Maintenance Planning of Railway Ballast

Ali Ebrahimi¹ and Andrew K. Keene²

¹ Research Associate, Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, e-mail: ebrahimi.ali59@gmail.com
² Research Assistant, Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, e-mail: akeene@wisc.edu

Abstract

A model for maintenance planning of railway substructure is proposed using a permanent deformation model for various materials in a track substructure. Among track substructure materials, railway ballast has a critical role on the maintenance frequency of a railway track. The deformation model for fouled railway ballast was developed using data obtained from a large-scale cyclic triaxial (LSCT) apparatus. The ballast deformation model introduces a strong correlation between the rate of plastic deformation (or strain) of ballast and different fouling and stress conditions. Substructure maintenance planning software was developed based on laboratory deformation data to model surface deviation of the railway track and consequent maintenance events. The software can determine the intervals between corrective maintenance activities (e.g., tamping) and necessity for preventive maintenance activities (e.g., undercutting or drainage systems, etc).

Keywords: Railway, maintenance, substructure, ballast

1 INTRODUCTION

Railway substructure maintenance is a main concern facing the freight rail industry. Increasing demand for higher freight capacity (greater loads and traffic volume) shortens intervals between maintenance operations and increases costs. Angular, uniform, large-size ballast particles play a significant role in distributing train loads to the subgrade. The frequency of railway maintenance is linked to the quality of ballast, which changes continually due to the generation
of fine particles (i.e., ‘fouling’). The cost of maintenance for ballast tamping and surface alignment is approximately $500M annually for the 150,000 kilometers of Class1 track in the USA ($3,800/km/yr, Christmer and Davis 2000). The fouling process is initiated by any of several potential fouling mechanisms including: fracture and abrasion of ballast particles (i.e., ‘mineral fouling’), infiltration from underlying layers (e.g., clay fouling), and spillage from surface sources (e.g., coal fouling) (Selig and Waters 1994; Darell 2003; Su et al. 2010; Huang et al. 2009). Ballast layer fouling leads to an accumulation of permanent deformation, increasing surface deviation of the track. Employing heavier freight loads in the US will likely increase the surface deviation of the track and related maintenance costs (Lee 2009). Larsson and Gunnarsson (2001) stated that a 20% increase in axle load results in 24% extra maintenance cost.

Timely maintenance of railway substructure is essential to provide continuous service at a reasonable cost. Maintenance decisions within the railway industry depend on available information from inspections, standards, and individual and institutional experience (Andersson 2002). Within the rail industry, there are limited standardized procedures or protocol for scheduling preventive maintenance activities or, and possibly more importantly, to evaluate their potential effects (Andersson 2002). There are two approaches for track maintenance planning; one is performance-based and the other mechanistic-based. For creating a comprehensive maintenance model based on a performance-based approach, significant historical data (e.g., traffic, maintenance activities, substructure conditions, and climate data) is required. However, in many cases, sufficient historical data is unlikely to be archived or accessible (Andersson 2002; Stirling et al. 1999). The key aspect of a mechanistic-based model assesses the performance of various track components based on their respective mechanical properties. During track service life, use of a mechanistic-based model can define and predict rate of track deterioration in various conditions.
and decrease prediction uncertainty. A comprehensive track deterioration model should combine both performance and mechanistic models to determine the track quality (Fazio and Prybella 1980; Zarembski 1998). A ballast deterioration model was proposed by Chrismer and Selig (1994) to predict ballast-related maintenance timing and costs based on field data. In our paper, the effects of changing fouling conditions, moisture contents, and state of stress, on ballast and rail track deformation are accounted for.

The objective of this study was to develop a deformation model for railway ballast to account for various fouling conditions, moisture (i.e., climate), traffic, freight capacity (i.e., level of stress), and substructure material quality (e.g., rate of fouling generation and subgrade conditions). A substructure maintenance planning software incorporates a deformation model of track substructure to predict surface deviation of the railway track.

