Heavy Axle Load Track Substructure Research by TTCI

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ABSTRACT: This paper gives an overview of the heavy axle load track substructure research conducted by the Transportation Technology Center, Inc., jointly funded by the Association of American Railroads and the Federal Railroad Administration. As North American railroads are placing increased demands on the track substructure (ballast, subballast, subgrade, and drainage) due to the ongoing trends of increased axle-loads and increased traffic, a significant part of railroads' track maintenance budget is allocated to cleaning and renewing ballast and correcting rough track caused by track substructure deformation. Poorly performing substructure not only results in high rates of track geometry degradation, but also promotes higher rates of wear and deterioration of the rails, ties, fasteners, and special trackwork. Currently, research activities are focused on the following areas: (1) ballast deterioration study to determine root causes through field investigations and to quantify how track performance is affected by ballast fouling and drainage conditions through laboratory testing; (2) maintenance and remedial methods for correcting and managing track substructure problems; and (3) diagnostics of track substructure problems in developing guidelines for using the ground penetrating radar technologies by North American railroads.

KEY WORDS: Ballast, subgrade, drainage, diagnostics, maintenance

1 INTRODUCTION

In North America, railroads are placing increased demands on the track substructure (ballast, subballast, subgrade, and drainage) because of ongoing trends of increased axle loads and increased traffic. A significant part of railroads' track maintenance budget is allocated to cleaning and renewing ballast and correcting rough track that is caused by problems and deformation in the track substructure under heavy axle load (HAL) (36-ton axle load) train operations. As axle load and traffic density increase, the condition of track substructure imposes an increasing influence on track performance. Poorly performing substructure not only results in high rates of track geometry degradation, but also promotes higher rates of wear and deterioration of the rails, ties, fasteners, and special trackwork.

Track substructure problems are typically associated with poor drainage, fouled ballast, subgrade failure or deformation, and longitudinal variation of track geometry conditions. In many cases, ballast fouling with poor drainage is the culprit of track problems under HAL train operations. Ballast that is highly fouled with mud can suffer significant loss of strength and is prone to rapid deformation under HAL, leading to excessive rail deflection and accelerated tie, fastener, and track geometry degradation. When muddy ballast dries up, its dynamic load attenuation capability deteriorates, because the fouled ballast layer stiffens up with poor damping properties. To deal with these problems, North American railroads spend hundreds of millions of dollars annually to clean and renew ballast and improve track drainage. Planning and optimization of such maintenance activities is challenging when the conditions of track substructure are not automatically and quantitatively inspected, and when the root causes of problems are not well understood.

The objectives of Transportation Technology Center, Inc.'s (TTCI) track substructure research include: (1) determine the effects of increased axle loads, traffic density, and train speeds on track substructure performance, (2) determine root causes of track substructure deterioration under HAL, (3) quantify the effects of track substructure problems on track component life cycles, and (4) develop methodologies and guidelines for track substructure diagnostics, remedy, and maintenance.

TTCI's research activities are focused on the following three areas: (1) ballast deterioration study to determine root causes through field investigations and to quantify how track performance is affected by ballast fouling and drainage conditions through laboratory testing, (2) maintenance and remedial methods for correcting and managing track substructure problems, and (3) diagnostics of track substructure problems in developing guidelines for using ground penetrating radar (GPR) technologies by North American railroads.

2 ROOT CAUSE OF MUDDY BALLAST

Mud clogs the ballast, which prevents effective drainage of water. Dealing with mud spots is an industry-wide challenge. Defining the root cause of muddy ballast was a major goal of TTCI's track substructure research (Read et al. 2010).

Preliminary inspections were performed at a number of mainline locations in Alabama, Kentucky, West Virginia, and Ohio, where muddy ballast was identified as an ongoing problem by local maintenance forces. The purpose of these preliminary inspections was to get a general idea of track conditions and to select several sites for more thorough investigation. Site selection criteria included local conditions considered to be fairly representative of other North American sites, and minimum annual tonnage of 30 million gross tons (MGT). As a result of these preliminary inspections, three sites were selected for further investigation:

- Site 1 — A location near Columbiana, Ohio, 55 MGT annually. Double track with reoccurring mud spots of moderate severity in shallow cut area on Track 1. There is a well-defined ditch about 12 feet from the south rail ballast shoulder.
- Site 2 — A location near Ravenna, Ohio, 46 MGT annually. Double track with a number of severe and recurring mud spots creating rough track geometry on Track 1. A well-defined ditch is located approximately 20 feet from Track 1. The adjacent Track 2 shows no sign of mud or rough track.
- Site 3 — A location near Georgetown, Kentucky, 73 MGT annually. Single track with numerous mud spots over several miles.

