LIFE CYCLE BENEFITS OF SUBGRADE REINFORCEMENT USING GEOCELL ON A HIGHSPEED RAILWAY – A CASE STUDY

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ABSTRACT

Track built on poor or weak subgrade will, in general, experience a greater rate of degradation than track built on good or adequate subgrades. This, in turn, results in shorter intervals between surfacing/tamping events, a costly endeavor for high speed railways with tight track geometry tolerances and limited track access. It is therefore paramount that this structure maintain adequate support properties to uphold the track geometry and to ensure the safety of the trains traveling over the rails.

A research effort sponsored by the Federal Railway Administration allowed for the determination of track geometry performance as a function of subgrade support during the renewal of a historically poor performing location of high speed track. In this research study, and in addition to additional drainage, a section of track was reinforced using a geocell layer designed to strengthen the existing ballast/subgrade material, while adjacent sections were rebuilt to traditional track standards. Pressure transducers were placed within the subgrade layer under both rails in the geocell and conventional track zones. The site was monitored over a period of one year with pressure and track geometry measurements recorded at regular intervals.

Data analysis showed a significant reduction in pressure at the ballast/subgrade interface on the order of 50% as well as a corresponding reduction in the rate of degradation on the order of a factor of 6+. Overall, the test showed significant benefits associated with the installation of the geocell material above and beyond that seen by more traditional rebuild and drainage improvement.

INTRODUCTION

Maintaining adequate track substructure strength is paramount to providing safe railroad operation with minimal maintenance requirements. In the event that issues arise with the subgrade and/or ballast, frequent and costly maintenance can be needed. If the root cause of the substructure problem is not properly identified and addressed, the maintenance/degradation cycle will continue, and eventually, accelerate.

A section of high speed rail had been experiencing ballast fouling and associated frequent maintenance due to rapid track geometry degradation. The root cause of this ballast fouling was traced back to undercutting conducted in the 1990s on the central of three adjacent tracks. The undercutting disturbed the underlying clay layer which caused the clay to migrate both into the track's ballast layer as well as into the ballast of the two adjacent tracks under saturated conditions with train traffic. Frequent surfacing was required to maintain track geometry in this area. Figure 1 illustrates the track roadbed degradation over time at the site.



FIGURE 1: CHOSEN REBUILD SITE

This paper presents the results of a total track rebuild which was performed on one of the three tracks in this region. As part of this total rebuild, a Novel Polymeric Alloy (NPA) Geocell material was utilized to increase substructure strength (additional drainage was also added). Previous studies have shown that adding substructure reinforcement via a geocell like material can improve the surfacing cycle (1, 2, 3) as well as improve overall substructure performance (4, 5, 6, 7). For this particular site, the effectiveness of using the NPA geocell material was quantified by studying subgrade pressure (measured via installed pressure transducers) and measured track geometry degradation over time. That information was used to produce a cost benefit analysis to ultimately determine under what surfacing conditions the installation of a geocell material yields a positive return on investment.

SITE DETAILS

The rebuild site (Figure 1) had been experiencing ballast fouling and development of mudspots (especially after periods of rain) ever since an undercutting procedure was conducted in the 1990s. This had led to a high rate of track geometry degradation and corresponding frequent maintenance. The site in question is FRA Class 7 track (8) and sees traffic from both high speed trains (125 mph) and higher speed regional trains (110 mph); some modest freight traffic is also seen on this segment of track. Due to its Class 7 rating, track geometry tolerances are very tight and in the event of excessive degradation, slow orders can be issued bringing the track class down to class 6 or class 5 depending upon the severity.

Pre-rebuild Site Details

Various measurements were collected on this site prior to its rebuild to support the approval of the maintenance activity. Soil investigation via cross-trench excavation and cone penetrometer testing conducted in 1996 on the central of three tracks indicated a particularly poor subgrade (Figure 2). The primary component of the subgrade was shown to be highly plastic clay. Cone-penetrometer testing indicated that this material in particular, and the overall substructure in general, was very weak. The top 5 ft. below the top of the ballast was exceptionally weak due to the fouling. Tip resistance was measured to

a maximum value of ~2000 PSI where the expected tip resistance at this depth is to be between 5000 to 6000 PSI.