2 BACKGROUND

2.1 Fouling index

Selig and Waters (1994) defined a fouling index (FI) that has been widely used in the USA as $FI = P4 + P200$, where P4 fraction is % mass $< 4.75$ mm, and P200 fraction is % mass $< 0.075$ mm.

2.2 Maintenance planning model for railway ballast

The main concepts of this model are track inspection, a track deterioration model, and standards for maintenance planning, which can be adopted for railway ballast. Prior to using the maintenance model, ballast quality is determined by inspection techniques. From the deterioration model (or deformation model for substructure), the surface deviation of the track due to the subgrade and ballast deformation can be predicted. Maintenance criteria are assigned with respect to rail class (i.e., passenger or freight rail and operating speed) to

© 2011 AREMA ®
estimate the timing for corrective (e.g., tamping) or preventive (e.g., ballast cleaning) maintenance activities.

3 MATERIALS AND METHODS

The ballast deformation model was based on experiments performed on granitic ballast samples provided from a BNSF Rail Company quarry in Wyoming. The ballast particle size was 25 to 63 mm. Different sources of non-plastic fouling were tested in this study, including fouling from subballast intrusion or ballast breakage (i.e., mineral fouling) and surface spillage (i.e., coal fouling).

A prototype large-scale cyclic triaxial (LSCT) apparatus was developed to test specimens with a 305-mm diameter and 610-mm length. Plastic deformation of ballast in various fouling, moisture, and stress conditions was determined over $2 \times 10^5$ traffic cycles. For studying the effects of fouling conditions, ballast specimens were tested at a reference stress state consisting of 90 kPa confining stress ($\sigma_{3 \text{ ref}}$) and 300 kPa cyclic stress ($\sigma_{d \text{ ref}}$). The method of determining the representative stress states of ballast is described in Ebrahimi (2011). The ballast specimens were also tested in various states of stress to determine the deformational behavior of ballast under heavier freight loads. Ballast specimens were prepared by compaction to the maximum dry unit weight of ballast $\gamma_d = 15.8 \pm 0.3$ kN/m$^3$, additional specimen preparation detail is provided in Ebrahimi (2011).

4 SUMMARY BEHAVIOR OF FOULED BALLAST

Plastic strain ($\epsilon_p$) of fouled ballast was measured as a function of loading cycles (N) for a wide range of FI and water contents (w). The rate of $\epsilon_p$ in semi-logarithmic scale, $r_p$, was calculated based on measured plastic strain in the cyclic triaxial test. The number of load repetitions (N)
was converted into million gross tones for rail cars with axle load of 264 kN (30 tones) \( \text{MGT} = \frac{N \times 30}{10^6} \). Mineral and coal fouling were called ‘non-cohesive fouling’ and have similar deformational behavior. As described by Ebrahimi (2011), the \( \varepsilon_p \) of ballast increases linearly up to \( N=10^4 \) (0.3 MGT) in a semi-log scale. This part of the deformation model is called the ‘initial compaction phase (ICP)’. The rate of plastic strain \( (r_p = \frac{d\varepsilon_p}{d\ln N}) \) of ballast is fairly constant in the ICP. When the ICP is passed, an increase in \( \varepsilon_p \) is pronounced. This part of the deformational behavior of ballast is called the ‘fouling impact phase - FIP’. Therefore, a deformation model was proposed as shown in Fig. 1 to account for ICP and FIP phases in the accumulation of plastic strain of fouled ballast. Parameters ‘a’ and ‘b’ in Fig. 1 represent the ICP and FIP in the deformation model of ballast.

5 DEFORMATION MODEL OF RAILWAY BALLAST

Ballast is typically placed in a railway track in a clean or slightly fouled condition. However, generation of fouling continues during track service life. To predict the deformation of ballast during the service life of rail track, three steps were taken: (1) the deformation model for railway ballast in a various fouling conditions (combination of \( w \) and FI) was characterized, (2) the deformation model for ballast at different states of stress was determined, and (3) an incremental analysis (integrating the change of FI, \( w \), and traffic loading during the service life of track) was performed.