Inspections were carried out by digging cross trenches across the track to a depth of 3–4 feet. The substructure layers were measured and sketched, and the layer material was identified in general accordance with the American Society of Testing Materials (ASTM) Visual-Manual soil identification procedure ASTM D2488. Samples of material from the layers were collected for laboratory tests. At each location, at least one trench was dug where mud was visible on the surface of the ballast, and one was dug where mud was not visible.

Three cross trenches were dug at Site 1. One trench was dug at the mud spot and labeled XT-1 (Figure 1), and two others were dug at nearby locations where mud was not visible on the surface and labeled XT-2 (Figure 1) and XT-3. The substructure layer conditions at all three trenches were similar, including the following: (1) a top granular layer consisting of loose to medium-dense aggregate that was wet and fouled primarily with mud slurry, (2) a second granular layer, denser than the top layer, very wet and fouled, but without the mud slurry, and (3) subgrade of moist plastic clay, gray in appearance and moderately stiff at the surface, becoming increasingly stiff a few inches below the subgrade surface. The only difference in the appearance of the three trenches was that the mud slurry in the top layer had pumped through the shoulder ballast at XT-1 to form a mud spot.

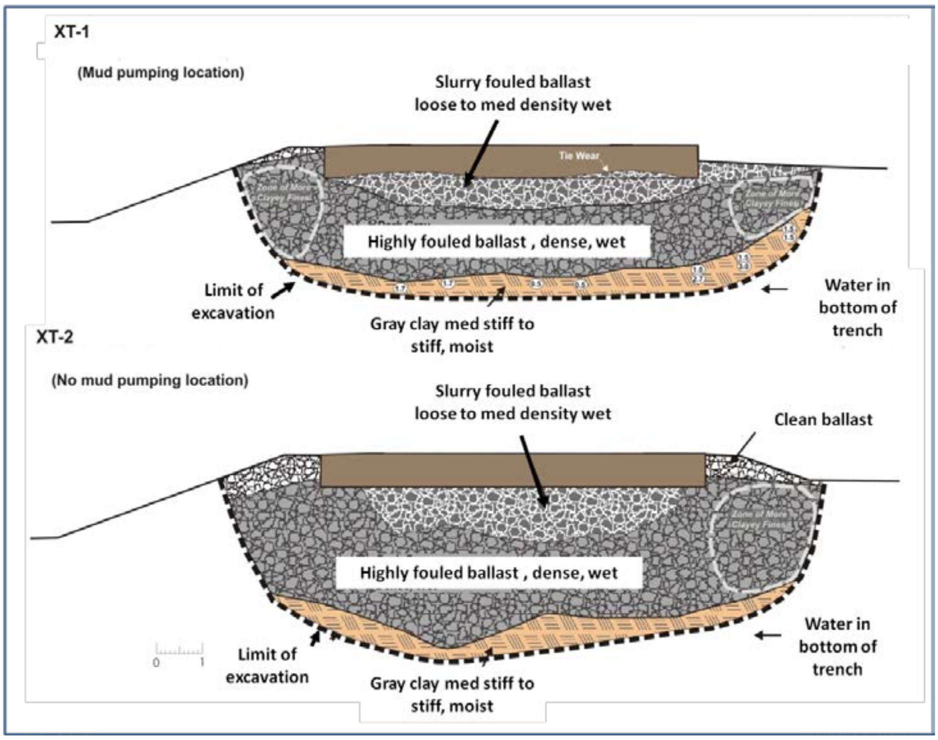

Figure 1: Similarity of XT-1 and XT-2 cross sections.

