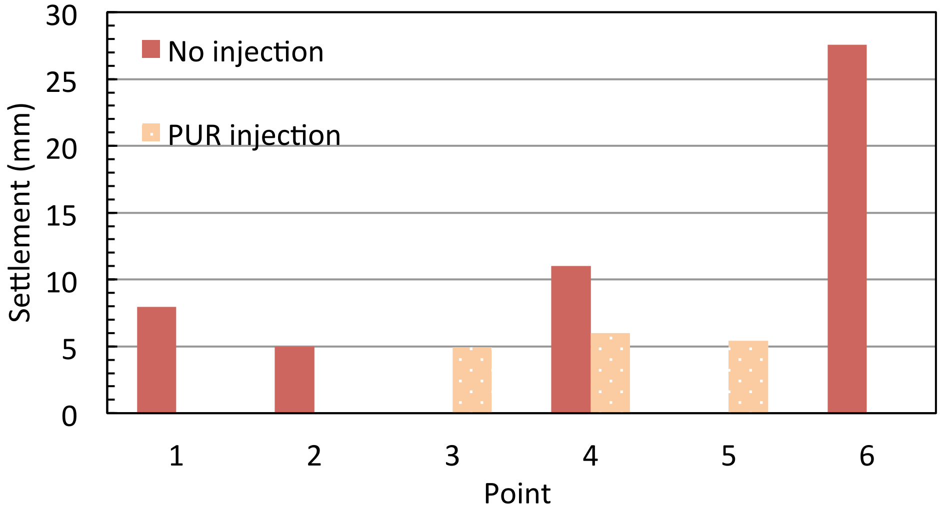


Figure 3.8: Post-injection deflection measurements for all points

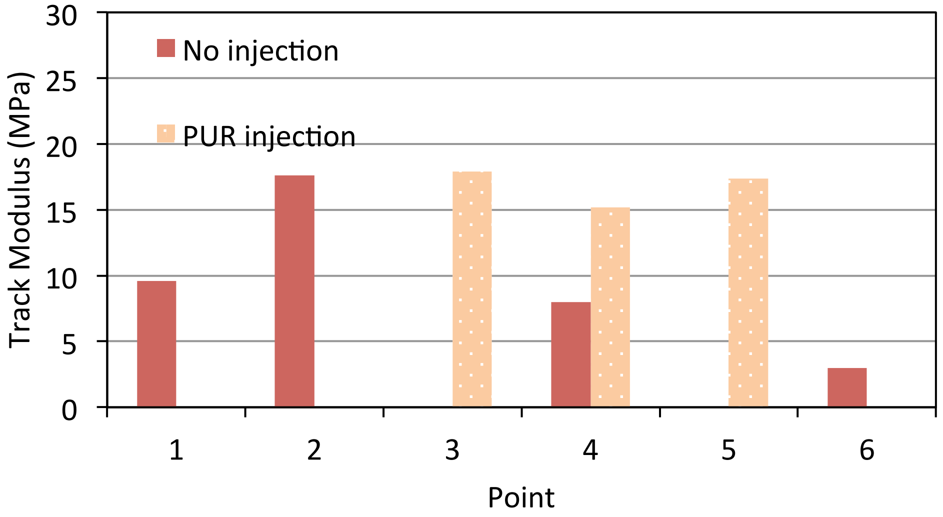


Figure 3.9: Post-injection track modulus measurements for railway siding 2

3.7 Post-injection Geophysical Images

After the PUR injection, the UW-Madison team obtained geophysical data of the post-injection track substructure. Figures 3.10 and 3.11 show the location of the ERT and GPR survey lines collected after the injection. The ERT results show the areas of the PUR injection as zones of increased electrical resistivity. Figures 3.12 and 3.13 show an increase in the electrical resistivity in the injection zone both in raw data and in the tomographic images. Figure 3.14 shows some indication of the injection on the GPR survey results.