FIGURE 2: EXCAVATED CROSS-TRENCH (LEFT) AND CONE-PENETROMETER RESULTS (RIGHT)

Track geometry measurements made before the rebuild also supported the existence of a subgrade issue. Figure 3 shows cross-level data compiled over an 8 month period before the rebuild. The central section C showed rapid degradation of not just the cross-level, but also other track geometry channels such as surface.





Rebuild Plan and Execution

The rebuild plan aimed to eliminate the ballast fouling and weak subgrade support which lead to rapid track geometry degradation. This was accomplished through the installation of both additional drainage and the use of a geocell based subgrade support material. During the rebuild, only the central section of the track zone would have the geocell material installed. This allowed for testing and evaluation of the geocell material solution for use in other track locations facing similar track support condition issues and corresponding high frequency maintenance cycles.

Using the available track condition information, section C from Figure 3 was chosen as the site for installation of the geocell material. This location was chosen because of its on-going maintenance issues as well as the availability of both a maintenance window and the geocell material¹. Two additional sections,

¹ The Novel Polymeric Alloy (NPA) geocell material chosen was PRS-Neoloy Geocell (provided by PRS Geo-Technologies) (9)

one on each side of section C were also rebuilt with additional drainage but without the geocell material. This allowed for comparative testing of the performance of both the geocell (reinforced) and control (non-reinforced) zones of the track using pressure load cells and track geometry measurements (instrumentation discussed in next section).

During the rebuild, the track and substructure was removed down to the subballast. After re-compacting of the subballast and installation of additional drainage, the track was rebuilt. Figure 4 shows the various material layers utilized during rebuild process in the section of track with the geocell material. The NPA Geocell material utilized has high elastic stiffness (>600 MPa @60^oC), high resistance to creep (deformation <3%) and high tensile strength (>19 kN/m) properties, which are important for maintaining long-term track geometry performance.



FIGURE 4: CROSS-SECTION OF THE SUBSTRUCTURE DURING REBUILD

SITE INSTRUMENTATION AND MONITORING

Two types of data were collected and analyzed to evaluate the effectiveness of the geocell reinforcement layer on the track rebuild. Specifically, load cell pressure data (measured above the subbase directly beneath the left and right rails) and track geometry data were recorded and analyzed.

Site Instrumentation- Pressure Load Cells

As part of the rebuild, pressure load cells were installed beneath each of the two rails (see Figure 5) at the top of the subbase layer (see Figure 6). The goal of this instrumentation was to study how the substructure dissipated the load of the passing train over time.



FIGURE 5: LOAD CELL POSITIONS AND CHANNEL ID NUMBERS IN TRACK

Figure 5 shows where the 4 load cells were positioned under the rebuilt track. In this configuration, 2 load cells were positioned within the geocell reinforcement zone (channels 2 and 4) and two were placed in the rebuilt track region which did not have a layer of geocell installed (channels 3 and 1); roughly 230 ft. apart. The load cells were placed at an equal depth below the rail at the top of the subgrade (Figure 6). In the geocell zone, this depth placed the load cell just under the geocell material.



FIGURE 6: LOAD CELLS SET IN SUBBASE

Load Cell Data

Pressure data measurements were initiated once normal traffic operations resumed after the rebuild. Pressure data was recorded at regular intervals at a variety of frequencies ranging from daily to monthly as more traffic and settlement of the track structure occurred. Table 1 lists the dates and temperatures of the various measurements taken from the load cells.

Phase	Date	Temperature °F (low)	Temperature °C (low)
Phase 1 Daily Measurements	October 31, 2015	57.2 (39.2)	14 (4)
	November 1, 2015	66.2 (53.6)	19 (12)
	November 2, 2015	64.4 (46.4)	18 (8)
	November 3, 2015	68.0 (41.0)	20 (5)
	November 4, 2015	73.4 (44.6)	23 (7)
Phase 2 Weekly Measurements	November 13, 2015	60.8 (50.0)	16 (10)
	November 23, 2015	42.8 (30.2)	6 (-1)
	December 7, 2015	57.2 (32.0)	14 (0)
	December 16, 2015	53.6 (44.6)	12 (7)
Phase 3 Monthly Measurements	January 29, 2016	42.8 (24.8)	6 (-4)
	February 26, 2016	39.2 (30.2)	4 (-1)
	March 30, 2016	57.2 (33.8)	14 (1)
	April 20, 2016	68.0 (44.6)	20 (7)
	May 18, 2016	66.2 (51.8)	19 (11)
	June 14, 2016	78.8 (60.8)	26 (16)

