Ballast Thickness Design for Changing Environment(s)

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Track

“A common corrective for poor track has been to lay new and heavier rail. The money might often be better spent in increasing the strength and stiffness of the rail support. One might as well try to stabilize a sinking building by adding another story to it.”

Ideal Track

An Ideal Roadbed

“Disregarding for the present the matter of initial cost, let us briefly consider the requirements for a roadbed that is ideal:
First: the load must be distributed over a large area of the subgrade.
Second: the rail must have continuous support.
Third: Economical means for adjusting the surface must be provided.”

“What is an Ideal Roadbed worth to the Railroad?”

Paul Chipman (1930)

Engineers Club of Philadephia

Source: Chipman, 1930
Outline

Track Design Concept and Philosophy
Risks Affecting Track Structure
Changing Environment(s)
Opportunities to Apply Design Philosophy
Summary
Track Design Concept And Philosophy
Track Design Concept

- **Track Cross Section**
  - Ballast
  - Subballast
  - Subgrade

- **Design Thickness and Profile**
  - Thickness for adequate load resistance
  - Profile for drainage

Source: Li et al, 2015
Load Distribution

- Load Distribution:
  - Rail load to group of ties
  - Ties load to ballast

- Load distribution along the track and along ties affected by track support
  - Stiff track support with little rail deflection concentrates load on tie most directly below wheel load
  - Soft track support increases rail deflection engaging larger group of ties

Source: Selig and Waters, 1994
Load Distribution

• Comparison of concrete and wood tie load distribution (GeoTrack)
  – Concrete tie track stiffer distributing load along tie
  – 10 psi contour to same depth but shape different
  – Wood tie distributes higher tie load to ballast at approximately same pressure

• Model Details
  – Ballast
    • 18 in. thick, 60 ksi modulus
  – Subgrade
    • 8 ksi modulus

Source: Li et al, 2015
Track Design Philosophy

Develop track cross section to:

• Distribute applied loads to subgrade at acceptable level by
• Protecting the layer below and
• Providing resilient support to the tie,
• Limiting plastic deformation and settlement

Source: Li et al, 2015
Ballast Design Criteria

Excessive Plastic Strain
• Subgrade Squeeze

Excessive Plastic Deformation
• Ballast Pockets

Source: Li et al, 2015
Design Method

Ballast Thickness Required for Subgrade Properties
• Based on Track Life / Number of Load Cycles (N)
• Design Wheel Load (Pd)
Considering
• $\rho_a$ = allowable subgrade deformation
• Subgrade soil type
• Subgrade and Ballast Moduli
• Subgrade strength
• T: Subgrade thickness
• L: 6 in. Constant

Source: Li et al, 2015
Design Method part b

\[ I_\rho = \frac{\rho_a}{L} \times 100 \]
\[ a \left( \frac{P_d}{\sigma_s A} \right)^m \]

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>a</th>
<th>b</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH (fat clay)</td>
<td>1.2</td>
<td>0.18</td>
<td>2.4</td>
</tr>
<tr>
<td>CL (lean clay)</td>
<td>1.1</td>
<td>0.16</td>
<td>2.0</td>
</tr>
<tr>
<td>MH (elastic silt)</td>
<td>0.84</td>
<td>0.13</td>
<td>2.0</td>
</tr>
<tr>
<td>ML (silt)</td>
<td>0.64</td>
<td>0.10</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Source: Li et al, 2015
Validating Design / Evaluating Performance

Same Equation: Track Life in Number of Load Cycles Considering

- Ballast Thickness and Properties
- Subgrade Thickness and Properties
- Design Wheel Load

Considering

- \( \rho_a \) = allowable subgrade deformation
- Soil Properties based on soil type (a, b, m)
- A & L constants

\[
N = \frac{\rho_a}{L} \left( \frac{P_d}{\sigma_z A} \right)^m I \rho \times 100
\]

Source:
Figure: Li et al, 2015
Data: O’Riordan and Phear (2001)
Risks Affecting the Track Structure
Overload

• Loads exceed available resistance
• Vertical
  – Tie Ballast Interface
  – Subgrade
• Lateral
  – Misalignment
  – Tie end-ballast gap
• Longitudinal
  – Tie Cavity
Environment

- **Heat**
  - Buckling
- **Cold**
  - Pull apart
- **Heavy Rain**
  - Saturation
- **Flooding**
  - Washout
  - Embankment failure with rapid drawdown
- **Dry/Arid**
  - Sand/dust blow into ballast/cover tracks