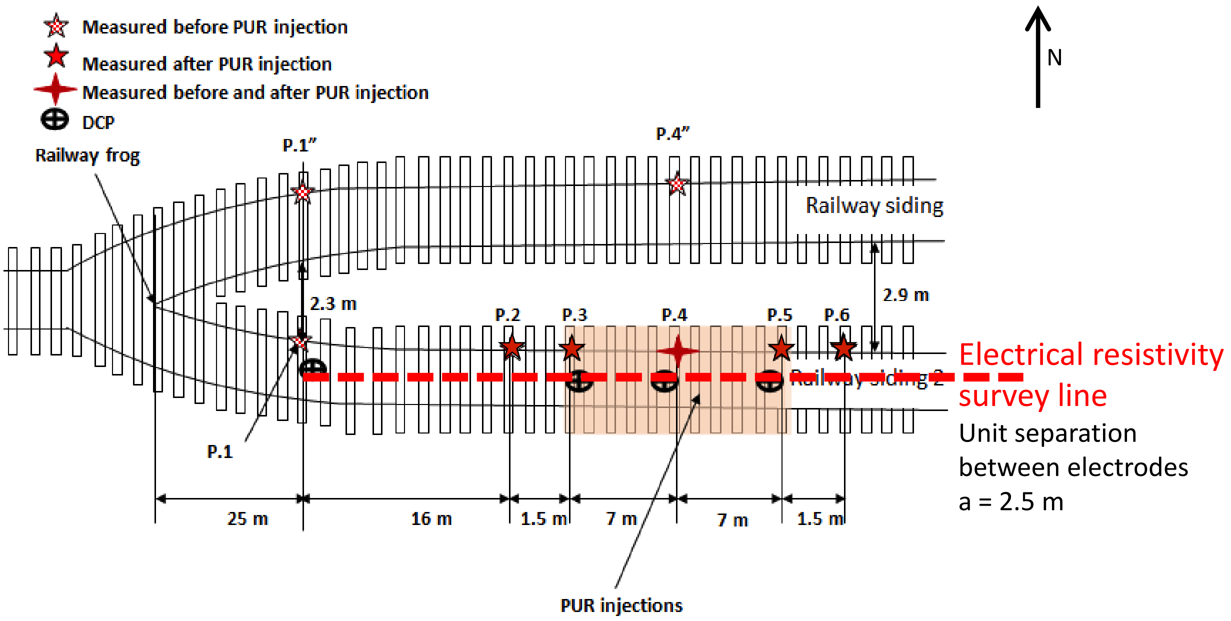


Figure 3.10: Location of ERT survey lines on railway siding 2

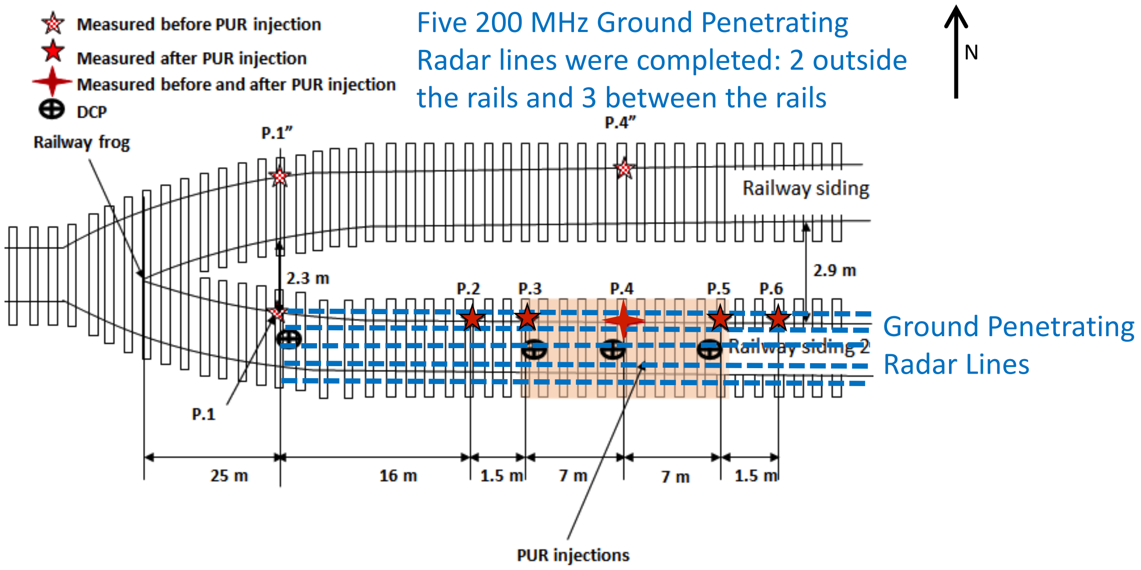
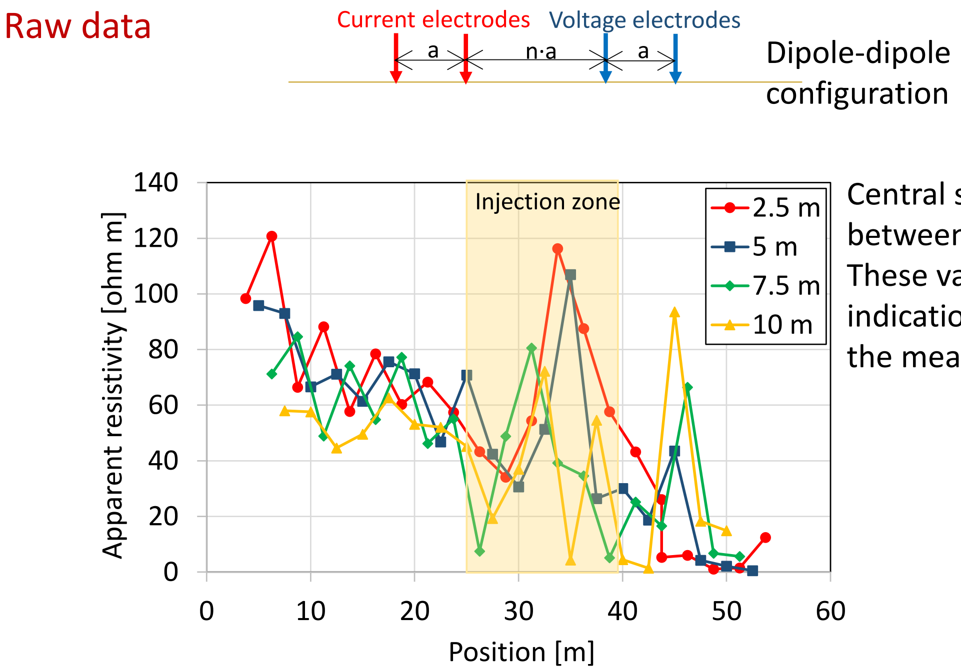


Figure 3.11: Location of 200 MHz GPR survey lines on railway siding 2



Central separation (n·a) between electrodes – These values yield an indication of the depth of the measurements.

Figure 3.12: Electrical resistivity raw data. These data collected using dipole-dipole configuration show an increase in electrical resistivity in the injection zone

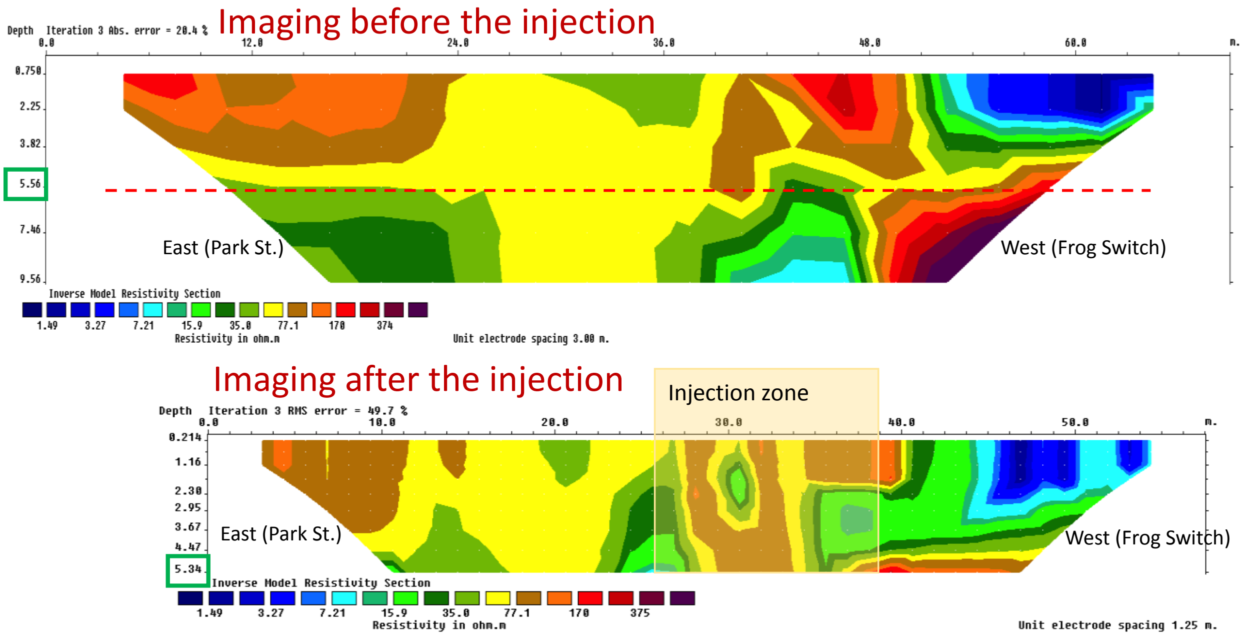


Figure 3.13: ERT imaging results showing an increase in resistivity in the injection zone

