Principles of Degraded Ballast and Their Track Safety Implications

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ABSTRACT

Fouling and moisture within the ballast layer of railway track can profoundly affect the mechanical behavior of the track under loading. The accumulation of fouling material in voids between ballast particles, and the subsequent retention of water in the ballast layer, eventually cause poor track geometry performance. Further, under these conditions, geometry corrections with tamping maintenance become less durable. Ballast life expires and should be cleaned or replaced when its voids become filled with this fouling material. Otherwise, track geometry roughness develops at an unacceptable rate and the required tamping cycles become impractically frequent. Even in a degraded condition, however, the ballast layer deformation is governed by the characteristics of the larger particles which still maintain their inter-particle contacts and act to resist deformation, especially as the ballast recompacts after tamping under traffic loading. This paper presents the geotechnical principles that govern the behavior of railway ballast with excess fouling and moisture. These principles are discussed in terms of maintenance management as well as in terms of their track safety implications.

INTRODUCTION

Efforts are underway in the rail industry to evaluate and quantify the safety implications of degraded ballast. Although the mechanism by which fouled ballast might become unsafe is not often specified, the apparent general concern is that it may, for some reason, suddenly deform and produce a large geometry deviation. To help determine if and how a fouled ballast may pose a safety risk, the authors considered the soil mechanics principles that govern granular material response to repeated loading, results from research and testing, as well as their own decades of experience in this area.

Ballast Deformation Over its Life

Ballast life is calculable [1, 2] and is expired when fouling material fills the voids between particles to the point where ballast permeability is significantly reduced and required track geometry corrections become very frequent. There are many definitions of ballast fouling, which are primarily based on the grain size distribution of the ballast material [3, 4]. Selig & Waters [5] quantified the amount of fouling using the Fouling Index; which is the percent of ballast material that passes a No 4 sieve plus that passing a No. 200 sieve. A reasonable limit on the Fouling Index, corresponding to the end of ballast life, is the amount of fouling that reduces ballast layer permeability so that the drainage function is lost. Figure 1 shows test results [6] indicating that a fouling index of approximately 30% produces a sudden reduction in ballast permeability. A rainfall rate larger than the critical rate exceeds the capacity of the ballast layer to drain the water away as fast as it enters. Therefore, water is retained in the ballast for a time which is dependent upon how much the critical rate is exceeded. Because of these research findings, a Fouling Index of 30% is sometimes used to indicate the end of ballast life due to loss of drainage capability.