5.1 Effect of fouling and water content on mechanistic-based deformation model

The mechanistic-based deformation model of ballast was determined at given FI, \( w \), and reference confining \( (\sigma_{3ref}) \) and cyclic \( (\sigma_{dref}) \) stresses of 90 kPa and 300 kPa, respectively. Change in FI during LSCT tests was assumed negligible (less than 0.5%), which is in
agreement with typical fouling generation rates of ballast, about 0.1%/MGT (Selig and Waters 1994). The rate of plastic strain \( r_p \) of ballast is defined:

\[
\frac{d\varepsilon_p}{d\ln N} = b \quad N < 10^4 \ (0.3 \text{ MGT}) \quad (\text{Eq. 1a})
\]

\[
\frac{d\varepsilon_p}{d\ln N} = b + a \log (N - 10^4) \quad N > 10^4 \quad (\text{Eq. 1b})
\]

The effect of fouling and moisture on parameters ‘a’ and ‘b’ at the representative state of stress were determined from the data in Table 1. The parameters \( a_{ref} \) and \( b_{ref} \) can be defined as:

\[
a_{ref} = S_a \ FI (w - 3) \quad (w > 3\%) \quad R^2=0.91 \quad (\text{Eq.2a})
\]

\[
b_{ref} = S_b \ FI (w - 3) + b_o \quad (w > 3\%) \quad R^2=0.87 \quad (\text{Eq.2b})
\]

When \( w \leq 3\% \), the \( r_p \) of ballast is constant (\( b_o = 0.08 \)) and \( r_p \) diminishes toward zero at FIP. \( S_a \) is 0.0012 and \( S_b \) is 0.0005 for fresh ballast conditions. \( S_a \) and \( S_b \) may change for different types of ballast (recycled or clean ballast) and fouling materials. Increasing FI and \( w \) accelerates the \( r_p \) of ballast both at the ICP and FIP, with corresponding parameters ‘a’ and ‘b’. At a given \( w \), the \( r_p \) of ballast at the ICP (i.e., parameter \( a \)) increases 2.5 times more than the \( r_p \) of ballast in the FIP (compare \( S_p \)). The parameters \( a \) and \( b \) increase relatively linearly with FI and \( w \) for the series of tests conducted on fouled railway ballast.

5.2 Effect of state of stress on deformational behavior of ballast

To include the state of stress in the deformation model of railway ballast, parameters ‘a’ and ‘b’ at various states of stress were calculated relative to those with the reference state of stress (i.e., \( a_{ref} \) and \( b_{ref} \)). The ratio of principal stresses \( (\sigma_1 / \sigma_3) \) is used to determine the deformational behavior of ballast in various states of stress, where \( \sigma_1 = \sigma_d + \sigma_3 \). The reference confining stress \( (\sigma_3_{ref}) \) of 90 kPa and cyclic stress \( (\sigma_d_{ref}) \) of 300 kPa results in \( \sigma_1 / \sigma_3 = 4.3 \). The range of
\( \sigma_1 / \sigma_3 \) from 3 to 10 was considered in the series of LSCT tests accounting for range of stresses ballast can experience in the track. The range of stresses was derived from a finite element analysis as described by Ebrahimi (2011).

The parameters of the deformation model (i.e., ‘a’ and ‘b’) at various states of stress are summarized in Table 1. The normalized parameters \( \frac{a}{a_{\text{ref}}} \) and \( \frac{b}{b_{\text{ref}}} \) as a function of \( \sigma_1 / \sigma_3 \) are described as:

\[
\frac{a}{a_{\text{ref}}} = 0.20 \left( \frac{\sigma_1}{\sigma_3} \right) \quad \text{R}^2=0.94 \quad \text{(Eq.3a)}
\]

\[
\frac{b}{b_{\text{ref}}} = 0.26 \left( \frac{\sigma_1}{\sigma_3} \right) - 0.26 \quad \text{R}^2=0.95 \quad \text{(Eq.3b)}
\]

Parameter \( a \) increases linearly by a factor of 0.20 and parameter \( b \) increases linearly by a factor of 0.26 with ratio of principal stresses. The \( r_p \) in initial compaction phase (i.e., \( b \)) approaches zero when \( \sigma_1 / \sigma_3 \) reaches to 1; i.e., isotropic stress condition for the ballast.