Two cross trenches were dug at Site 2: one at a mud spot and the other at a non mud spot. The conditions at these trenches were somewhat similar to Site 1, including: (1) the mud spot had a top layer less than 12 inches deep that was wet and fouled with mud slurry material; (2) it had a second layer, denser than the top layer, also wet and fouled, but without the slurry, with water also collected at the bottom of the trench similar to Site 1; and (3) the hardpan layer, consisting of cemented limestone and slag, was located between the second granular layer and the subgrade, and the subgrade was moist clay.

Cross trenches were dug at Site 3. Similar to the other sites, the granular layers were very wet with water collecting in the bottom of the trench, as well as slurry-fouled top layer and a denser, highly fouled second layer. However, there was a third layer of medium-dense granular limestone gravel subballast sitting on a hardpan layer (Figure 2). This site was slightly different from the others in that there was more water present, and the slurry tended to pump through the ballast shoulder near the toe, rather than pumping up around the ties.

For all three sites, the underlying fouling conditions at the mud and non mud spots were found to be similar. The similarity in underlying conditions indicated that mud spots can rapidly develop on tracks that visually appear to have a clean ballast surface.

These investigations have also revealed that water trapped in the fouled ballast layer was the main cause of the deterioration. Although well-defined ditches were located next to and below the elevation of the ballast layer, the very low permeability of the fouled ballast shoulder and clay subgrade effectively blocked lateral drainage from the ballast section to the ditch. As a result, the top ballast layer was fouled with mud slurry that, in some cases, was being pumped up around the sides and ends of the ties.

Maintenance activities, such as cribbing to remove fouled ballast between ties, surfacing, and ballast undercutting/cleaning to depths of 12 inches or less, are commonly used to deal with muddy ballast conditions. However, these methods do not necessarily restore adequate permeability of the ballast layer. Installing cross drains or ballast renewals that are deeper than 12 inches below the ties are required to restore the lateral drainage path.

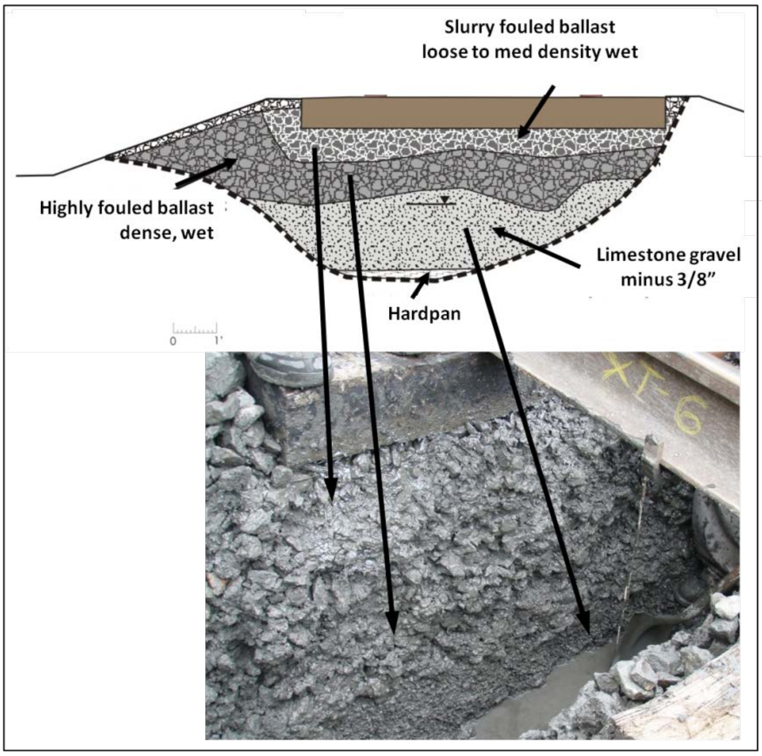

Figure 2: Ballast layers at Site 3.