TABLE 1: LOAD CELL MEASUREMENT INTERVALS

During any particular date, multiple train car pressure measurements were taken to generate a large distribution of data. Measurements were identified as either high speed or regional trains due the weight differences in both the passenger cars and the associated locomotives as well as the variation in train speeds. A typical pressure response of a passing high speed train is shown in Figure 7. Examination of this data shows that in the section of track which was reinforced with the geocell material, recorded pressure data magnitude was roughly half that of the pressures in the non-reinforced rebuilt section of track. This was typical of the pressure cell data recorded during this phase of the activity.



FIGURE 7: TYPICAL LOAD CELL RESPONSE OF PASSING HIGH SPEED TRAIN (WEST SIDE RAIL)

At the conclusion of the data collection activity, the pressure data was compiled and analyzed to understand how the substructure was behaving and if the geocell material had an effect on performance from a pressure distribution standpoint. Figure 8 illustrates how maximum passenger car wheel response varied by location (load cell number) and train type/speed for the full entire dataset. As can be seen from Figure 8, the distribution of measurements show that the pressure readings for the track section reinforced by the geocell material are significantly lower than the non-geocell track sections. In addition, the distribution of the pressure readings (e.g. the standard deviation of the data) is more highly concentrated (has a lower deviation) for the geocell zone than for the non-geocell zones. Figure 9 shows how the substructure pressure varied over time. Again, it can be seen that for the zone with the geocell material, load cell measurements were consistently below that of the unreinforced (non-geocell) region of track.



FIGURE 8: DISTRIBUTION OF MAX WHEEL PRESSURES (PASSENGER CARS)





Load Cell Validation via Classical Models

As noted above, field observation and analysis of measured pressure data indicated that the application of the geocell material had a significant effect on the loading of the substructure. However, it is also important to compare these measured values to expected pressures of the non-reinforced test zone² (e.g. without geocell) as determined from established methods of substructure load quantification (10). To accomplish this, three different substructure stress models were compared to the measured results (11, 12):

Load Spread with 1:2 load distribution

² The referenced models are for analysis of conventional ballasted track and cannot be applied to track with a geocell reinforcing layer.

- Talbot Model for subgrade pressure distribution
- Boussinesq model

To properly apply these models, various track and traffic parameters needed to be calculated from known or assumed properties. Table 2 presents the properties of both the locomotives and passengers cars of the regional and high speed trains used in this analysis³. Also presented are the associated tie/ballast pressures calculated from those properties. It should be noted that the tie/ballast pressure was derived from beam on elastic foundation theory $(11, 12)^4$.

		Regional		High Speed	
Property	Units	Locomotive	Passenger Car	Locomotive	Passenger Car
Car Weight	lbs.	252590	145000	200000	146000
Axles	#	4	4	4	4
Static Load	lbs.	31574	18125	25000	18250
Car Velocity	mph	110	110	125	125
Wheel Diameter	In.	40	36	40	36
Dynamic Load	lbs.	60227	36401	50781	39161
Tie Load	lbs.	20962	12670	17675	13630
Effective Area	in.^2	374	374	374	374
Tie/Ballast Stress	PSI	56.0	33.9	47.3	36.4

TABLE 2: PASSENGER CAR/LOCOMOTIVE PROPERTIES

The data in Table 2 was utilized as inputs to the three indicated models. Analysis showed that two of the three models (Load Spread 1:2 and Boussinesq) are similar to actual measurements⁵. It can therefore be implied that the measured stress values were consistent with expected results derived from the conservative, classical models. Table 3 tabulates the results of the comparison.

TABLE 3: MEASURED VS. MODEL RESULTS

		Regional		High Speed	
Property	Units	Locomotive	Passenger Car	Locomotive	Passenger Car
Tie/Ballast Stress	PSI	56.0	33.9	47.3	36.4
Measured Stress	PSI	11.7	7.0	11.3	8.1
Load Spread 1:2	PSI	13.0	7 9	11.0	8.5
Load Spiead 1.2	1.51	15.0	7.5	11.0	8:5
Variation from measured stress	%	11.1%	12.9%	-2.7%	4.9%
	1				
Talbot	PSI	17.7	10.7	14.9	11.5
Variation from measured stress	%	51.3%	52.9%	31.9%	42.0%
			E Contraction of the second se		
Boussinesq	PSI	13.8	8.3	11.6	9.0
Variation from measured stress	%	17.9%	18.6%	2.7%	11.1%

³ The dynamic load was calculated using the AREMA dynamic load formula based on static load, speed and wheel diameter.