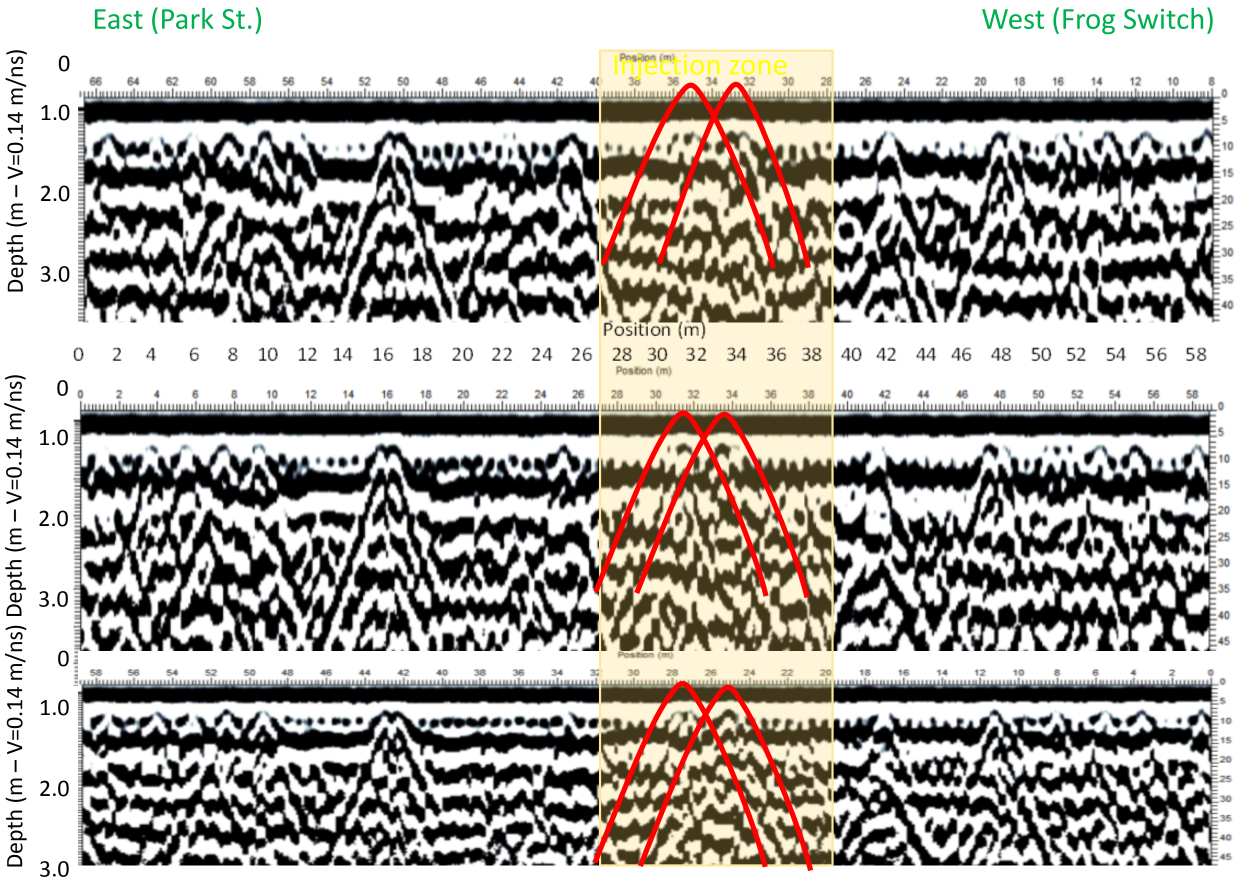


Figure 3.14: GPR results of 200 MHz antennas. (While there are several reflection marks across the GPR survey lines, two strong reflections match the location of the PUR injection)

4. Life Cycle Assessment of Polyurethane Stabilization of Tracks

4.1 Life Cycle Assessment Background

With an environmentally conscious society, decisions are both economically and environmentally driven. Environmental impact of a project can be a great concern for companies as natural resources have a finite quantity and their conservation saves money and reduces potentially harmful pollutants. A life cycle assessment (LCA) is a tool used to examine the associated processes with a product from inception to the end of its useable life (Baumann and Tillman 2004). LCA has been recognized as a valuable tool and the International Organization for Standardization (ISO) has created a guideline for which one can design an LCA for a product, service, or construction. Shown below in Figure 4.1 is a typical LCA design backbone.

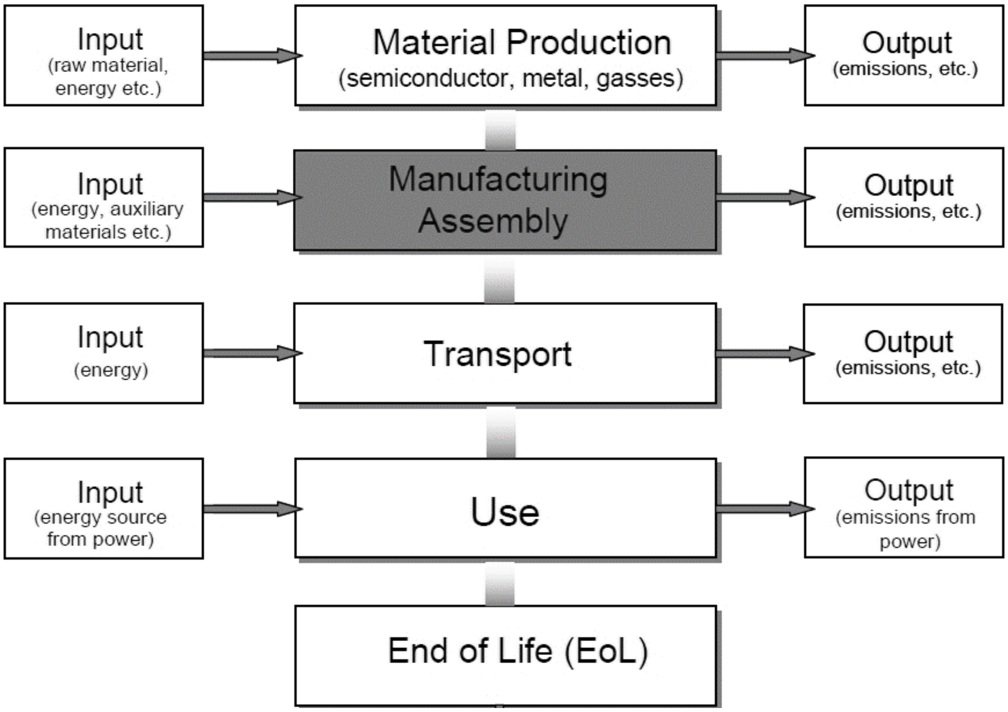


Figure 4.1: Typical life cycle assessment (LCA) construction modified from (wrtassoc.com)

An LCA consists of four parts (ISO 2006b):

1. definition of goal, scope, and functional unit,
2. life cycle inventory,
3. life cycle impact assessment, and
4. Interpretation of the study.

LCA is similar to a life cycle cost analysis (LCCA). LCA is concerned with emissions and environmental impact, whereas LCCA is primarily a life cycle economic method of studying the impact of a project. An accounting LCA compares multiple products or processes. Studies similar to this may be used to determine which alternative is the best choice.

New railroad construction and maintenance is an energy-intensive task. Although, railroads are efficient in conducting maintenance events, the activities still require time, material, and energy. New construction is particularly energy intensive. For example, steel rails are recyclable; however, they require a high amount of energy to repurpose. Therefore, it would be beneficial if a maintenance activity could extend the life of the entire structure.

LCA is prevalent in infrastructure construction and roadway design. The application of LCA in railroad construction is less widespread. Most LCA's conducted in the railroad sector pertain to bridges and transportation by train (Stripple and Uppenberg 2010; Du 2012; Du and Karoumi 2012, 2013). Past research has found that conventional ballasted tracks achieved better environmental performance. The LCA method, boundary conditions, and available information are essential in producing repeatable results.

4.2 Monte Carlo Simulation

Another facet of conducting an LCA is uncertainty. Inputs vary by range or distribution and this has an effect on the outcome. Distributions and ranges are necessary to determine how representative the average is after being chosen for analysis (Sonnemann et al. 2003). Monte Carlo simulation has been used extensively in understanding the variation and limitations of an LCA. Limitations can be overcome by the use of a Monte Carlo simulation. A Monte Carlo simulation is a method of managing uncertainty in information. The simulation uses the distribution of the data, a random number generation, and builds a model of potential results. The results are in the form of a probability distribution, and to generate this distribution, a discrete number of simulations are conducted. Data fed into the simulation typically have their own distribution, with common ones being normal, lognormal, uniform, and triangular. The random number generator randomly chooses a point of each distribution to sample and create iterations of the same process, but with different values.

The Monte Carlo technique uses a large (thousands) number of stochastic simulations. The values used for the analysis are chosen randomly from the input product data distributions. Upon completion, an estimate of the probability density function (PDF) is formulated (Salve 2008). Another method of visualizing the Monte Carlo simulation is a method that replaces discrete values with random variables drawn from PDFs (LaGrega et al. 1994). Conducting a Monte Carlo simulation provides a PDF of where the true value may lie.

4.3 LCCA Inputs and Results

The field site in Dayton, IL, (Dayton Dip) area owned by WSOR was used to demonstrate the LCCA and LCA benefits of PUR injection in comparison to traditional maintenance methods.