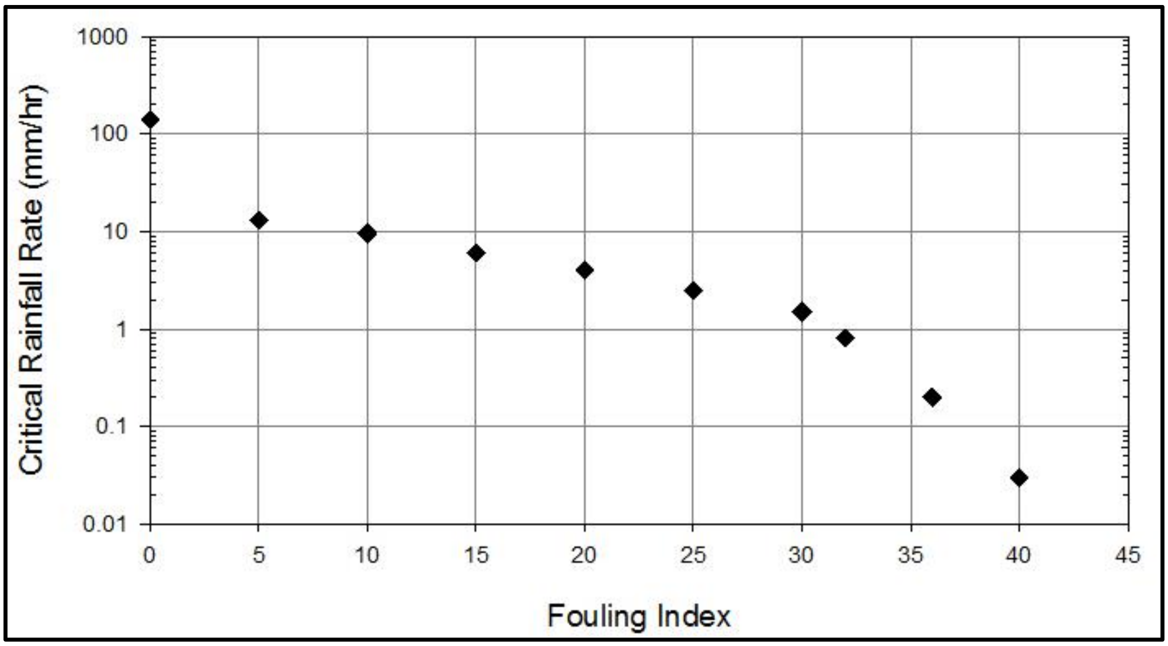

Figure 1: Critical Rainfall Rate with Ballast Fouling Index [6]

The link between this degraded ballast condition and track geometry performance must also be established. Figure 2 shows the rate of vertical surface geometry deterioration of more than 200 sites with stable subgrade conditions and various ballast fouling conditions from clean to highly fouled [7]. This figure supports the conclusion from Figure 1 that ballast with a Fouling Index greater than approximately 30 has increasingly higher rates of deterioration.

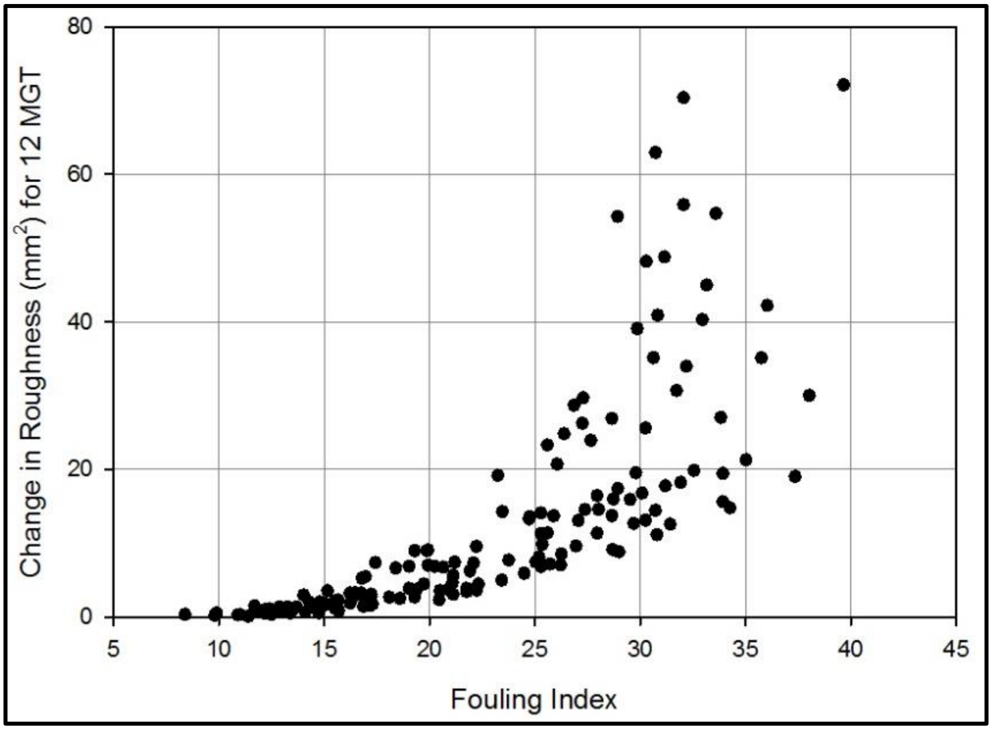

Figure 2: Vertical Surface Geometry Deterioration Rate vs. Fouling [2]

Before ballast life expires, the accumulating fouling material starts to retain water. This is the link between Figures 1 and 2: that is, increasing fouling results in both loss of ballast permeability and increased track settlement and roughness. In addition, degraded ballast will allow faster resettlement after it is disturbed and loosened by tamping and, for this reason, tamping will become less effective yet will be required more often toward the end of ballast life. Figure 3 shows an example of this behavior from actual measured data for a ballast at the end of its life due to excessive fouling.

