“Maintaining Adequate Trackbed Structural Support – An Important Railway Infrastructure Issue”

Jerry G. Rose
Professor of Civil Engineering
University of Kentucky

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University of Illinois at Urbana-Champaign

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Best wishes to

Suey for success with
his railroad classes.

5/24/82

Wlf Hay
Maintaining Adequate Trackbed Structural Support: An Important Railway Infrastructure Issue

Outline

Evolution of Trackbed Designs
Problems
Idealized Trackbed/Roadbed Configuration
Various Structural Design Methods
Innovative European Practices
Concluding Comments
Railroad Track and Roadbed Designs in the U. S. -----
The Track was Laid on the Natural Ground
Then came the Ballast Rock and Ditches
So the All-Granular
Trackbed/Roadbed ---
Evolved
And is by far the most prominent type of Track Structure today

Plus larger and better rail

Plus concrete, steel and composite ties

Plus more significant fastenings and OTM
Surface Problem (Cross level)

Track Settlement and Pumping
Profile Trouble Spots
Pumping and Settlement

Settlement
Purpose: Adjust Geometry ---
Horizontally (line) and
Vertically (surface and cross level)

Add Ballast
Adjust Ballast
Tamper Pulling Track

Restore Geometry
• Railroad track and structure are designed to be economical and easy to maintain

Constantly evaluating Alternatives

Benefits compared to Additional Costs
• Basic Requirements
  • Track must support the loadings and guide the train’s path

• Track Quality Determines
  • Permissible wheel loadings
  • Safe speed of the train
  • Maintenance of track geometrics
  • Overall safety of operations
  • Dependability/Efficiency of operations
  • FRA Class of Track -- 1,2,3,4,5,6,7,8,9
Class 1 Track
10 mph or less

Class 2 Track
25 mph freight
30 mph passenger

Class 4 Track
60 mph freight
80 mph passenger
Track Functions

• Maintain vehicles on a fixed guideway

• Provide a high vehicle ride quality

• Withstand and distribute loadings
  • Static (36 tons/axle) or  
    (36,000 lbs./wheel)
  • Plus Dynamic (Impact)
Trackbed/Roadbed Functions

Combined as a System

• Ballast

• Subballast

• Subgrade

Support the Track and the Imposed Loadings
Interaction, Vertical Load Distribution, and Deflections

Components do not function independently!
Each component layer must protect the one below.
Each component contributes.
It is a System.....
Ballast

- Supports the Track
- Distributes Loadings**
- Drains the Track
- Provides Resilience
- Anchors the Track
- Must be Adjustable
Subballast

Similar to highway base material (DGA)

Fine grained – has smaller top size and more fine-size particles than ballast

Compacts tight and dense with low % voids

Supports/Confines the ballast
Distributes loadings to subgrade
Separates ballast from subgrade
Waterproofs the subgrade

Use AREMA Recommended Practices
Subgrade

- Supports and distributes the loadings
- Confines the subballast
- Facilitates drainage
- Serves as a working platform for roadbed and trackbed

Can be either foundation or embankment
Subgrade

Use Typical Soils/Geotechnical Technology

Very Important
Subgrades Vary
Must Evaluate
Consider Stabilizing
Top 2 Feet Important
Structural Design
Methods used to design track and cross-section

• Trial and Error – based on experience
• Empirical – based on trial and error
• Empirical/Rational – measure loadings and material properties
• Rational – stress/strain analysis and measurements

Typical All-Granular Trackbed is NOT the permanent way – varies greatly, must be maintained continuously
MANUAL FOR RAILWAY ENGINEERING

Volume 1 - Track
- Ch. 1 - Roadway & Ballast
- Ch. 4 - Rail
- Ch. 5 - Track
- Ch. 30 - Ties

Volume 2 - Structures
- Ch. 7 - Timber Structures
- Ch. 8 - Concrete Structures & Foundations
- Ch. 9 - Seismic Design for Railway Structures
- Ch. 15 - Steel Structures