4.3.1 Conventional Maintenance

Conventional railroad maintenance is an energy and labor-intensive process. Railroad maintenance could require many other inputs with respect to equipment and materials. These initial capital costs can be included in an LCCA; however, for simplicity, costs including equipment, labor, and fuel can be formulated into a package. Interviews with WSOR proved beneficial for understanding the costs associated with railroad maintenance. The maintenance can be broken down into two categories: light and intensive. Light maintenance consists of tamping, a ballast regulator, associated labor, and mobilization cost. Intensive maintenance consists of undercutting the track and removing the problematic ballast, placing clean ballast, and tamping to Class 1 track specifications. The respective costs are given in Table 4.1.

Table 4.1 General maintenance costs

Light Maintenance (tamping with associated machinery/labor)	
Smaller project - $2.50/ft	Larger project - $1.25/ft
Intensive Maintenance (over soft ground)	
$105.70/ft	

WSOR owns a group of tampers and regulators on the WSOR network that mostly perform tamping on WisDOT-funded rehabilitation projects to optimize cost and track elevations.

WSOR has found that they are able to better control costs by using their own labor and equipment to perform the tamping to complete the projects (Marsh and Schlaama 2015).

To obtain a baseline for which to measure the costs of maintenance, a 10-year maintenance interval was used. At year zero (0), a large maintenance event would occur, entirely replacing the fouled ballast. Each succeeding year, one maintenance event would occur, consisting of approximately 0.2 m of ballast rock and tamping to adjust elevations to Class 1 specifications.

The field site in Dayton, IL (Dayton Dip) area had been undergoing maintenance events 3 to 4 times per year. However, one assumption made was that with an intensive maintenance intervention in year 1, future maintenance would decrease.

Chrismer and Davis (2000) determined that increased granular layer thickness was a viable method of track improvement and was cost effective. In the maintenance method used in this study, no geosynthetic fabric, grid, or textile was used to separate the subballast from the subgrade. Water management issues can significantly affect the performance of the subgrade. Because of this and the conditions found at the Dayton Dip, yearly maintenance was assumed to be a reasonable estimate for maintenance events.

The net present value (NPV) analysis has benefits and drawbacks; however, it can supply crucial information to project owners who need to make a decision based on a monetary expenditure or return. The aggregate present value of a time series of cash flows, both incoming and outgoing, is defined as the sum of the present values of the individual cash flows (Angeles 2011). NPV can provide a correct decision assuming that a perfect market exists and projects will be mutually exclusive. It also provides the advantages of providing an absolute value, considering the length of the cash flow period. The main drawback of conducting an NPV analysis is the reliance on discount rates. A small increase or decrease in the discount rate will have a considerable effect on the final output (Angeles 2011). NPV provides an effective metric for evaluating project costs over time.

To determine magnitude of annual savings or profits, an NPV analysis was conducted on the gathered data. Quantifying savings or profits from maintenance expenditure is an item that was not explored. For conventional maintenance, many variables are involved: ballast price, maintenance cost, and aggregate quantity variations. To explore the bounds of the NPV, 12 possible combinations of ballast price, maintenance cost, and reclamation depth were examined for 76 m (250 ft) length of the Dayton Dip. The effect of the combinations can be observed in Figure 4.2.

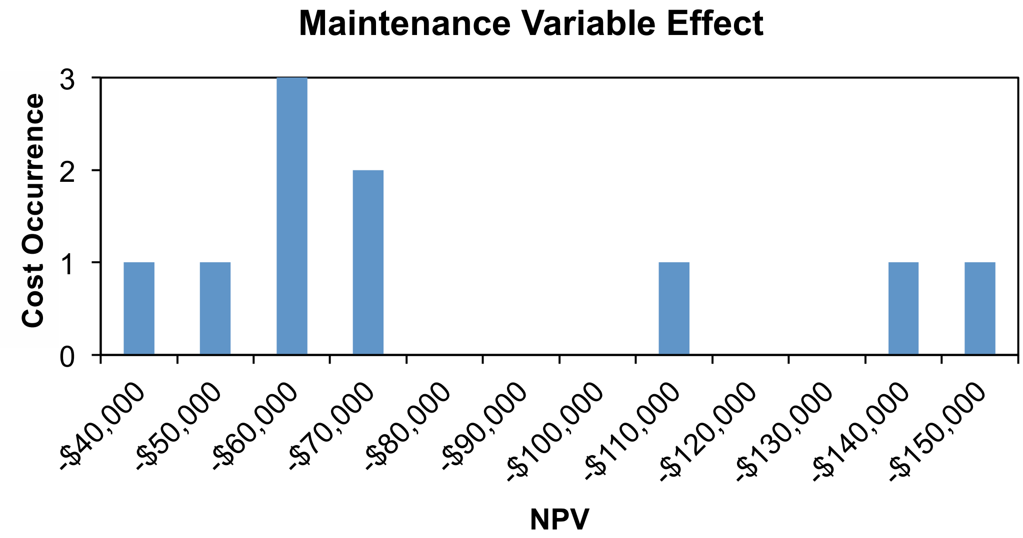


Figure 4.2: Maintenance variable effect

Uncertainty in cost aspects produces a wide range of projected maintenance costs. The range of expected NPV is approximately $100,000. The average cost of yearly maintenance was approximately $7,250 with the median cost being $5,670. The median cost provides a more realistic value for simplistic yearly maintenance. The cost of the maintenance intervention is similar to that in the study conducted by Chrismer and Davis (2000).

NPV is also highly dependent on the discount rate used. In choosing a discount rate, it is important for clients to choose the minimum rate of return when compared to alternative investments (Glick 2007). For an owner or railroad to choose a new method of maintenance, the new method should provide the same rate of return if not higher than the conventional method. Discount rate affects the rate of return, and if an overly conservative discount rate is chosen, costs are underestimated. For this exercise, an initial rehabilitation cost and yearly maintenance cost were chosen, and the discount rate was varied between 0% and 10%. Table 4.2 presents the tabulated results.

Table 4.2: NPV results using different discount rates

Discount Rate	NPV for Maintenance
0%	-$75,350
1%	-$72,759
2%	-$70,365
3%	-$68,148
4%	-$66,093
5%	-$64,187
6%	-$62,414
7%	-$60,766
8%	-$59,229
9%	-$57,797
10%	-$56,458

Initial Rehabilitation	**$26,350**
Yearly Maintenance	**$4,900**

To provide a yearly maintenance value, the median price of ballast cost and thickness was used; this was $4,263 (for the entire 76 m section). A tamping cost of $2.50/ft was chosen as well, because of the small/isolated maintenance. This resulted in a $4,900/year maintenance cost for the 76 m (250 ft) Dayton Dip section. Table 4.2 lists the prices with the applied discount rates. If technology, quarry location, and other details remain constant, the NPV has a maximum value of $75,350 and a minimum of $56,460 over a 10-year period.

The payback period for the PUR injection is the period of time in which the PUR treatment is effective and conventional maintenance can be neglected. Because the time value of money is not taken into account when calculating the payback period, the present value of maintenance was used for the calculation. The payback period for PUR injection was calculated using the median and expected maintenance values ranging from 7.5 years to 11.2 years, with the average being 8.5%.

URETEK supplied a bid package for the PUR injection of the Dayton Dip. The bid package included everything necessary for the injection to occur. Based on Kennedy et al. (2013) who used a similar product, XiTrack™, the product decreased maintenance cycles from 4 times per year to no intervention over a 10-year period. It was assumed from prior research, without available long-term observations, that a 10-year period without maintenance was feasible with the injection strategies and PUR placement. The total cost for the PUR injection by URETEK ICR was $56,000.