⁴ Assuming that 2/3 of the tie area distributes the load to the top of the ballast

⁵ Because the Talbot equation is an empirically derived model, if the data inputs are outside the range of the original data used in the model development, the model may not be appropriate to use. This may have been the case here.

Track Geometry Data

Since the test zone was part of an active high speed track, track geometry was routinely measured at the site on a monthly basis both before and after the rebuild. This information was made available to the analysis team and processed over time. Both individual track geometry channel data and track quality index (TQI) data were analyzed to include trending analysis.

Figure 10 shows surface 62⁶ data plotted for multiple dates across the rebuild region. The August 2015 data plots show how the rails were behaving before the rebuild which occurred late September 2015. Note that on the southern end of the geocell zone (~MP63.76 to 63.80), the surface data indicated that prior to rebuild there was significant degradation of the track geometry as illustrated by the large deviations from the mean. After rebuild and installation of the geocell material, which corresponds to the geometry data presented for January, April, and June of 2016 (a 6 month period after the rebuild), there was little track geometry degradation. A peak, relative to the surrounding area but still within an acceptable level of magnitude, was still present after the rebuild at roughly 63.725 indicating that a possible underlying issue was not dealt with.



FIGURE 10: LEFT AND RIGHT SURFACE 62 PRE AND POST SEPT. 2015 REBUILD

Overall, these results suggest that the geocell layer "stabilized" track geometry degradation which only exhibited a modest amount of degradation post-rebuild. The same improvement was seen for other track geometry measurements made within the geocell zone. In contrast, in the rebuilt section outside the geocell zone in the vicinity of MP 63.60 to 63.64, the high rate of geometry degradation continued after the rebuild as illustrated in the January, April, and June of 2016 geometry data.

⁶ Track surface measured with a 62 foot chord.

In order to better analyze the rate of track geometry degradation and the effect of the geocell rebuild, a combined TQI was calculated for each rail side. The combined TQI included both surface and cross level data using the equation:

$$TQI_{Rail \ Side} = STDEV(Surface_{62_{Rail \ Side}}) + STDEV(Cross \ Level)$$

Figure 11 and Figure 12 present the combined TQI analysis for both left and right rails from May 2013 through August 2016. Two regions of the rebuild site are presented, one with the geocell layer (reinforced / MP 63.76 to 63.80) and one without (non-reinforced / MP 63.60 to 63.64). For the segment with geocell material added (Figure 11) the TQI shows a significant reduction in the rate of degradation (slope of the TQI vs time curve) after installation of the geocell material in late September 2015. In addition, the low TQI value achieved after the rebuild was being maintained by the geocell material in the reinforced zone around MP 63.80. This was not the case with the non-reinforced segment (no geocell added during rebuild) which, as can be seen in Figure 12, shows that the high rate of geometry degradation observed before rebuild continued after the rebuild.



FIGURE 11: COMBINED TQI OVER TIME - REINFORCED ZONE (MP 63.76 TO 63.80)



FIGURE 12: COMBINED TQI OVER TIME – NON-REINFORCED ZONE (MP 63.60 TO 63.64)

The rate of track geometry degradation, as measured in combined TQI, was then be calculated for the rebuilt geocell zone. The results from the southern end of the geocell installation zone (MP 63.76 to 63.80: Figure 13) were used to define the improvement in rate of track geometry degradation. Before the rebuild and geocell material installation, a TQI degradation rate of 0.0265 inches/month⁷ was calculated. After rebuild with the geocell material, a rate of 0.004 inches/month was calculated. This resulted in a reduction in the rate of track geometry degradation rate reduction on the order of 6.7.



FIGURE 13: COMBINED TQI OVER TIME FOR THE SOUTHERN END OF GEOCELL ZONE

COST BENEFIT ANALYSIS

Based on the improvement in track structure performance observed in this study, a cost benefit analysis (CBA) was undertaken to establish rough guidelines on where the installation of geocell material would have the greatest benefit. The CBA used a Net Present Value calculation to compare the cost of surfacing uncorrected track (at a surfacing frequency or cycle) with the cost of correcting the support condition using geocell (using manufacturer's and railroad's costs) and the cost of surfacing at the increased surfacing cycle. Surfacing cycle extension was the metric used to establish the CBA. As noted above, the data suggest an improvement in geometry degradation rate of the order of 6.7.