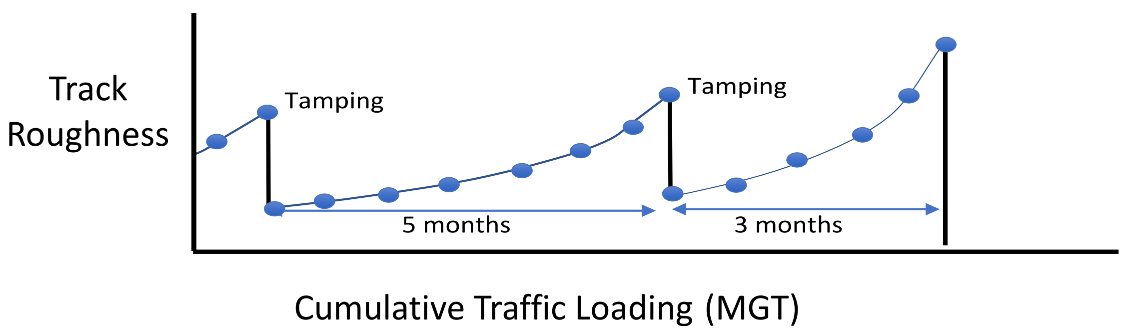

Figure 3: Trend of Decreasing Tamping Correction Durability with Ballast Fouling

Ballast, being an assemblage of granular soil particles, deforms under cyclic loading based on a power function equation, expressed as [5]:

$$\varepsilon_N = \varepsilon_1 N^b \quad \text{Eq. 1}$$

Where ε_N is the vertical ballast strain with N load cycles, or alternatively ε_{MGT} for cumulative loading measured in million gross tons, ε_1 is the first load cycle strain, and N is the number of load cycles. This equation may also be written as

$$\varepsilon_{MGT} = \varepsilon_1 \, MGT^b \qquad \text{Eq. 2}$$

Or, if ballast settlement (δ) is desired rather than ballast strain, the equation is written

$$\delta_{MGT} = (\varepsilon_1 \, MGT^b) * \text{Ballast Layer Thickness} \qquad \text{Eq. 3}$$

The initial settlement, ε_1 and the exponent b are affected by factors such as the degree of fouling, moisture content, lateral stress, and level of in-place density. Figure 4 shows the typical behavior, as expressed by the above equation, for increasingly fouled ballast. The "moderately fouled" variables of initial settlement (ε_1) and exponent (b) in Figure 4 are based on testing at the FAST site at TTCI in Pueblo, CO [5], and the "moderately clean" plot is based on laboratory results [8]. The "highly fouled" and "clean" plots in Figure 4 were derived by adjusting the initial settlement and exponent relative to the other two settlement curves.

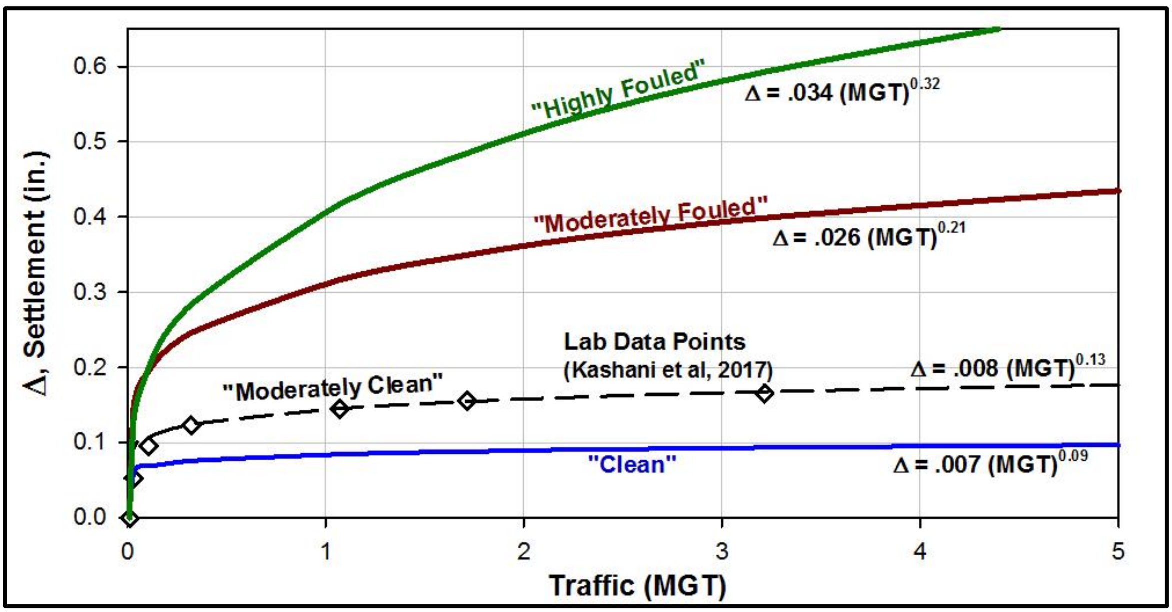

Figure 4: Settlement After Tamping of Ballast in Various Fouling Conditions

After tamping, ballast settles under traffic loading as shown in Figure 4, with an initially high rate of settlement that decreases with further traffic (MGT). With more fouling and moisture, the amount of settlement increases causing increased geometry roughness with traffic. However, the rate of settlement decreases with traffic loading, even for highly fouled ballast.