Volume 3 - Infrastructure and Passenger
- Commuter, Transit & High Speed Rail
- Ch. 6 - Buildings & Support Facilities
- Ch. 11 - Commuter and Intercity Rail Systems
- Ch. 12 - Rail Transit
- Ch. 14 - Yards and Terminals
- Ch. 17 - High Speed Rail Systems
- Ch. 18 - Light Density and Short Line Railways
- Ch. 27 - Maintenance-of-Way Work Equipment
- Ch. 33 - Electrical Energy Utilization

Volume 4 - Systems Management
- Ch. 2 - Track Measuring Systems
- Ch. 13 - Environmental
- Ch. 16 - Economics of Railway Engineering and Operations
- Ch. 28 - Clearances
- AAR Scale Handbook

www.arema.org
Track Analysis (Pressure Distribution)

- Must determine allowable loads and deformations
- Must determine actual loads and deformations
- Compare and Adjust (component materials and thicknesses)

- Much early work performed by A.N. Talbot and Committee
- Many early researches idealized systems – Winkler, Westergaard, Boussinesq, etc.
- Talbot treated track as a continuous and elastically supported beam
- Computer systems (finite element and layered analysis) have been developed recently
- Geotechnical and Pavement Design Technologies are applied
• Thickness Design

• Talbot
  \[ P_c = 16.8 \frac{P_a}{h^{1.25}} \]

Subgrade       Tie

• Somewhat Arbitrary Standard

• Mainly Empirical
• Distribution of Pressures

• For ballast pressure

\[ P_a = \frac{2P_{dyn}}{\left(\frac{2}{3}\right)bL} \times \approx 0.40 \]

<65 psi

• Talbot developed empirical formula for subgrade pressure

\[ P_c = \frac{16.8P_a}{h^{1.25}} \]

<20 psi

2.11.2.3 Depth of Ballast Plus Sub-ballast

a. The distribution of loads to depth is approximately the same regardless of the granular material. Therefore the combined depth of sub-ballast and ballast is calculated as a single unit to develop the pressure on the subgrade. Talbot developed an empirical formula for vertical pressure exerted by the ballast under the tie at its intercept with the rail at a depth below the bottom surface of the tie.

\[ p_c = 16.8 \ p_a / h^{1.25} \]

where:

\( p_c \) = bearing pressure on subgrade including safety factor
\( p_a \) = uniformly distributed pressure over tie face
\( h \) = depth below face in inches

b. If the tie pressure \( p_a \) in pounds per square inch and the bearing capacity of the subgrade \( p_c \) are known, the minimum depth of ballast in inches required to produce a stable structure is:

\[ h = (16.8 \ p_a / p_c)^{4/5} \]

c. Assuming an allowable subgrade pressure of 18 psi (a safety factor of 2) and using the unit tie face pressure developed above of 55 psi, solve for ballast depth:

\[ h = (16.8 \times 55/18)^{4/5} = (924.0/18.0)^{4/5} = 23.4 \text{ inches} \]

d. The capacity of the subgrade including the safety factor must always be equal to or greater than the load placed upon it.
Track Stiffness (or Modulus)

- Up and down movement (pumping) of track under repetitively applied and released loads is a prime source of track deterioration.
- Design of track should keep deflection to a minimum.
- Differential movement causes wear of track components.
- Modulus is defined: load per unit length of rail required to depress that rail by one unit.
Track Deflections: Loaded and Unloaded
KENTRACK 4.1: A Railway Trackbed Structural Design Program – Rational Method

- Kentrack is a computer program designed to analyze a railroad track segment as a structure
- Uses Bousinessq’s Elastic Theory
- Uses Burmister’s Multi-Layer System and Finite Element Analysis to perform calculations
Critical Stresses and Strains are Calculated at Various Interfaces within the Track Structure

Design Lives are Predicted for Trackbed Support Layers based on Fatigue Effects (Cumulative Damage Criteria) of Repeated Loadings

Uses DAMA Program – Developed for Highway Pavements (Applicability for RR Trackbeds?)