### 5.3 Incremental analysis by integrating change of fouling, moisture, and state of stress

The continual change of fouling content (i.e., due to generation of fouling), moisture (i.e., effect of climate), and stress (due to heavier freight load or higher speed) should be incorporated into the deformation model of railway ballast to determine the track surface deviation during traffic loading. To account for changes in fouling, moisture, and stress, the \( \varepsilon_p \) of ballast should be calculated in increments of traffic (i.e., \( \delta N \) or \( \delta \text{MGT} \)). Fig. 2 demonstrates schematically how change of fouling, water content, and state of stress is captured in an integrated deformation model for railway ballast. Based on this approach, FI is determined from the rate of fouling generation from the field data and quality of materials, while moisture and state of stress are
from the climate and traffic data. Accumulation of $\varepsilon_p$ of ballast ($\delta\varepsilon_{pi}$) in a period of $N_i$ to $N_{i+1}$ traffic loading is calculated by integrating the $r_p$ of ballast:

$$\delta\varepsilon_{pi} = \int_{N_i}^{N_{i+1}} \frac{d\varepsilon_p}{d(lnN)} d(lnN)$$  \hspace{1cm} (Eq.4)

where $N_i$ is the $i^{th}$ increment of integration for the plastic strain. Accumulation of $\varepsilon_p$ of ballast in different fouling conditions is calculated by summing the $\delta\varepsilon_{pi}$ in increments of traffic, as:

$$\varepsilon_p (N) = \sum_{i=1}^{N} \left( \int_{N_i}^{N_{i+1}} \frac{d\varepsilon_p}{d(lnN)} d(lnN) \right)$$  \hspace{1cm} (Eq.5)

In Eq.13, the $r_p$ of ballast ($\frac{d\varepsilon_p}{d(lnN)}$) in $i^{th}$ increment of traffic is a function of $F_l$, $w$, and stress level at the beginning of each traffic (or time) increment and is calculated from the developed mechanistic-based deformation model of railway ballast in this study.

**6 DEFORMATION MODEL OF RAILWAY SUBGRADE**

To determine the surface deviation of railway track due to accumulation of deformation in the rail substructure, deformational behavior of both ballast and subgrade layers are required. The deformation of subgrade can be predicted using the equation proposed by Li and Selig (1994), as follows:

$$\varepsilon_{ps} (N) = c \left( \frac{\sigma_{ds}}{\sigma_s} \right)^m N^d$$  \hspace{1cm} (Eq.6)

where $\varepsilon_{ps}$ (%) is the plastic strain of railway subgrade, $\sigma_{ds}$ is the deviator stress on the subgrade, and $\sigma_s$ is the unconfined subgrade strength described by Li and Selig (1994). Parameters ‘$c$’, ‘$d$’, and ‘$m$’ are related to the type of subgrade materials and proposed by Li and Selig (1994) and summarized in Table 2. The incremental accumulation of plastic strain within the subgrade
is also calculated with similar approach to the railway ballast to incorporate the strength of subgrade (i.e., \( \sigma_s \)) and the state of stress (i.e., \( \sigma_{sd} \)).

Talbot’s equation (1985) was used to find the cyclic stress on subgrade (\( \sigma_{sd} \)). The stress beneath the centerline of the tie at depth \( h \) (mm) below the tie, \( \sigma_{sd} \), (kPa) is a function of stress over the bearing area of the tie (\( \sigma_i \), kPa). Therefore, for a given thickness of ballast equal to \( h \), stress on the subgrade is,

\[
\sigma_{sd} = 957 \frac{\sigma_i}{h^{1.25}}
\]  

(Eq.7)

7 RAIL TRACK SURFACE DEVIATION

Chrismer and Selig (1994) showed that the change in surface deviation of the railway track (\( \delta_v \)) is a function of initial surface deviation (\( \delta_{v0} \)), and the deformation of the track (\( d_L \)) under traffic loading is:

\[
\delta_v = \delta_{v0} + 0.15d_L
\]  

(Eq.8)

where \( \delta_{v0} = 2.5 \) mm was recommended if input data is lacking. \( d_L \) is the track deformation (from fouled ballast and subgrade), which is calculated from the deformation model presented in this study. This approach is adopted here.