Because settlement will be non-uniform along the track, this differential ballast settlement produces track roughness. Figure 5 combines the trend of ballast settlement shown in Figure 4 with the corresponding development of track roughness over the life of the ballast. The data in Figure 5, from geometry roughness measurements on revenue service track, shows the increasing rate of roughness from about

100 MGT to 250 MGT due to increasingly fouled ballast. Also included on Figure 5 are ballast settlement curves based on the power equation (Eg. 3) for 20 MGT of traffic following tamping at three different stages of ballast fouling. The settlement of ballast, which increases at a decreasing rate as defined by the power equation, is consistent with the trend of increasing track roughness in Figure 5 as the ballast becomes more fouled. Even though track settlement and the corresponding track roughness occur at an increasing rate over ballast life due to fouling, after each tamping application the ballast itself becomes more compact under traffic and settles at a decreasing rate.

Figure 5 shows how this ballast behavior affects the growth of track profile roughness after tamping at various stages in ballast life. For ballast at its mid-life, tamping can provide a reasonably durable geometry correction as the ballast returns to the dense state it had before tamping and rejoins its general trend of deformation and track profile roughness as shown. But tamping a degraded ballast near the end of its life will provide a far less durable correction because the ballast will return to its denser condition more quickly.

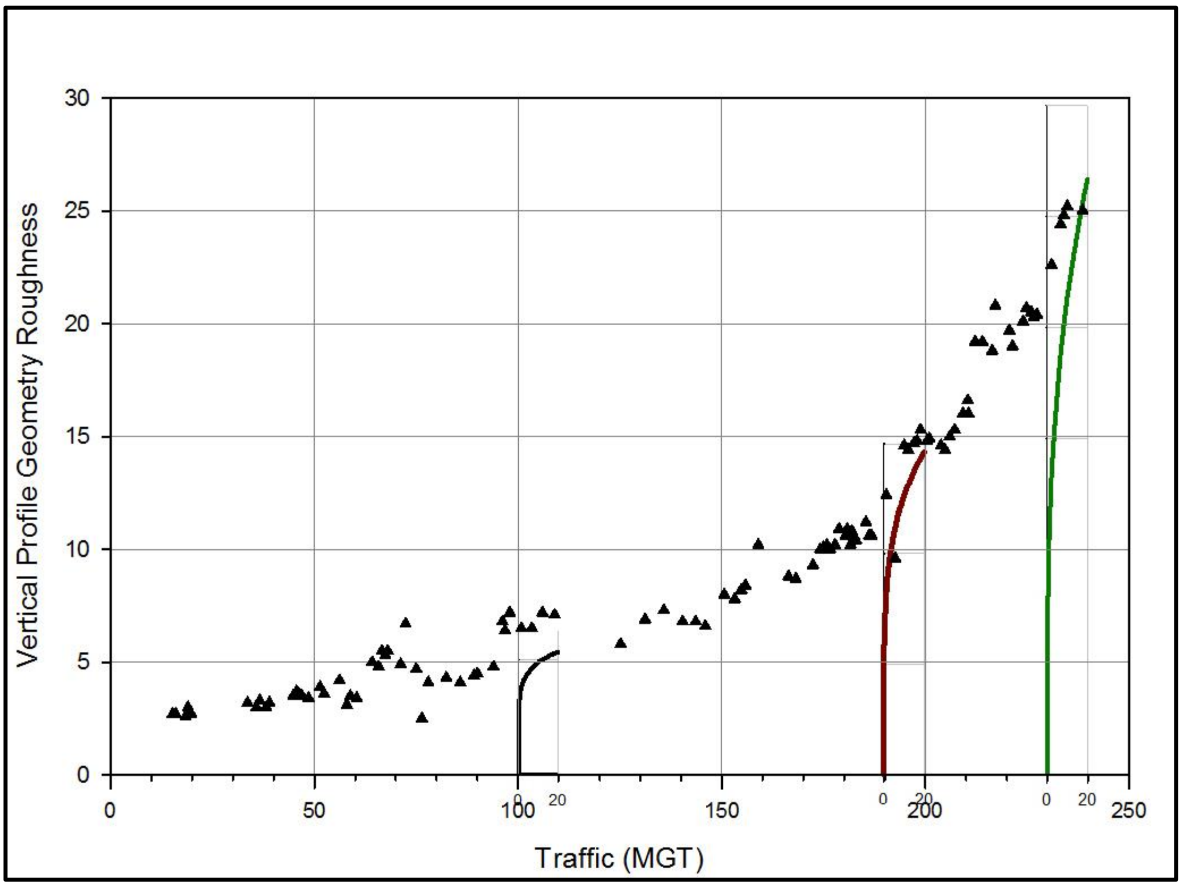

Figure 5: Trend of Track Profile Roughness with Increasing Ballast Fouling and Fouled Ballast Response to Tamping at 100 MGT, 190 MGT and 230 MGT