The resulting cost benefit analysis was performed assuming a conservative 50 year NPA Geocell life span⁸, a cost of \$550,000/mile for the geocell material to be installed⁹ (this value can vary based on project scope and experience level with installation procedures), a surfacing cost of \$12,000/per mile¹⁰, and approximately \$25,000/mile in train delay costs¹¹. Based on these inputs, and the corresponding extension of surfacing cycle by a factor of 6.7, the test section of track where the geocell material was installed had a calculated return on investment (ROI) of approximately 112%.

A sensitivity analysis was performed assuming a range of historical surfacing cycles, and assuming an improvement factor of 6.7. Figure 14 shows the results of this analysis and results are displayed as total savings over the assumed geocell life cycle (50 years). When the identified savings is greater than the current installation cost (shown as a yellow line on Figure 14) there is a positive benefit and associated return on investment (ROI). It can therefore be seen that there are clear benefits if the surfacing cycle is one year or less. Note that this analysis only considers the geocell installation cost compared to the savings associated with extension in surfacing cycle. It is assumed that additional life cycle savings can be achieved (not quantified as part of this study) associated with reduced track component and vehicle damage, delay costs due to track occupancy, and increased safety. For track locations where the current surfacing cycle is between 1 and 2 years, it will be prudent to identify these additional savings.

⁷ Change in TQI over time, in this case inches/month

⁸ Based on survey of available geocell materials. Utilized geocell material had a stated life of 75 years while others geocell materials have lower life expectancies.

⁹ Installation cost estimates provided by railroad; however a sensitivity analysis was undertaken to account for variability

¹⁰ Consistent with reported industry standard costs

¹¹ Combination of delay costs due to surfacing and delay costs due to poor track quality leading to slow orders. Based on (13).



FIGURE 14: SENSITIVITY ANALYSIS: TOTAL SAVINGS VS. SURFACING

Due to the variability in installation costs, a sensitivity analysis was completed to quantify the ROI based on a range of possible scenarios. The installation cost per mile of track can vary based on:

- Project scope
 - o Length of install
 - Type and amount of work done (example: estimates provided by railroad included costs for additional drainage)
- Railroad experience with geocell installation procedure
 - More experience \rightarrow faster installation speed \rightarrow more track completed in a work window

Figure 15 illustrates how ROI can vary based on the installation cost of the geocell material on a per mile basis while again holding the surfacing cycle extension constant at 6.7. For this study, the cost per mile was ~\$550,000/mile which corresponds to a ROI of 112%.



FIGURE 15: SENSITIVITY ANALYSIS: ROI VS. INSTALLATION COSTS

CONCLUSIONS

This paper presents the result of a comprehensive performance test conducted on a section of high speed railroad track that had been experiencing substructure problems and accelerated track geometry degradation. Specifically, this test represents a case study for the installation of a geocell material to add subgrade support and stiffness on a poorly performing segment of high speed track. The segment of track which was chosen had been experiencing frequent surfacing cycles (every 5-7 months) due to clay migration and ballast fouling. A complete rebuild of the chosen section of track was conducted with the installation of a geocell material and additional drainage with the hope of alleviating the substructure issues. Two control segments, were also rebuilt, without the geocell material, one on either side of the geocell zone.

A test program which included subgrade pressure and track geometry degradation monitoring was performed to assess the improvement associated with this geocell installation. Track geometry measurements were performed on a regular monthly interval and load cell data collected over a 9 month period immediately after the restart of regular traffic. This data was analyzed to evaluate the relative performance of the rebuilt geocell and non-geocell segments. A significant overall improvement in both subgrade pressure distribution and rate of track geometry degradation was realized.

Finally, a Cost Benefit Analysis (CBA) was performed showing the return on investment and overall (life cycle) savings over a conservatively assumed 50 year life span of the geocell material. The results suggested that a track site which was experiencing a high rate of track geometry degradation due to poor substructure performance and receiving a surfacing cycle of at least one cycle per year could be a candidate for geocell installation with a positive return on investment (ROI).

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