8 MECHANISTIC-BASED MAINTENANCE PLANNING MODEL FOR RAIL SUBSTRUCTURE (WiscRail™)

A computer software program was developed using MATLAB™ to predict the surface deviation of the railway track due to railway substructure deformation. This program incorporates the mechanistic-based deformation model of railway ballast and subgrade as described above. The graphical user interface of the mechanistic-based maintenance planning model for railway substructure, called ‘WiscRail™’, is shown in Fig. 3. This program is capable of predicting the

© 2011 AREMA ®
surface deviation of railway track for different fouling conditions, weather conditions, subgrade materials, and traffic loads. As shown in Fig. 3, the program includes traffic data, change in axle load (indication of heavier freight load), moisture in fouled ballast, ballast conditions (i.e., initial fouling condition), subgrade materials, initial track condition, rate of fouling generation (due to particle breakage, subgrade infiltration, and external fouling), and depth of tamping. It was assumed that rate of plastic deformation of ballast deeper than depth of tamping continues from previous traffic loading (i.e., smaller rate of plastic deformation due to a denser condition), however rate of plastic deformation within the tamped layer starts over (i.e., fouled ballast is rearranged to a looser condition after tamping). When track surface deviation, due to substructure deformation, exceeds the assigned limit (based on various classes of railway systems and operation speeds), then maintenance is required. An example of required track alignments (i.e., tamping) with specified 10-mm limit for surface deviation is shown in Fig. 3. As predicted in summary results, for the given traffic and track conditions, five tamping maintenances are required in seven years of track operation, while the fouling content of ballast increases from 5 to 29%.

10 SUMMARY AND CONCLUSIONS

A maintenance planning program was presented based on a deformation model of railway substructure. Predicting the permanent deformation of ballast, the approach taken was based on a mechanistic-based ballast deformation model based on the data obtained using large-scale cyclic triaxial apparatus. Two main phases were distinguished in the deformation model: (1) an initial compaction phase, where the semi-logarithmic rate of plastic strain of ballast \( r_p \) remains constant for loading cycles, \( N \) up to 10 000 and (2) a fouling impact phase, where \( r_p \) increases linearly in a semi-log scale due to the presence of fouling materials. Parameters ‘a’ and ‘b’ were used to characterize the FIP and ICP in the deformation model. A correlation between ‘a’ and
'b' parameters and fouling index, moisture, and state of stress are presented. An incremental integration of plastic deformation of railway ballast in different fouling, moisture, and traffic loading conditions is used, along with a subgrade deformation model, to predict the surface deviation of the railway track. Finally, a mechanistic-based maintenance planning software program was developed by incorporating the mechanistic-based deformation model for railway substructure. The developed model is based on laboratory tests and, although powerful, is recommended for a field validation prior to full-scale implementation in the profession.

**ACKNOWLEDGEMENT**

Funding for this research was provided by the National Center for Freight and Infrastructure Research and Education (C-FIRE). Assistance from the BNSF Railway and Wisconsin and Southern Railroad Company for providing the ballast is appreciated.