Source: Library of Congress
Drainage

- Local Effects
  - Abrasion
  - Ballast Pockets
  - Subgrade Squeeze
  - Ballast Fouling/Mud Pumping

- Global Effects
  - Track Structure Deterioration
  - Track Geometry
  - Layer Intermixing
  - Embankment Stability

Source: Hay Lecture by Gary Wolf
Dynamic Pore Water Pressure

Void Ratio

Liquefaction
Undrained

Cyclic
Mobility

Dense (Dilative Soils)

Drained

Undrained

Loose
(Contractive)

Desnification
Drained

Minor Effective Principal Stress

Axial Strain

Compression

Failure Governed by
Static Strain

Failure Governed by
Cyclic Strain

Number of
Load Cycles

σ_d = Initial Deviator Stress

No.

Shear Stress
Reversal?

Yes.

Static Strain
Governs Failure

Cyclic Strain
Governs Failure

Δσ_d = Cyclic Deviator Stress
Principal Stress Rotation

- Factor in dynamic pore water pressure development
- Shear stress reversal affects track life predictions
Changing Environment
Environmental Changes

• Severe precipitation events present risks that vary locally
• Railroads first infrastructure after water based transportation (canals)
  – Many lines follow rivers and canals
  – Railroads tend to be some of the lowest elevation infrastructure
• Preserving lifelines will require improved knowledge of local factors
Operations

Factors
• Wheel Load
• Train Length/Speed/Headway
• Train Makeup/Load Distribution
• Coupler Length/Axle Spacing
• Precision Scheduled Railroading

Effects
• Load and Traffic affect design life
• Axle Spacing/Coupler Length affect load cycle count
• PSR affects impact of delays due to unplanned maintenance

Source:
Figure: Li et al, 2015
Data: AAR, 2012
Maintenance

• Historic
  – Large Track Gangs
  – Section Personnel

• Current
  – Division Mechanized Gangs
  – Division Personnel

• Future
  – Internet of Things: IoT
  – Fourth Industrial Revolution: RR4.0

Source: Library of Congress
Source: Li et al, 2015
Right of Way

• Historic
  – Large number of track miles
  – Alternative Routes

• Current
  – Rationalized Route Miles
  – Concentrated Traffic on Main Routes

• Future
  – Dedicated corridors for select traffic
  – Combined corridors for highway, rail, pipeline, data...

Source: Library of Congress
Past Right of Way

1853 Connecticut Infrastructure: Rail

2016 Connecticut Rail Map

Source: CT DOT and Library of Congress
Future Right of Way

• 1850
  – Canal
  – Train
  – Trolley
• 1950
  – Train
  – Automobile & Truck
• 2050
  – Driverless Auto
  – Hyperloop
  – Train
  * Predictable Rail Freight, Transit...

Source: Nasa
Opportunities to Apply Design Philosophy
Opportunities: Address Risks

• Natural / Environmental Hazards
  – Drainage
  – Hardening Embankments Against Erosion
  – Floodplain Design

• Local GeoHazard
  – Subgrade Performance
  – Ballast Performance

• Global GeoHazard
  – Slope Instability
  – Landslide

Source: Li et al., 2015 and co-author Steve Chrismer
Common Questions

- Damage analysis
  - Load Increase Ratio\(^4\)
- Traffic volume changes
- Wheel load changes
- Track condition changes
- Maintenance requirements

Source: Ebersohn, 1997
Design for Risk Mitigation

- Roadbed Design provides ballast requirements for subgrade condition based on traffic volume and design load
- Convert design life into a degradation forecast as basis for design validation
  - Did track meet life expectation
  - Is track deteriorating faster than design
  - Possible causes:
    - Increased Load
    - Inadequate ballast performance
    - Weaker Subgrade
    - Environmental Conditions
    - Incorrect design approach/constraints
- Better questions, better maintenance plan

Source: Li et al., 2015 and co-author Jim Hyslip
Summary

• Ballast Design methodology assesses tradeoffs among:
  – required ballast thickness
  – design life requirements
  – traffic volume
  – design wheel load

• Railroad environment is changing
  – Understanding the tradeoffs provides insight

• Risks associated with changes are difficult to evaluate
  – Setting performance expectations can help mitigate risks