Comparing the two maintenance strategies is straight forward. With a reasonable discount rate of 10% or less, the PUR maintenance approach is justified economically. Without long-term observation and results, the 10-year interval may be an over assumption. Operation costs were also not included for both PUR injection and maintenance due to train movements, as the study was limited to maintenance methods. Another limitation was that periodic maintenance and renewal work do not usually interrupt the scheduled train movements and can be planned not to disturb the train schedules (Andrande 2008).

To ensure that the results of the LCCA were reasonable, they were compared with existing figures. AMTRAK in the USA has had annual renewal and maintenance cost of $208,000 per track mile. The average expenditure for maintenance of some European railroads is $174,000 per main track mile (AMTRAK 2009). Individually maintained private railroads had maintenance costs ranging from $91,000 to $380,000 per main line track mile (Amtrak Office of Inspector General 2009). Using the average yearly cost of conventional maintenance (tamping) established in the LCCA for the ballast section ($4,900/year per 76 m), extrapolation to a longer track section (1.6 km or 1 mile) was conducted. The expenditure for maintenance per track mile would be $105,000. Including the initial rehabilitation over a 10-year period increases the yearly expenditure to $7,535. Extrapolating to 1 mile, this results in a yearly maintenance cost of $154,800/mile. With the range of costs anticipated from the sensitivity analysis of the LCCA, a maintenance cost of $150,000 per track mile would be expected. These values fall within the findings of the Amtrak (2009) report on maintenance expenditures for railroads. As this is a regional railroad, the maintenance per track mile is expected to be lower than a Class I freight or AMTRAK-serviced line.

Another finding was that the use of PUR injections requires a high initial capital cost. This high initial cost of PUR injection may not make it feasible to be applied for a large section of railroad. Based on an initial cost of $56,000 per 76 m, to inject 1 mile of track with the designed injection would cost $1,158,000. PUR injection requires field observation and monitoring; with time and data, proof of effectiveness can be shown, and the initial capital cost can be justified.

Track maintenance is one of the most important aspects of railroad transportation and with increased heavy axle loads, increased maintenance can be expected (Hesse et al. 2014). Maintenance should be conducted to meet track specifications; however, it should also be achieved at a minimum cost (Esveld 1990). Predicting which maintenance activity would be more cost effective is difficult; however, progressive technology may provide the necessary means to decrease maintenance cost in the future.

4.4 LCA Inputs and Results

4.4.1 Definition of goal, scope, and functional unit

Sustainability and conservation are important to preserve resources for future generations. Railroad maintenance requires multiple processes and steps that are energy intensive. The goal of this study was to quantify three metrics by which PUR injection and conventional maintenance could be assessed. Energy, CO_2 emissions, and water usage were investigated and compared.

In the overall scope of a study, it is important to quantify resources; for example, one may not want to include truck manufacturing for transportation of goods, but consider the fuel consumption and emissions for transportation. For the PUR injection LCA, the scope included PUR production, transportation, materials/fuel used during injection, and end of life being repurposed as an embankment fill. Conventional maintenance included ballast extraction and washing, transportation, maintenance, yearly tamping, and yearly ballast additions, with the end of life consisting of repurposing the ballast for embankment construction. During the life of the track operations, various processes occur such as train traffic and inspections. For simplification, train operations and inspections were assumed the same between the two scenarios and were not included.

The functional unit was used to make the LCA study applicable to more than just the Dayton Dip. For the conventional maintenance, the unit was defined to be 1000 kg (1 t) of aggregate, and for the PUR application, it was 1 kg of PUR.

4.4.2 Life cycle inventory

Background and foreground data were both used to compile the necessary inputs for the analysis. A SimaPRO multi-user license (Analyst) was obtained and the professional database was used. USLCI, Ecoinvent 3, and Industry Data 2.0 were used to obtain background information and to fill in gaps for other required data. For example, USLCI provides data on train transport, limestone/dolomite mining, transit by truck, and generators.

Engine information for different maintenance equipment was gathered from an engine manufacturer, Cummins Inc., to provide information on fuel consumption during maintenance events. Consumptive water usage was determined by typical production rates, a closed system, and evaporation assumptions.

The study is limited because many background data were taken from the databases provided within SimaPro. Some of the limitations can be overcome by the use of a Monte Carlo simulation. The simulation uses the distribution of the data rather than a single value. Train traffic on the track was not included. Track use is impacted by maintenance scenarios, which can significantly affect final environmental performance.

4.4.3 Life cycle impact assessment

ReCiPe World was chosen as the assessment tool to carry out the study based on previous studies. The tools are used to transform the list of resources, processes, and materials into a few unique indicators. The indicators used in this project were water consumption (m^3), energy usage (kg oil), and CO_2 emissions. ReCiPe can provide a detailed examination into midpoint analysis, which is easy to understand, interpret and contains less uncertainty. Midpoint indicators are the environmental impacts of the life cycle inventory. ReCiPe can also provide information on the endpoint of the data, i.e., effects to human health, ecosystems, and resource availability. Owing to the limited scope of the project, midpoint indicators were only used for the analysis. The results were not weighed; ReCiPe itself does not contain weighing factors for midpoint indicators.

A period of 10 years was chosen for the study duration. The same maintenance interval used in the LCCA was mirrored here. The ballast section would receive yearly maintenance consisting of 0.15 m of ballast replenishment from the same quarry. The quarry was located 5 km from the site and ballast was transported by a diesel locomotive. After placement of ballast, the track would be adjusted to a final elevation and tamped. The typical engine used in tamping equipment is a large-displacement (6.7 L to 8.3 L) diesel engine used to power hydraulic movements. At the 10th year, an undercutting machine would remove the upper ballast and replace it with clean ballast. The old ballast would be transported using a front-end loader to a final disposal location of an embankment or slope flattening nearby.

The PUR injection was structured over the same 10-year period. It was assumed that the interventions would happen only at time zero and after 10 years. The specialized truck containing the PUR injection equipment would be driven from Denver, CO to the location in Ottawa, IL. The injection equipment requires a power source (diesel generator) to operate the pumps and air supply to inject the PUR into the subsurface. Once injected, it would remain in place for 10 years, then the ballast layer would be undercut and fresh ballast would be placed. The soil containing PUR grout would be transported using a front-end loader to a final disposal location of an embankment construction or slope flattening nearby.

Table 4.3 provides the average amounts of the categories of interest for both maintenance situations. Table 4.4 presents the contributing values from each step of maintenance. Over the study period, the results show that conventional maintenance methods use more water and produce more CO_2 emissions; however, PUR injection uses more energy (oil).

Table 4.3: Average category quantities for LCA

	Conventional Maintenance	**Polyurethane Injection**
kg CO_2	13,710	12,300
Water depletion (m^3)	75.4	13.6
kg Oil	4578	5,720

Table 4.4: Contributions of processes in LCA

	Conventional Maintenance			Polyurethane Injection		
	kg CO_2	Water ($m^{3)}$	kg Oil	kg CO_2	Water ($m^{3)}$	kg Oil
Material Production/Extraction	9,720	72.3	3,150	10,400	-	5,170
Transportation to site	187	-	58	450	-	139
Maintenance event	3,990	3.14	1,370	724	0.7	249

The results shown in Figure 4.3 indicate the quantities of the categories found in conducting the LCA. In Figure 4.4 PUR injection has been normalized with respect to the conventional maintenance categories. The magnitude of the units and categories are different; thus, the different categories are normalized within one another. The PUR injection consumes less water and exhibits less CO_2 emissions. Oil (energy) consumption for PUR injection shows an increase of 25% above that of conventional maintenance. During the material manufacturing, a substantial amount of energy is needed to create foam. PUR injection, as a maintenance strategy, avoids using traditional maintenance methods over 10-years. During this period many products and processes are avoided, such as ballast extraction, transportation, and tamping. The PUR injection alternative gains the benefit over 10-years of not conducting traditional maintenance. Production of the rigid polyurethane foam accounts for most of the resource consumption and emissions. The amount of PUR used for a project will have the largest impact on LCA. For the traditional maintenance, the ballast extraction uses water to wash the aggregate and depletes much more water (i.e., 90%) than maintenance activities (placement, tamping etc). The ballast extraction accounts for about 70% of the consumption of energy and CO_2 emissions.