**REFERENCES**

Andersson, M., 2002, *Strategic Planning of Track Maintenance*, Swedish National Rail Administration (Banverket), TRITA-INFRA 02-035


© 2011 AREMA ®


Huang, H., Tutumluer, E., Dombrow, W., 2009, Laboratory Characterization of Fouled Railroad Ballast Behavior, 88th annual Mtg. of Trans. Res. Board, on CD-ROM


Stirling, A.B., Roberts, C.M., Chan, A.H.C., Madelin, K.B., and Bocking, A., 1999, Development of A Rule Base (Code of Practice) for the Maintenance of Plain Track in the UK to Be Used in An Expert System, 2nd Inter. Conf. on Railway Engineering, London, UK


Talbot, A.N., 1985, Stresses in Railroad Track-The Talbot Reports, American Railway Engineering Association


© 2011 AREMA®
<table>
<thead>
<tr>
<th>FI</th>
<th>w</th>
<th>$\sigma_3$</th>
<th>$\sigma_d$</th>
<th>b</th>
<th>a</th>
<th>$\frac{\sigma_1}{\sigma_3}$</th>
<th>$\frac{b}{b_{ref}}$</th>
<th>$\frac{a}{a_{ref}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>13</td>
<td>35</td>
<td>300</td>
<td>0.45</td>
<td>0.3</td>
<td>9.5</td>
<td>2.36</td>
<td>1.875</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35</td>
<td>200</td>
<td>0.35</td>
<td>0.23</td>
<td>6.7</td>
<td>1.84</td>
<td>1.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>300</td>
<td>0.19</td>
<td>0.16</td>
<td>4.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>200</td>
<td>0.1</td>
<td>0.1</td>
<td>3.2</td>
<td>0.52</td>
<td>0.62</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>90</td>
<td>300</td>
<td>0.19</td>
<td>0.02</td>
<td>4.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>35</td>
<td>300</td>
<td>0.4</td>
<td>0.05</td>
<td>9.5</td>
<td>2.10</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>200</td>
<td>0.02</td>
<td>-0.0315</td>
<td>3.2</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>200</td>
<td>0.07</td>
<td>0.1346</td>
<td>6.7</td>
<td>1.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>300</td>
<td>0.05</td>
<td>-0.003</td>
<td>4.3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>12</td>
<td>35</td>
<td>201</td>
<td>0.2</td>
<td>0.22</td>
<td>6.7</td>
<td>0.5</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90</td>
<td>205</td>
<td>0.12</td>
<td>0.1</td>
<td>3.27</td>
<td>0.48</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92</td>
<td>304</td>
<td>0.25</td>
<td>0.17</td>
<td>4.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>300</td>
<td>0.5</td>
<td>0.33</td>
<td>9.5</td>
<td>2</td>
<td>1.94</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>33</td>
<td>301</td>
<td>0.12</td>
<td>-0.05</td>
<td>10.1</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>88</td>
<td>303</td>
<td>0.05</td>
<td>0</td>
<td>4.4</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>198</td>
<td>0.02</td>
<td>0</td>
<td>3.1</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* The rate of plastic deformation decreases (i.e., fouling impact phase (FIP) was not observed) at water $w < 3%$. 

© 2011 AREMA®
Table 2  Deformation Model Parameters for Railway Subgrade (from Li and Selig 1994)

<table>
<thead>
<tr>
<th>Model Parameters</th>
<th>Subgrade Classification (USCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ML</td>
</tr>
<tr>
<td>d</td>
<td>0.1</td>
</tr>
<tr>
<td>c</td>
<td>0.64</td>
</tr>
<tr>
<td>m</td>
<td>1.7</td>
</tr>
</tbody>
</table>
Figure 1  Deformation Model for Railway Ballast Presented by Deformation of Clean ballast and Fouled Ballast with Fl=24% and w=14%
Rate of Plastic Deformation,
\[ r_p = \frac{d\varepsilon_p}{d \ln(N)} \]

Fouling in Ballast, FI
Traffic Loading (or MGT)

Moisture of Fouling, \( w \)
Summer, Fall, Winter

Traffic Loading, Tones

Rate of Plastic Deformation
\[ r_p = \frac{d\varepsilon_p}{d \ln(N)} \]

Integrated Plastic Deformation

Plastic Strain,
\[ \varepsilon_p \]

Figure 2 Maintenance Planning Using Incremental Analysis of Deformation Model for Ballast with Changing States of Fouling, Moisture, and Traffic
Figure 3 Graphical User Interface Software of Mechanistic-Based Maintenance Model of Railway Substructure (called, ‘WiscRail™’)