3 EFFECTS OF BALLAST DEGRADATION ON TRACK PERFORMANCE

Breakdown and abrasion of ballast particles from repeated wheel loads and tamping operations, plus infiltration of material from the outside are root causes of ballast fouling and loss of functionality. The American Railway Engineering and Maintenance-of-Way Association (AREMA) recommends several gradations for mainline ballast that can be generally defined as having uniformly graded particle sizes between 2 1/2 inch and 3/4 inch and no material smaller than the No. 4 sieve (approximately 3/16 inch). The large inter-particle void spaces found in the AREMA gradations facilitate drainage and permit some initial particle size breakdown before ballast performance is compromised. Over time, the percentage of fine material increases, filling the voids and reducing the ballast drainage capacity and strength.

Ballast performance under HAL coal traffic is being investigated at a high tonnage revenue service site near Ogallala, Nebraska (Read et al. 2012, Gehringer et al. 2012). This site carries about 250 MGT of coal traffic annually on Track 2, and is the HAL revenue service mega test site (Li et al. 2010). Particle size degradation and track deformation behavior of five ballast materials are being conducted through field monitoring and laboratory testing.

In November 2010, degradation monitoring began with new ballast material from four separate sources, labeled Types I–IV, along with the control ballast being installed in test zones established at a 2-degree curve and a tangent location. Types I–IV were sieved after delivery and prior to being installed to discard material smaller than 3/8 inch. The four control ballast boxes contained Type II material, which was installed in the as-delivered condition without additional sieving. The ballast types were separated by 14-feet long and 12-feet wide steel boxes in both zones (Figure 3), with ballast depth beneath the ties of about 14 inches. The boxes in the curve zone have steel bottoms, but the boxes in the tangent zone have fabric bottoms to isolate the ballast from the subgrade.

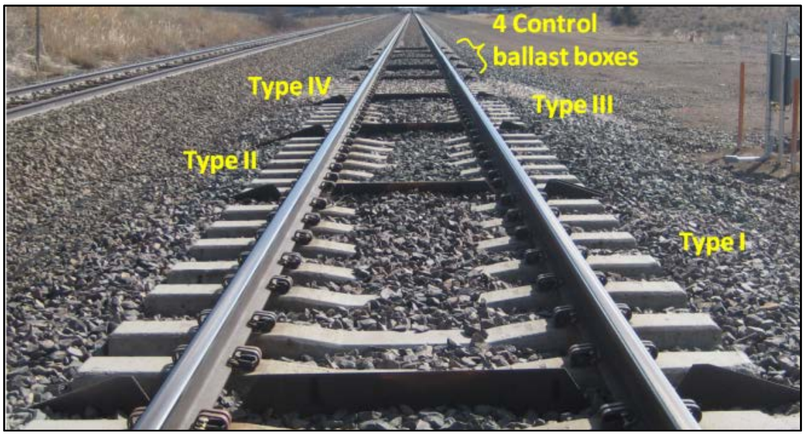

Figure 3: Tangent zone ballast box layout.

Ballast was sampled before installation and then twice a year at various MGT levels. Figure 4 compares percentages of the collected ballast material passing the 1/2-inch sieve and No. 4 sieve at 0 and 320 MGT (May 2012). Material passing the 1/2-inch sieve is roughly equivalent to the waste from a ballast undercutting operation, and material passing the No. 4 sieve (3/16 inch) is considered to be fines. Types I and III ballast show substantially less degradation than the control ballast and Types II and IV. After 320 MGT, Types I and III are still below the AREMA gradation limit of 7 percent passing the 1/2-inch sieve and show no appreciable degradation of material passing the No. 4 sieve. The control ballast and Types II and IV have 2 to 4 times the percentage of material passing the 1/2-inch sieve compared to Types I and III, and roughly 2 to 3 times the percentage of material passing the No. 4 sieve.