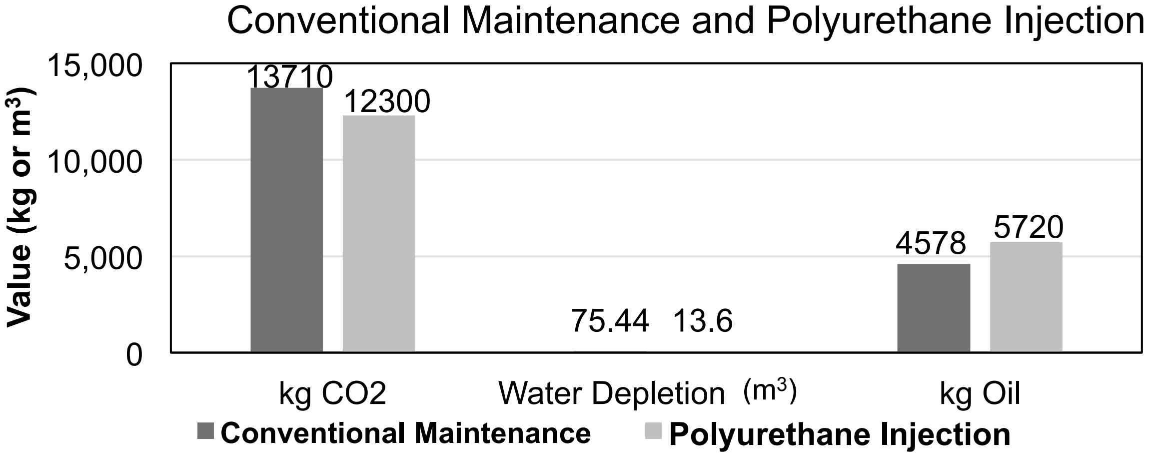


Figure 4.3: LCA quantity comparison

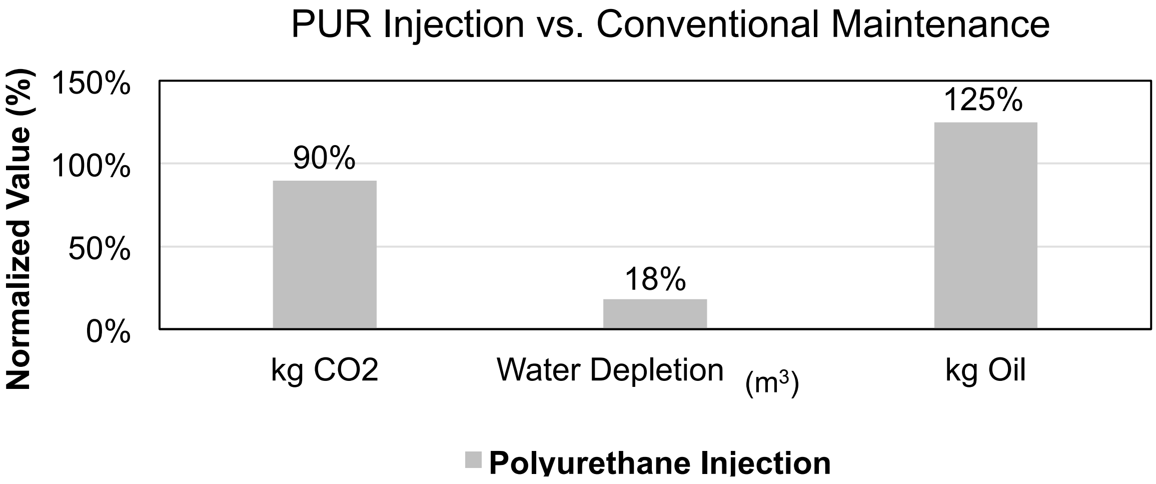


Figure 4.4: Normalized comparison of PUR injection and conventional maintenance methods

As mentioned before, all LCAs have some uncertainty in the data: parameter uncertainty, model uncertainty, choices, spatial variability, and temporal variability. The quality of the data collected is dependent on the measurement quality, sample size, and date of the measurements. For a better understanding of where the true values may lie and their distribution, a Monte Carlo simulation was conducted on both maintenance types.

4.4 Monte Carlo Simulation

To come up with a measure of uncertainty and to determine where the range of expected values may occur, a Monte Carlo simulation was conducted for both conventional maintenance and PUR injection.

4.5.1 Conventional maintenance

Uncertainty is found in all data sets, especially when specific values are estimated. To estimate conventional maintenance variation in the categories of interest, distributions of the variable were determined through data analysis or logical bounds.

Ballast production is fairly standardized; limestone is quarried from open pits by blasting, followed by mechanical crushing, screening, and washing to obtain the desired particle size distribution. Aggregate production facilities attempt to recycle as much water as possible (approximately 85%); however, some amount is lost through evaporation, wetting of aggregates, and spraying. A lognormal distribution of the water usage was applied to the data with a square of the standard deviation of 1.5 to introduce an uncertainty of 50% from the average value (1 is zero uncertainty). When distributions are unknown to an extent but reasonably estimated, the distribution can be considered as the default (SimaPro). Previous research in LCA distributions often find a median value, then apply either a lognormal or normal distribution with geometric standard deviation of 1.1 to 2 (Kucukvar et al. 2014; Sonneman et al. 2003).

Shipment of the ballast between quarry and project site was limited to a rectangular (bounded uniform) distribution. The quarries in close vicinity to the Dayton Dip were approximately 4 km and 10 km away from the selected site. Provided the quarries produce a ballast rock suitable for track substructure, the rock would most likely come from those locations.

Tamping a railroad track includes production rates. A ballpark production rate was found from an interview with a worker, which resulted in approximately 400 m/h (Tarry 2014). During the tamping process, a typical lift of the track is limited to 50 mm per pass (Tarry 2014). With a known site length and a historical dip of 150 mm, as observed in the field, it would take three passes, which is approximately an hour to complete the tamping of the study site. Using this time and fuel consumption data from different Caterpillar engines employed in maintenance equipment, an average fuel consumption and distribution were established.

The railroad substructure/ballast end of life scenario was simplified; however, it was confirmed through an interview with an engineer. The old ballast and substructure would be undercut and the wastes from the activities would be used to build up an embankment or flatten out slope geometry.

4.5.2 Polyurethane injection

A similar approach was used to establish distributions for the resources and products used in PUR injection. Estimates from URETEK USA were used to find the average and distribution of the PUR used for the injection. A contingency of ± 10% of the estimated weight of PUR would be used. Values for ± 10% of the projected quantity were used to establish a uniform distribution of possible injection. Steel rods are used to inject the PUR into the ground. A contingency of ±10% was applied to the steel rods as well to correspond to the PUR used. The PUR was assumed to be manufactured as near as possible to the equipment that required mobilization.

Mobilization distance was governed where the injection equipment was last used. For the study, URETEK had the equipment designed for use on railroads located around Denver, CO. To reach the site located in Dayton, IL, three possible routes could be taken—I-70, I-80, and a combination of the two (I-80 & I-70). The distances are 1,700 km, 1,510 km, and 1,710 km, respectively. Uniform distribution of the data was included, because the return trip would be with less weight.