© 2011 AREMA®
Mechanistic Maintenance Planning of Railway Ballast

1 Ali Ebrahimi, 2 Andrew Keene
1 Senior Staff Engineer, Geosyntec Consultant
2 Graduate Student, UW-Madison
Sustainability of Transportation Structures

Environment

Economy

Society

Life Cycle

Maintenance cycle is important
Railway Track Components

- Superstructure
- Substructure
- Subballast
- Compacted Subgrade
- Natural Subgrade
- Ballast
- Tie
- Fastening System
- Rail
- Shoulder
Derailment damage: $256 million/year for 1,980 derailments in 2007 (~ 80% of total train accidents)

Maintenance of ballast is $500M/year

for 150,000 km of class 1 freight rail in the US
(Chrismer and Davis 2000)

Fouling Level Increases During Service Life of Track
Railway Maintenance and Sustainability

Surface Deviation
Mechanistic-Based Evaluation

Plastic (permanent) Strain

\[ \varepsilon_p = \delta_p / L \]

Resilient Modulus

\[ M_r = \sigma_d / \varepsilon_e \]
\[ \varepsilon_e = \delta_e / L \]

Ballast in railway track
Railway Research Components

a. Testing Protocol

b. Mechanisms and New Findings

2011 ANNUAL CONFERENCE
September 18-21, 2011 | Minneapolis, MN
Methods: Large-Scale Cyclic Triaxial (LSCT) Test

Cyclic loading machine to simulate railway traffic

Axle load: 20, 30, and 40 tones

Automated data acquisition system (LabView)

600-mm

300-mm
Representative State of Stress for LSCT Equipment
Type of Fouling and Contaminated Contact Points of Ballast

Non-Cohesive Fouling

Coal Fouling

Mineral Fouling

Clay Fouling

Cohesive Fouling
Deformation of Cohesive Fouled Ballast

- Change strength properties of fouling $\rightarrow$ deformation
- Contaminated contact points between ballast particles
Permanent Deformation with Moisture

- **w**: % of moisture
- **FI**: Fouling Index (%) = P4 + P200

### Graph Details
- **Cumulative Plastic Strain, **$s_p$**, (%)**
- **Number of Loading Repetitions, **$N$**, or 30 × N (GT)**

**Key Points**
- $w = 14$: Coal Fouling
- $w = 10$
- $w = 8$
- $w = 3$
- Clean Ballast

- **Gross Tones for Traffic (GT)**
- **Million Gross Tones (MGT)**
  \[
  MGT = \frac{N \times 30}{10^6}
  \]
New Fouling Indices

Non-Cohesive Fouling (Mineral and Coal)

Cohesive Fouling (Clay)

Plastic Strain after $N=2 \times 10^5$, $\varepsilon_{pu}$ (%)

$\varepsilon_{pu} = 0.79 \times NFI + 0.98$

$R^2 = 0.92$

Plastic Strain after $N=2 \times 10^5$, $\varepsilon_{pu}$ (%)

$\varepsilon_{pu} = 0.63 \times e^{5CFI}$

$R^2 = 0.91$

Non-Cohesive Fouling Index, NFI

Cohesive Fouling Index, CFI

\[
NFI = FI \left( \frac{w - 3}{100} \right)
\]

\[
CFI = FI \times CMI \times \frac{P200}{P4}
\]

Moisture index: \(CMI = (1+w-LL) \times PI^{0.5}\)

Ebrahimi et al. (Submitted to ASCE J. of Geotech. and Geoenvir. Eng, 2011)
New Fouling Indices

Performance of ballast = \( f \)

\[
\begin{align*}
&\text{1. amount of fouling,} \\
&\text{2. moisture,} \\
&\text{3. size of fouling particles,} \\
&\text{4. compositional properties}
\end{align*}
\]

\[
\begin{align*}
\text{NFI} &= \text{FI} \left( \frac{w - 3}{100} \right) \\
\text{CFI} &= \text{FI} \times \text{CMI} \times \frac{P_{200}}{P_4}
\end{align*}
\]