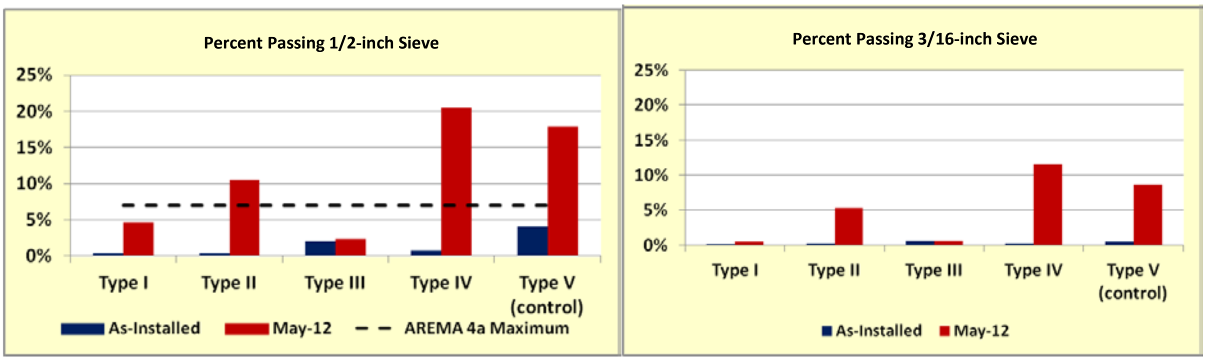

Figure 4: Ballast degradation comparison.

Ballast deformation as a function of ballast degradation for different ballast materials is being evaluated using a repeated loading triaxial tester by the University of Illinois at Urbana-

Champaign. This triaxial tester can accommodate a 12-inch diameter by 24-inch high cylindrical ballast specimen. The loading sequence has a 0.4-second duration load pulse, representing the combined input generated by the trailing truck of the leading car and the leading truck of the trailing car followed by a 0.6-second rest period. This load sequence is roughly equivalent to a car with 40-foot truck centers operating at 40 mph. For comparison of different ballast types, only 10,000 load cycles of 24-psi vertical stress are applied while maintaining a confining stress of 8 psi (much larger number of load cycles are needed to understand life-cycle ballast degradation behavior). Three longitudinal displacement transducers positioned 120 degrees apart and one circumferential displacement transducer mounted on a horizontal chain are used to measure axial and radial deformation. The recorded axial deformation is computed as the average output of the three longitudinal transducers.

The accumulated axial deformation of the 320 MGT ballast samples after 10,000 load cycles is plotted in Figure 5, which also includes the Type IV material tested dry and with water added to create 3-percent moisture content.

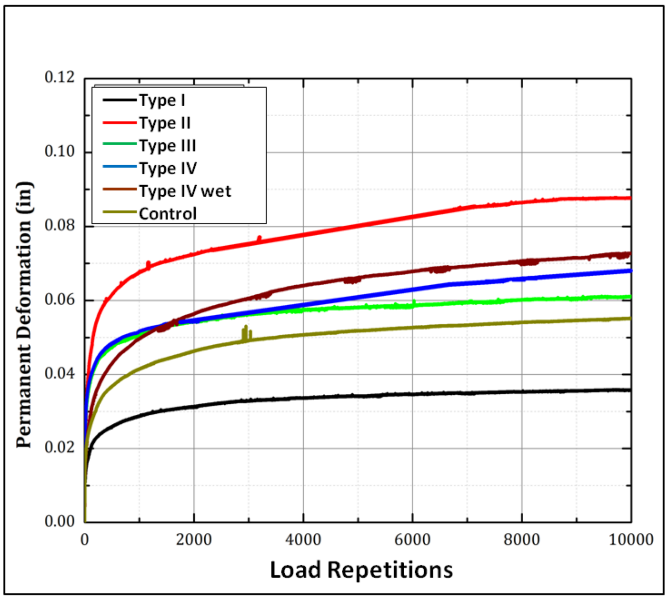

Figure 5: Axial deformation of 320 MGT ballast samples.

Unlike the particle degradation trends observed in Figure 4, the permanent deformation accumulation in Type II ballast was the highest, followed by Type IV and Type III. The Type II ballast produced the most deformation, but was midrange in terms of the material passing the No. 4 sieve. The Type IV and Control ballasts with the most particle size degradation tested midrange in terms of deformation. The best correlation was the Type I material that had the least amount of material passing the No. 4 sieve and the least deformation.

Results of mill abrasion tests on as-installed ballast samples are as follows: Type I = 4.4%, Type II = 8.3%, Type III = 1.2%, and Type IV = 1.2%. Note that the mill abrasion test is a wet abrasion test that determines the amount of material finer than the No. 200 (0.003-inch) sieve as a percentage of the total sample weight, and its result gives an indicator of ballast material hardness and abrasion resistance. Other lab tests for ballast mechanical properties have also been done and are being investigated how they are related to ballast performance.