During the injection processes, a generator must be used to power hydraulic pumps, heaters, and possibly other tools. A reasonable estimate for fuel consumption was made with a lognormal distribution with a square root of distribution interval of two; 95% of all the values are between the estimated values divided by two and the estimated value multiplied by two.

After 10 years, the railroad substructure/ballast end of life scenario was simplified; however, it was confirmed through an interview with an engineer. The old ballast and substructure would be undercut and the wastes from the event would be used to build up an embankment or flatten out slope geometry.

4.6 Monte Carlo Simulation Results & Discussion

The Monte Carlo simulation was run for a fixed number of iterations (1000), which was experimentally determined to achieve reproducible results (Salve 2008). The tabulated results of the Monte Carlo simulation after 1000 trials are given in Table 4.5.

Table 4.5: Monte Carlo results

	Conventional Maintenance			Polyurethane Injection		
Category	**Mean**	**Median**	**95 % Range**	**Mean**	**Median**	**95% Range**
kg CO_2	13,900	13,800	10,200–18,700	12,300	12,300	10,800–13,900
Water Depletion (m^3)	75.2	73.7	50.4–108	13.6	13.6	11.9–15.4
kg Oil	4,590	4,530	3,350–6,160	5,740	5,750	5,050–6,510

The results based on the ReCiPe World method show considerable variance of the categories, which would be expected with the data distributions. The ranges of the categories found with a 95% confidence interval are logically reasonable. A few of the inputs were provided as a uniform distribution, which equally applies probability to the whole data set. A proper determination of the probability distribution is only possible if extensive data are available (Sonnenman et al. 2002). The probability density functions (PDFs) for the categories related to conventional maintenance all have a slight lognormal distribution. The resulting probability distributions for each category of both conventional maintenance and PUR injection show semi-symmetrical distributions. The values determined previously for the average (mean) do not vary significantly from the mean and median calculated using the Monte Carlo simulations. Because of the inputs for the PUR injection, the final PDFs show a more normal distribution shape. Using a probability distribution for the input data, all category results have a mean value and a PDF of expected values.

To reiterate many previous studies, it is difficult to quantify uncertainty in LCAs. This includes determining the actual distribution of the data, because large quantities of data are required for meaningful statistics. Improvement could be made in the LCA by conducting a traffic analysis of the spur line to estimate the average train traffic. Foreground data regarding both the Bayer PUR product and ballast production should be collected.

5. Summary and Conclusions

This project documents the results of a field study on the use of expanding rigid polyurethane (PUR) foam to remediate substructure deficiencies in a railroad track at a field site in Madison, Wisconsin. To clarify the contributing underlying problems at the track field site, geotechnical and geophysical investigations were conducted. URETEK ICR provided dynamic cone penetrometer logs, which provide an indication of soil strength. The UW-Madison team conducted ground penetrating radar, electrical resistivity tomography, and excavated test pits to take samples to run engineering property tests in a laboratory setting. In addition, track modulus was measured to quantify the structural integrity of the railway track. The data from these different tests collectively indicated that railway siding 2 is considered to be in poor condition. Furthermore, the midsection of the middle railway siding, 50 m (165 ft) east of the frog, is observed to be softer than the section 25 m (82 ft) east of the frog.

The investigation assisted in the design of two types of polyurethane injections: one to strengthen the railway substructure at 1.2 m (4 ft) depth and one to strengthen and stiffen the soft subsurface material at 1.8 m (6 ft) depth. With URETEK ICR's background and expertise in PUR injection for infrastructure projects including rail crossings, designing a functional and economical injection package was possible. The injection was proposed as a combination of subballast layer strengthening and URETEK deep injection (UDI) to strengthen and stiffen the subgrade. Owing to imposed restrictions on the railroad, PUR could not be placed within 30 cm of the bottom of the tie.

PUR injections showed no significant effect on the geometry of the railway with or without loading. PUR injected areas showed a higher track modulus with average track rating, i.e., 15 or more based on u-values; whereas, non-injected areas exhibit a poor track rating, i.e., mostly less than 10. Furthermore, the control point showed a 90% increase in track modulus (increase from 8 MPa to 15.2 MPa) after PUR injection.

.The post-injection track substructure geophysical data were obtained. The ERT results showed the areas of the PUR injection as zone of increased electrical resistivity. In addition, GPR survey results showed some indication of the injection.

A life cycle cost analysis was conducted with inputs from URETEK ICR and Wisconsin and Southern Railroad considering a ten-year period. Over a 10-year period, PUR injection appears to be a superior improvement methodology to traditional maintenance resulting in a cost savings from $1000 - $20,000 depending on discount rate. A life cycle assessment indicated that PUR injection results in reduction of water use and CO2 emissions, 82%, and 10% respectively, compared to conventional maintenance methods, however, it consumes an estimated 25% more energy compared to conventional maintenance methods.

6. References

Ahlf, R.E., 1975. “M/W Costs: How Are They Affected by Car Weight and the Track Structure,” Railway Track and Structures, pp. 34-37 and pp. 90-92.

Alsabhan, A. H., 2016. Experimental Monitoring of Geotechnical Response of Railway Track Systems,” PhD Thesis, Department of Civil and Environmental Engineering, University of Wisconsin, Madison

Amtrack Office of Inspector General. Retrieved from http://www.amtrakoig.gov/sites/default/files/reports/EVALUATIONREPORT-92809.pdf

Andrade, A. R., 2008. “ Renewal decisions from a Life-cycle Cost (LCC) Perspective in Railway Infrastructure: An integrative approach using separate LCC models for rail and ballast components,” Doctoral dissertation, Technical University of Lisbon (IST).

Angeles, J. V. V., 2011. “The development of a life cycle cost model for railroad tunnels,” Doctoral dissertation, Massachusetts Institute of Technology.

Bayer Material Science, 2010. “486STAR Polyurethane Foam Grout.” Technical Data Sheet, Spring, Texas.

Boler, H., 2012. "On the Shear Strength of Polyurethane Coated Railroad Ballast." MS Thesis, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champagne.

Bribian I.Z., Uson A.A., and Scarpellini S., 2009. “Lifecycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification,” Building and Environment Vol. 44, pp. 2510–2520.

Brill, G.T., and Hussin, J.D., 1992. “The use of compaction grouting to remediate a railroad embankment in a karst environment.” In-situ soil modification. Louisville, Kentucky.

Buzzi, O., Fityus, S., and Sloan, S. W., 2010. “Use of expanding polyurethane resin to remediate expansive soil foundations.” Canadian Geotechnical Journal, Vol. 47(6), pp. 623-634.

Cai, Z., Raymond, G. P., & Bathurst, R. J., 1994. “Estimate of static track modulus using elastic foundation models,” Transportation Research Record, Vol.1470.

Chrismer, S., and Davis, D., 2000. ” Cost comparisons of remedial methods to correct track substructure instability,” Transportation Research Record: Journal of the Transportation Research Board, Vol. 1713, pp. 10-14.

Dersch, M. S., Tutumluer, E., Peeler, C. T., and Bower, D. K., 2010. “Polyurethane Coating of Railroad Ballast Aggregate for Improved Performance.” In 2010 Joint Rail Conference, American Society of Mechanical Engineers, pp. 337-342.

Dolcek, T., 2013. “Mechanical Behavior of Polyurethane Stabilized Fouled Ballast (PSFB).” MS Thesis. Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

Du, G., and Karoumi, R., 2013. “Life cycle assessment of a railway bridge: comparison of two superstructure designs,” Structure and Infrastructure Engineering: Maintenance, Management, LifeCycle Design and Performance, Vol. 9 (11).