The trend of increasing track roughness toward the end of ballast life and just after tamping a heavily fouled ballast as shown in Figure 5 is sometimes pointed to as an unsafe and unstable condition with "runaway" track deformation. However, rather than an indication of instability, this is a result of a fouled ballast more quickly returning to the compact configuration it had before tamping. But to more fully consider if there is a mechanism that could cause fouled ballast to produce track settlement that increases at an increasing rate, some possible scenarios of rapid fouled ballast failure are considered next to assess if any of these could occur.

Consideration of Potential Mechanisms for Rapid Settlement of Fouled Ballast

Potential for Liquefaction of Fouled, Wet Ballast

Liquefaction is the loss of strength of a saturated soil due to the build-up of water pressure in the voids between particles from cyclic loading. The soil types most susceptible to liquefaction during cyclic loading are silt and fine sand. However, a highly fouled ballast with silt and fine sand in the voids between ballast particles forms a dense matrix that is highly resistant to liquefaction. High pore-water pressures are required to liquefy particle sizes greater than silt and fine sand and can only happen when the material is completely saturated and unable to release pressure under cyclic loading from trains. Fouled ballast typically includes these fine-grained particles but the ballast layer resistance to liquefaction is controlled by the much larger ballast-sized particles and the inability to develop high pore-water pressures.

Figure 6 shows the fine-grained constituent in a highly fouled ballast together with the coarse-grained particles surrounding them. As fouling progresses, successively smaller voids are filled with smaller particles until a dense matrix is formed, as in the lower photograph in Figure 6. However, as the smaller voids become filled the larger particles do not lose contact from each other. Ballast particles in this dense packing arrangement are responsible for transmitting loading stresses through layer and they provide the resistance to deformation. Under these conditions, liquefaction of a fouled ballast layer is highly unlikely.