Ballast Type II had the highest mill abrasion value (8.3%) of the four ballast types, as well as the most deformation, but not the most particle size degradation. There is a good agreement between the triaxial and mill abrasion test results, but lack of agreement with the sieve analysis suggests the possibility of the Type II particles undergoing significant abrasion during the triaxial load cycles that results in higher permanent deformation.

At the Facility for Accelerated Service Testing (FAST) located near Pueblo, Colorado, a test is also in progress to monitor track settlement under 39-ton axle load train operations for a section of track that includes five zones of wood tie and concrete tie tracks built on the ballast of various fouling degrees: clean, moderately fouling (15% undercutter waste), and heavy fouling (25% undercutter waste). The undercutter waste came from a HAL coal line that included 41 percent of materials passing No. 4 sieve. About 130 MGT has accumulated on this test track. Without water present in the ballast with fouling materials, these test zones have not developed significant track roughness. The next step is to monitor track settlement growth with water added to the five test zones.

The above described research and testing activities continue in order to determine how ballast degradation/fouling grows under HAL, and how fouling affects track drainage and track performance in terms of differential track settlement. The ultimate goal of the research is to develop guidelines for ballast undercutting operations based on the degree of ballast fouling, which can be inspected by GPR technologies as described in the following section.

4 DIAGNOSTICS OF TRACK SUBSTRUCTURE PROBLEMS

In the last several years, TTCI's research in diagnostics of track substructure problems has focused on evaluating and developing guidelines for the use of GPR technologies to inspect ballast fouling and drainage conditions (Li et al. 2010, Read et al. 2011). The earlier phase of the research was an evaluation of several GPR technologies on the test track at FAST. Five commercial GPR systems participated in the evaluation with required outputs of ballast fouling analysis, layer depth interpretation, and moisture content sensitivity. The outputs of the systems were compared to each other and to the known track substructure conditions of the test track at FAST.

The systems participating in the evaluation and producing final results are described generically in Table 1. The mix of antenna types, antenna manufacturers, engineering and geophysics providers included: 400MHz, 1GHz, and 2GHz time domain pulsed antennas from two different manufacturers; a stepped-frequency continuous-wave (SFCW) frequency-domain antenna from a third manufacturer with 31 transmitter-receiver dipoles spaced about 4 inches apart (this SFCW system transmits a sine wave of constant amplitude and stepwise frequency variation); and two engineering/geophysics teams.

Table 1: GPR systems description.

System	Antenna Description	Fouling Analysis
1	Time domain pulsed radar, 400 MHz used for layer depth mapping and 2 GHz used for ballast fouling	Scattering
2	Time domain pulsed radar, 1 GHz	Dielectric dispersion
3	Time domain pulsed radar, 400 MHz antenna manufacturer 1	Dielectric dispersion
4	Time domain pulsed radar, 400 MHz antenna manufacturer 2	Dielectric dispersion
5	SFCW radar manufacturer 3, 150 MHz to 2.5 GHz frequency range, air coupled	Dielectric dispersion

The evaluation approach was primarily a head-to-head comparison of the ballast fouling and layer depth outputs of the different systems for the test track sections at FAST. Fouling values were normalized to a generic categorization with 4 being clean and 1 being highly fouled. The generic fouling categories represent an average fouling condition over the top ballast layer of 16 to 20 inches.

The fouling comparison shown in Figure 6 is a statistical distribution of the normalized fouling categories for each system over test track sections for a total distance of 9,511 feet. Results of the analysis can be summarized as follows:

- All systems showed a low percentage (<6%) of the track as being highly fouled.
- System 5 distribution had a much lower percentage of clean ballast, generally less than 40 percent, compared to the pulsed radar Systems 1, 3, and 4, which showed clean ballast percentages of 70 percent or higher.
- System 2 showed clean ballast percentages between 65 and 45 percent on the shoulders, which were also lower than Systems 1, 3, and 4.
- The 2 GHz signal scattering method (System 1) and 400 MHz dielectric dispersion method (Systems 3 and 4) produced similar results for the ballast shoulders, with roughly 80 percent or more of the track falling into the clean ballast category. However, System 1 showed an approximate 20 percent reduction in the clean ballast percentage for the track center that was not seen by Systems 3 or 4.