Du, G., and Karoumi, R., 2012. “Life cycle assessment framework for railway bridges: literature survey and critical issues.” Structure and Infrastructure Engineering, Life-Cycle Design and Performance, Ahead-of Print, DOI: 10.1080/15732479.2012.749289

El-Kelesh, A., Matsui, T., and Tokida, K., 2012. “Field Investigation into Effectiveness of Compaction Grouting.” Journal of Geotechnical and Geoenvironmental Engineering.

Esveld, C., 1990. “Computer-aided maintenance and renewal of track,” Railroad Conference, Technical Papers Presented at the 1990 ASME/IEEE Joint, pp.165-170.

Gallagher, P. M., Spatari, S., and Cucura, J., 2013. “Hybrid life cycle assessment comparison of colloidal silica and cement grouted soil barrier remediation technologies,” Journal of hazardous materials, Vol. 250, pp. 421-430.

Glick, S., 2007. Life-cycle assessment and life-cycle costs: A framework with case study implementation focusing on residential heating systems. ProQuest

Hassan, M., 2009. “Life-Cycle Assessment of Warm-Mix Asphalt: an environmental and economic perspective,” In Proceedings of 88th transportation research board annual meeting. Washington D.C., USA, pp. 1–15.

Hay, W., 1982. Railroad engineering (2nd ed.). New York: Wiley.

Herrick, J.E., and Jones, T.L., 2002. “A dynamic cone penetrometer for measuring soil penetration resistance,” Soil Science Society of America Journal, Vol. 66, pp. 1320-1324.

Hesse, D., 2013. “Impact of Increasing Freight Loads on Rail Infrastructure from Fracking Sand Transport.” MS thesis, Department of Civil and Environmental Engineering, University of Wisconsin-Madison.

Hesse, D. E., Tinjum, J. M., and Warren, B. J., 2014. “Impact of increasing freight loads on rail substructure from fracking sand transport,” Transportation Geotechnics, vol. 4, pp. 241-256.

Indraratna, B., Salim, W., and Rujikiatkamjorn, C., 2011. Advanced Rail Geotechnology- Ballasted Track, Book, CRC Press, Taylor & Francis Group, London, UK.

Keene A. K., 2012. “Mitigating ballast fouling impact and enhancing rail freight capacity”. Master’s thesis, Department of Civil and Environmental Engineering, University of Wisconsin, Madison.

Kennedy, J., Woodward, P. K., Medero, G., and Banimahd, M., 2013. “Reducing railway track settlement using three-dimensional polyurethane polymer reinforcement of the ballast,” Construction and Building Materials, Vol. 44, pp. 615-625.

Kerr, A.D., 2003. Fundamentals of railway track engineering, Simmons-Boardman Books, Inc., Omaha, Nebraska.

Klentzman, R., 2015. "URETEK mobilization distances." Message to Benjamin Warren. (May 12th). E-mail.

Kucukvar, M., Noori, M., Egilmez, G., and Tatari, O., 2014. “Stochastic decision modeling for sustainable pavement designs,” The International Journal of Life Cycle Assessment, Vol. 19(6), pp. 1185-1199.

LaGrega, M.D., Buckingham, P.L., and Evans J.C., 1994. Hazardous Waste, 761 Management. New York: McGraw-Hill.

Li, D., and Davis, D., 2005. “Transition of railroad bridge approaches.” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 131(11), pp. 1392-1398.

Lichtberger, B., 2005. Track compendium. Hamburg: Eurailpress, Tetzlaff-Hestra GmbH and CO. KG.

Marsh, B., and Schaalma, R., 2015. "WSOR Maintenance Information." Message to Benjamin Warren. (January 28th to February 6th). E-mail.

Mroueh, U., Eskola, P., and Laine-Ylijoki, J., 2001. “Life-cycle impacts of the use of industrial by-products in road and earth construction,” Waste Management, Vol. 21(3), pp. 271-277.

Oertel, G., and Abele, L., 1985. Polyurethane handbook: chemistry, raw materials, processing, application, properties. Hanser Publishers. Distributed in USA by Scientific and Technical Books, Macmillan.

Priest, J. A., & Powrie, W., 2009. “Determination of dynamic track modulus from measurement of track velocity during train passage,” Journal of Geotechnical and Geoenvironmental Engineering, Vol. 135(11), pp. 1732-1740.

Randall, D., and Lee, S., 2002. The polyurethanes book. Wiley.

Read, D., Chrismer, S., Ebersohn, W., and Selig, E., 1994. “Track modulus measurements at the Pueblo soft subgrade site,” Transportation Research Record, Vol. 1470.

Rose, J., Brown, E., and Osborne, M., 2000. “Asphalt Trackbed Technology Development: The First 20 Years.” Transportation Research Record, pp. 1-9.

Salve, J.L., 2008. “Dealing with uncertainties in Life Cycle Assessment for emerging technologies.” Master’s thesis, School of Science, Open University of the Netherlands.

Selig, E. T. and Walters, J. M., 1994. Track Geotechnology and Substructure Management, Book, Thomas Telford, New York, NY.

Selig, E. T., and Li, D., 1994. “Track modulus: Its meaning and factors influencing it,” Transportation Research Record, Vol.1470.

Sharma, P. V., 1997. Environmental and engineering geophysics, Book, Cambridge University Press.

Sonnemann, G. W., Schuhmacher, M., and Castells, F., 2003. “Uncertainty assessment by a Monte Carlo simulation in a life cycle inventory of electricity produced by a waste incinerator,” Journal of Cleaner Production, Vol. 11(3), pp. 279-292.

Stripple, H., 2001. “Life cycle analysis of road; A pilot study for inventory analysis,” Swedish Environmental Research Institute (IVL), Gothenburg, Sweden.

Stripple, H., and Uppenberg, S., 2010. “Life cycle assessment of railways and rail transports – Application in environmental product declarations (EPDs) for the Bothnia Line.” IVL Swedish Environmental Research Institute. Ltd.

Szycher, M., 1999. Szycher's handbook of polyurethanes. Boca Raton: CRC Press.

Tarry, P., 2014. “How the track tamping machine is used,” Response to comments. www.evra.org.uk/engineering/How%20the%20tamper%20works.doc

Walls III, J., and Smith, M. R., 1998. “Life-cycle cost analysis in pavement design-interim technical bulletin,” (No. FHWA-SA-98-079,).

Warren B. J., 2015. “Field application of expanding rigid polyurethane stabilization of railway track substructure,” Master’s thesis, Department of Civil and Environmental Engineering, University of Wisconsin, Madison.

Webb, G., Webb, D., Zarembski, A.M., Gauntt, J.C., and Corallo, D.L., 2012. “Tie Guide”. Fayetteville, GA.

Woodward, P. K., Kennedy, J., Laghrouche, O., Connolly, D. P., and Medero, G., 2014. “Study of railway track stiffness modification by polyurethane reinforcement of the ballast.” Transportation Geotechnics, Vol. 1(4), pp. 214-224.

Woodward, P. K., Kennedy, J., Medero, G. M., and Banimahd, M., 2012. “Application of in situ polyurethane geocomposite beams to improve the passive shoulder resistance of railway track.” Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 226(3), pp. 294-304.

Zapata, P., and Gambatese, J. A., 2005. “Energy consumption of asphalt and reinforced concrete pavement materials and construction,” Journal of Infrastructure Systems, Vol. 11(1), pp. 9-20.

This page is intentionally left blank.

NATIONAL CENTER FOR FREIGHT & INFRASTRUCTURE RESEARCH & EDUCATION

CFIRE

University of Wisconsin-Madison
Department of Civil and Environmental Engineering
2205 Engineering Hall
1415 Engineering Drive
Madison, WI 53706
Phone: 608-263-9490
cfire.wistrans.org