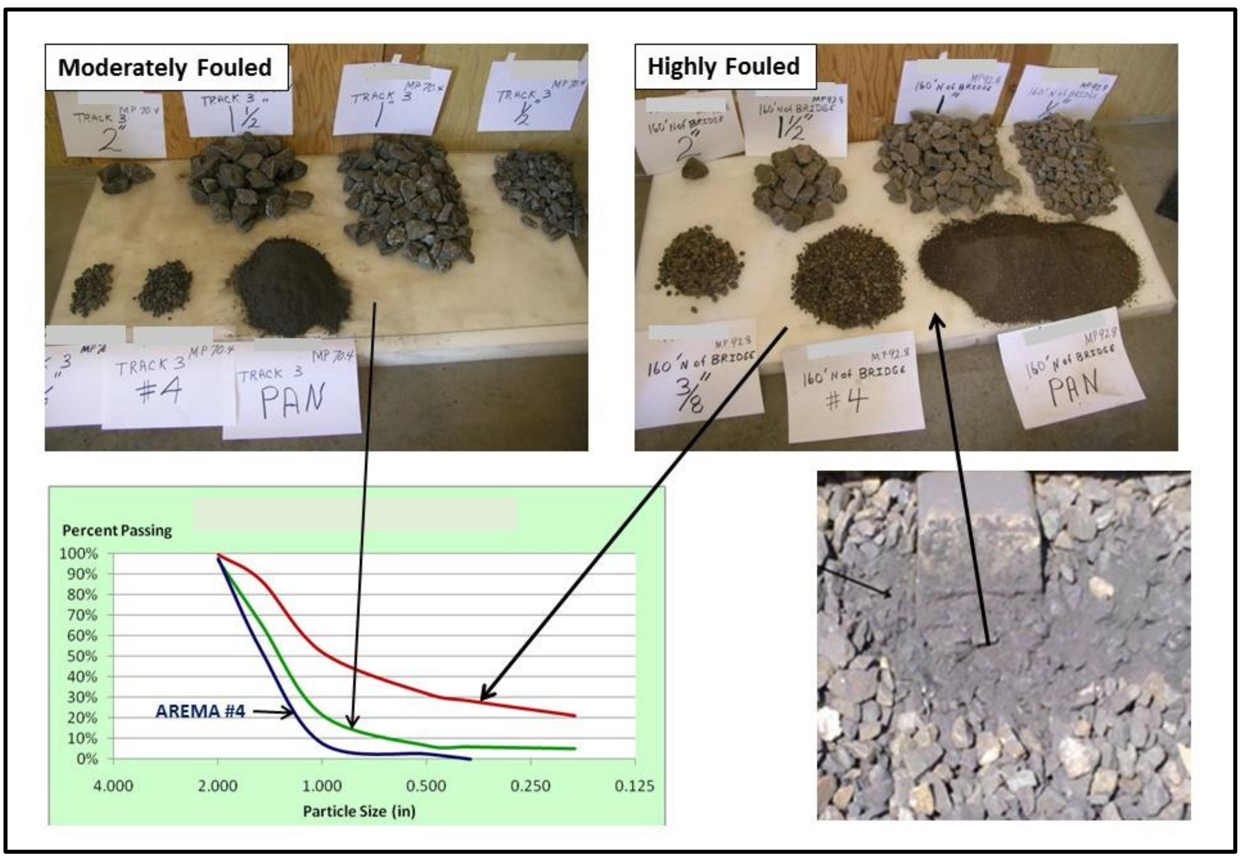

Figure 6: Changing Ballast Gradations with Increasing Fouling

Plastic Fine Particles Controlling Ballast Layer Deformation

Another concern, separate from the possibility of fine sand and silt becoming unstable by liquefaction due to vibration, is that fouling material may include plastic fine particles that become so abundant that the coarse ballast particles lose contact with each other and become surrounded by the fine material. If this were to occur, the ballast would essentially be "floating" in the fine-grained, plastic material and the mechanical properties of ballast and its deformational response to loading could be dominated by this fine material and produce a "runaway", progressive deformation.

However, the progression of fouling produces a condition where, even in the latter stages of ballast life, the larger ballast particles are not separated from each other. Instead, plastic fine particles, if present, would be a minor constituent of the particle size range of fouling material. These plastic fines would not have sufficient abundance to isolate the coarse-grained ballast particles from each other to produce a ballast layer deformation of a plastic nature.

Shear Failure of a Fouled Ballast Section

Traffic loading produces shearing stresses in ballast as with any material. However, the authors consider a shear failure of the ballast layer to be extremely unlikely. This is because of the large resistance to shearing deformation expected from ballast that has been compacted by train loading. A heavily fouled ballast layer near the end of its life would likely be even more dense and resistant to such deformation than a clean, unfouled ballast.

Track Settlement at End of Ballast Life

The most plausible mechanism that may explain a sudden increase in rate of track settlement in a fouled ballast is the condition in Figure 7, at the end of ballast life when its drainage function fails. When ballast remains in track beyond its life, the lack of drainage and standing water allows this slurry to form under and around the tie. The slurry forms from loading in the presence of water which erodes the fine particles held between the ballast particles which in turn creates a void under the tie. As this void under the tie grows so does the tie settlement and geometry deviation when loaded by traffic.

Figure 7. Ballast with Slurry-Formed Voids Under and Around Ties After Ballast Life Has Expired

The best way to avoid the potential for such an event is to periodically maintain the ballast to keep fouling material from accumulating or renew ballast that has already become too fouled with subsequent loss of the ballast layer's ability to drain. Of course, it is difficult to determine the amount of fouling in ballast by visual inspection. However, there have been advances in measurement systems that can provide a rapid assessment of ballast fouling along the track. One method that has been successfully used is ground penetrating radar (GPR) which can provide the results in the "heat plot" of Figure 8, where the "hotter" (or darker) colors indicate locations along the track with increased levels of fouling.