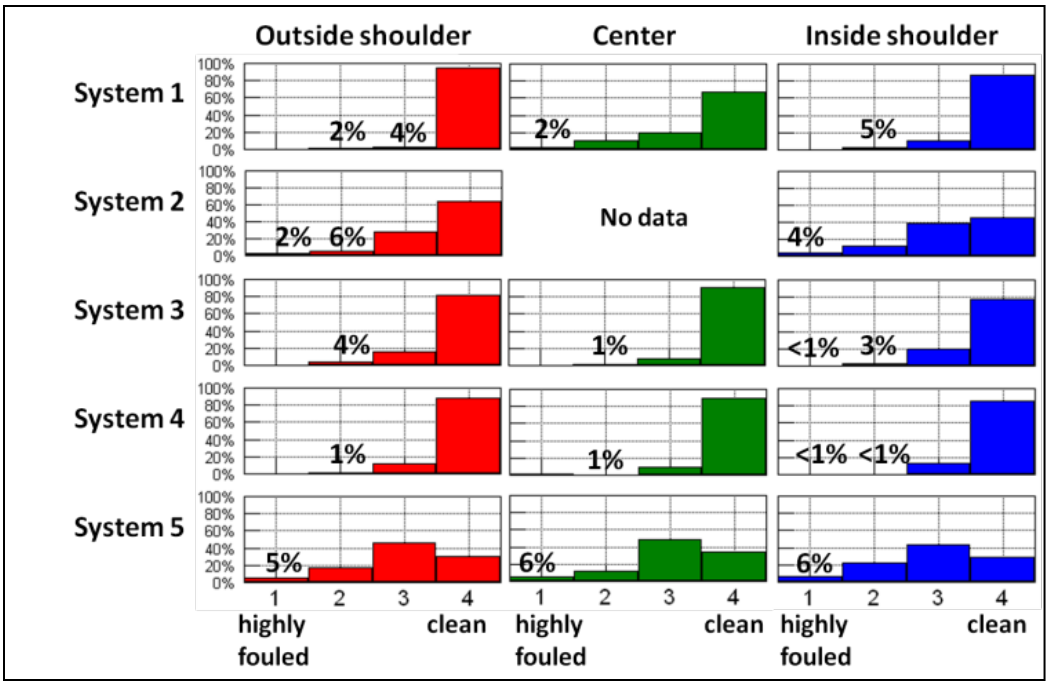

Figure 6: Distribution of ballast fouling categories for all systems.

The layer depth interpretation for System 1 was based on an assumed dielectric constant of 4.5, and the interpretation for Systems 2–5 was based on an assumed constant of 6 for the ballast layer and 9 for the subballast layer. The similarity of the dielectric constants produced similar depth output data, 10 to 15 inches, for the systems. The test track at FAST has roughly equivalent ballast types and conditions and uniform ballast depths, and the primary depths of 10 to 15 inches accurately represent the top ballast layer.

The largest inconsistency in the primary layer data occurred in one test section (Section 33) where System 5 indicated a primary layer depth of 20 to 25 inches as opposed to depths of 10 to 15 inches for the other systems.

All ballast systems were involved in a moisture condition test performed in a test section (Section 33). A GPR survey was taken before and after water was artificially added to the track (using a fire truck) over a distance of about 50 feet. All the systems were able to distinguish the increase in moisture and to determine that the water was draining by a change in the moisture profile with depth.

The results have confirmed the well established ability for GPR to sense relative changes in moisture. However, the outputs of Systems 2–5 also showed a strong correlation between relative moisture level and relative ballast fouling, which is not surprising given the strong effect of water on the GPR signal response. Therefore, the ability of GPR to determine absolute moisture content in the ballast layer was not confirmed by this evaluation. It is recognized that high moisture content that would occur where water is trapped at the bottoms of ballast pockets is readily visible to GPR as a strong interface reflection.