Moisture index: \( \text{CMI} = (1+w-\text{LL}) \times \text{PI}^{0.5} \)

Ebrahimi et al. (Submitted to ASCE J. of Geotech. and Geoenvir. Eng, 2011)
Components of Railway Track Maintenance

1. Track Inspection
2. Initial Track Condition, $t = i$
3. Deterioration Model
4. Track Condition, $t = i+1$
5. New Track Condition, $t = i'$
6. Maintenance Standards
7. Exceeding limit
8. Maintenance Operation
Maintenance Cycle

1. Deformation Model

2. Mechanistic-Based Maintenance Model
Deformation Model of Fouled Ballast

- $w=14$
- $w=10$
- $w=8$
- $w=3$

Coal Fouling
FI=24%

Clean Ballast

Cumulative Plastic Strain, $e_p$ (%)

Number of Loading Repetitions, $N$

$10^1$  $10^2$  $10^3$  $10^4$  $10^5$  $10^6$
Deformation Model of Fouled Ballast

Rate of Plastic Strain, $d\varepsilon_p / d\ln N$

Initial Compaction Phase (ICP) — Fouling Impact Phase (FIP)

- $F_1 = 24\%$, $w = 14\%$

Number of Loading Repetitions, $N$

- $a$
- $b$
a and b = f (1. amount of fouling, 
2. moisture, 
3. type of fouling, 
4. state of stress)
Maintenance Cycle

1. Deformation Model

2. Mechanistic-Based Maintenance Model
   a. Fouling
   b. Moisture (weather condition, e.g., rainfall)
   c. Loading condition (track operation)
Maintenance Planning Using Deformation Model

- Rate of Fouling Generation
- Traffic Loading (or MGT)
- Moisture of Fouling, w
- Summer, Fall, Winter, Spring
- Traffic Loading, Tones
- Fouling in Ballast, F

Input Information:
- Rate of Fouling Generation, Moisture, Intensity of Loading
Maintenance Planning Using Deformation Model

Fouling in Ballast, $F_l$

Rate of Fouling Generation

Rate of Plastic Deformation, $r_p = \frac{\partial \varepsilon_p}{\partial \ln(N)}$

MGT~0.3

$N \sim 10^6$

Traffic Loading (or MGT)

Integrated Plastic Deformation

Plastic Strain, $\varepsilon_p$

Traffic Loading (or MGT)
Mechanistic-Based Maintenance

Mechanistic Deformation Model For Rail Substructure

Traffic
- Traffic (MGT): 300
- Annual Traffic (MGT/Yr): 50

Seasonal Change
- % of Annual Traffic
  - Summer: 30
  - Fall: 20
  - Winter: 15
  - Spring: 35
- Axle Load (t/axle): 30
- Moisture (%): 9.5, 14, 8, 15

Ballast Conditions
- Ballast Thickness (mm): 400
- Depth of Tamping in Ballast (mm): 150
- Coeff. of Surface Deviation (alpha): 0.15

Subgrade Conditions
- Effective Subgrade Thickness (mm): 450
- Unconfined Subgrade Strength (kPa): 60
- Subgrade Deformation Model, c: 0.84
- Subgrade Deformation Model, d: 0.13
- Subgrade Deformation Model, m: 2

Developed at the University of Wisconsin-Madison

Tamping (resurfacing) event is shown by drops.

Initial Conditions
- Initial Fouling (%): 5

Surface Deviation (SD) after Tamping (mm): 3.75

Maintenance Limit for SD of Surface (mm): 10

Rate of Fouling Generation
- Tamping (%/Event): 0.2
- Traffic (%/MGT): 0.03
- Airborne (%/Yr): 0.3
- Spillage (%/Yr): 1.5

Summary
- Years: 6
- Number of Tamping: 4
- Final Fouling Content (%): 25.6
Method for predicting maintenance cycle is developed

This method need to be validated by field data
Questions?