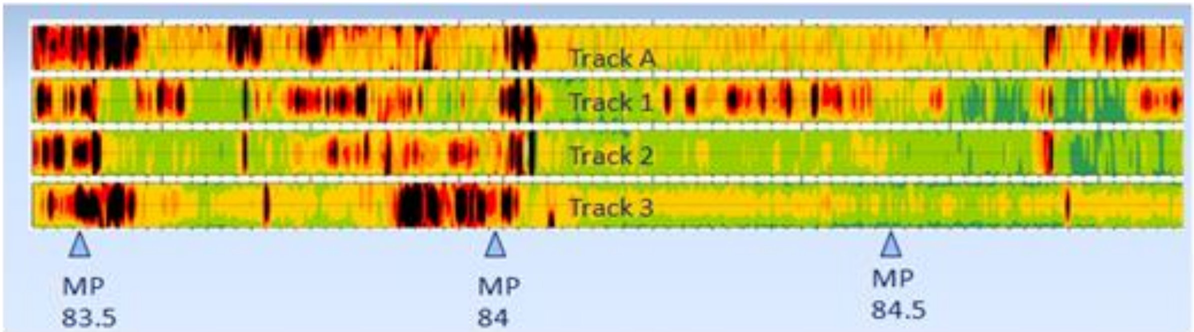

Figure 8. Ground Penetrating Radar Used to Indicate Degree of Ballast Fouling Using "Heat Plot" (View is from above track looking down.)

CONCLUSIONS

The trend of ballast settlement increases at a decreasing rate under loading, even when it is fouled. After considering possible mechanisms under which fouled ballast settlement could affect safety, it is concluded that the main effect of high levels of fouling on ballast settlement is to allow the track to more quickly return to the rough profile that it had prior to tamping. Following surfacing maintenance, the ballast layer compacts under traffic at a decreasing settlement rate and overall stability of the ballast layer increases. However, a potential source of a safety-critical increase in the ballast settlement rate could be the formation of voids under the tie due to the buildup of slurry and erosion of ballast support directly under the tie. If ballast remains in track beyond its life, a slurry of fine material can form under and around the tie which also allows the formation of voids between the bottom of tie and ballast, increasing track deflection under load. To avoid this condition, it is recommended that ballast is replaced before its permeability decreases to the fouling level associated with end of ballast life. This amount of fouling is estimated as 30 using the Selig Fouling Index. Once ballast fouling exceeds a Fouling Index of approximately 30, ballast maintenance becomes less effective and renewal of the ballast layer through cleaning or replacement becomes necessary. Left untreated, the ballast layer can eventually deteriorate to the point where voids and slurry begin to form around the tie, which can be a potentially unsafe condition.

REFERENCES

1. Chrismer, S. and Selig, E., 1991. "Mechanics-based Model to Predict Ballast-related Maintenance Timing and Costs". Proceedings of International Heavy Haul Railway Conference, Vancouver.
2. Hyslip, J. and Kashani, H. F., and Trosino, M., 2017. "Ballast State of Good Repair". Proceeding of the 2017 AREMA Annual Conference and Exposition, Indianapolis.
3. Sussmann, T., Ruel, M., and Chrismer, S., 2012. "Source of Ballast Fouling and Influence Considerations for Condition Assessment Criteria". Transportation Research Record No.

2289, Journal of the Transportation Research Board of the National Academies, Washington, DC. Pp. 87-94.

4. Li, D., Hyslip, J., Sussmann, T. and Chrismer, S., 2016. Railway Geotechnics, published by CRC Press, London, UK.
5. Selig, E. and Waters, J.,1994. Track Geotechnology and Substructure Management. Thomas Telford Publications: New York.
6. Parsons, B., 1990. “Hydraulic Conductivity of Railroad Ballast and Track Substructure Drainage”, Mater’s Thesis, University of Massachusetts, Amherst, MA.
7. Hyslip, J., and Kashani, H. F., 2017. “Defining Ballast Life”. Proceedings of Railway Engineering Conference, 22-22, June, 2017, Edinburgh, Scotland.
8. Kashani, H.F., Hyslip, J. and Ho, C., 2017. “Laboratory Evaluation of Railroad Ballast Behavior Under Heavy Axle Load and High Traffic Conditions”. Transportation Geotechnics Journal, 11, pp.69-81.

List of Figures