Currently, the focus of research in implementing GPR technologies for ballast inspection has been shifted onto its abilities to monitor ballast degradation over time (traffic) and to differentiate the fouled ballast with or without accumulated water. Two field test sites have been established for this research effort: one in eastern United States with a passenger railroad where variation of moisture in the ballast is more prevalent, and the other in western United States on a high tonnage freight track (the same track where ballast degradation is being monitored for five different ballast types as described earlier in the paper).

5 REMEDIATION OF TRACK SUBSTRUCTION PROBLEMS

TTCI’s track substructure research also includes testing and monitoring of remedies for localized track substructure problems such as mud pumping and chronic track geometry defect growth. Currently, TTCI is working with a freight railroad to install and monitor a remedy at a location with chronic track geometry problems associated with deep ballast pockets. The field investigations including cone penetrating testing and track modulus test using TTCI’s Track Loading Vehicle have indicated that the subgrade has deformed over time, but is not extremely soft. Water softening of the subgrade surface caused incremental subgrade deformation, but movement of a thick ballast layer (5-7 feet) resulting from lack of lateral confinement appears to be the main cause of the problem.

In late 2012, a layer of geogrid will be installed 12 inches below the bottom of the ties to reinforce the ballast layer, and installation will be done during a ballast undercutting operation. This triaxial geogrid product is designed for coarse aggregate material such as ballast. Because of the large ballast layer at this site, use of geogrid is expected to provide lateral confinement of ballast particles, thus reducing track settlement as a result of ballast movement (Figure 7). After installation, monitoring will be conducted to measure long-term benefits of the geogrid layer in providing tensile strength to the ballast, reducing and providing more uniform ballast pressure, and thus solving chronic track problems at this site.

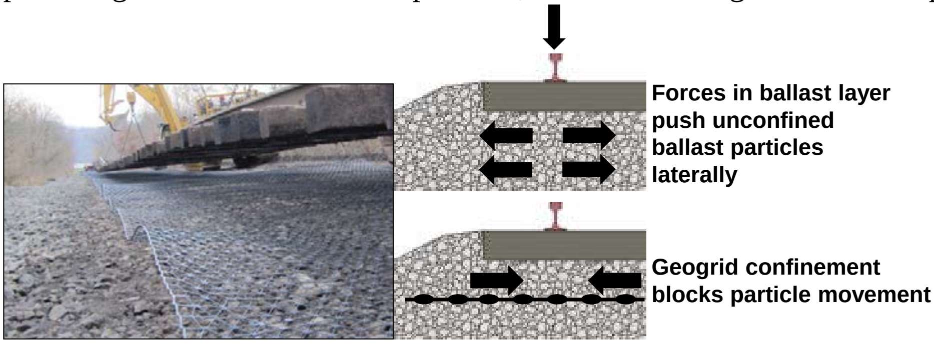

Figure 7: Use of geogrid in deep ballast layer to provide confinement to ballast movement.

6 SUMMARY

This paper gives an overview of a HAL track substructure research program conducted by TTCI. Results and findings from several research activities are presented to describe the research in the root cause determination of muddy ballast and chronic track geometry problems, ballast degradation and its effect on track settlement, evaluation of GPR technologies for inspecting ballast conditions, and remediation for localized track problems.

Investigations have shown that water trapped in the fouled ballast layer is often the main cause of track substructure deterioration, and muddy ballast can rapidly develop on tracks that visually appear clean on the ballast surface. Ballast undercutting of 12 inches or less may not necessarily restore adequate permeability of the ballast layer.

Use of GPR technologies was demonstrated to be capable of inspecting ballast conditions, but differentiating fouling from accumulated water will need further evaluation. The ongoing ballast degradation research is to determine how track performance (deformation and strength) is affected by ballast fouling and drainage conditions. It is the goal of this research to develop guidelines for ballast undercutting operations, based on GPR ballast inspection results as well as the relationship between track performance and ballast fouling and drainage conditions.

Remediation of localized track substructure problems is also part of this research, with the current activity focused on monitoring track performance following the installation of geogrid in the ballast in conjunction with an undercutting operation. Geogrid layer is intended to reinforce a large ballast layer that has experienced chronic deformation under HAL train operations.

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