Applicable of both Unbound (elastic layers) Granular Trackbeds and Bound (elastic and viscous layers) Granular Trackbeds
Trackbed Types

- All-Granular
  - Ballast, Subballast, and Subgrade

- Asphalt Underlayment
  - Ballast, Asphalt and Subgrade

- Combination
  - Ballast, Asphalt, Subballast, and Subgrade
An Equal Opportunity University

Damage Analysis

Subgrade

- Excessive permanent deformation controls failure
- Deformation is governed by the vertical compressive stress on the top of the subgrade
- \( N_d = 4.837 \times 10^{-5} \sigma_c^{-3.734} E_s^{3.583} \)

Asphalt

- Fatigue cracking controls failure
- Fatigue cracking is governed by the tensile strain in the bottom of the asphalt
- \( N_a = 0.0795 \times \varepsilon_a^{-3.291} E_a^{-0.853} \)

Service Life Prediction

\[ L = \frac{1}{\sum_{i=1}^{n} \frac{N_p}{N_a \text{ or } N_d}} \]

Subgrade Service Life

Asphalt Service Life
Effects of Varying Subgrade Modulus – Sensitivity Analysis Example

- A very critical parameter influencing the quality and load carrying capability of the track structure.
- A subgrade with high moduli provides a stiffer foundation that has greater bearing capacity and increases load carrying capability.

Subgrade Compressive Stress vs. Modulus

Subgrade Service Life vs. Modulus
Empty Coal Train at Conway

P-Cell 209 on 5 in. HMA Layer

Initial 5 Cars

4 6-Axle Locos
Reduction of Dynamic Stresses*

*Source -- AAR Transportation Test Center – Pueblo, CO
Table 2a. Comparison of the KENTRACK Predictive Values (KPV) Versus In-Track Data (ITD) for the CSX Mainline at Conway, Kentucky

<table>
<thead>
<tr>
<th>Thickness Ballast/HMA inches</th>
<th>Vertical Compressive Stress on <strong>Ballast</strong> KPV/ITD, psi</th>
<th>Vertical Compressive Stress on <strong>HMA</strong> KPV/ITD, psi</th>
<th>Vertical Compressive Stress on <strong>Subgrade</strong> KPV/ITD, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 / 5</td>
<td>47.9 /</td>
<td>21 / 16</td>
<td>13.6 / -</td>
</tr>
<tr>
<td>10 / 8</td>
<td>48.7 /</td>
<td>22 / 15</td>
<td>11.7 / -</td>
</tr>
</tbody>
</table>

Table 2b. Comparison of the KENTRACK Predictive Values (KPV) Versus In-Track Data (ITD) at TTCI in Pueblo, Colorado

<table>
<thead>
<tr>
<th>Thickness Ballast/HMA inches</th>
<th>Vertical Compressive Stress on <strong>Ballast</strong> KPV/ITD, psi</th>
<th>Vertical Compressive Stress on <strong>HMA</strong> KPV/ITD, psi</th>
<th>Vertical Compressive Stress on <strong>Subgrade</strong> KPV/ITD, kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 / 4</td>
<td>43.5 / -</td>
<td>11.7 / 14.9</td>
<td>8.3 / 8.0</td>
</tr>
<tr>
<td>8 / 8</td>
<td>47 / -</td>
<td>21.9 / 14.9</td>
<td>8.2 / 7.7</td>
</tr>
</tbody>
</table>
International Applications

Italy

France

Germany

Japan

Spain

Austria
• Rome-Florence: 252 km (1977-1986)

• Debated between cement and asphalt

• Asphalt – designated on all future high-speed passenger lines
• Prevents rainwater from infiltrating the layers below the embankment

• Eliminates high stress loads and failures of the embankment

• Protects the upper part of the embankment from freeze/thaw actions

• Gradually distributes static and dynamic stresses caused by trains

• Eliminates ballast fouling

Buonanno, 2000
Typical Cross Section

- 12 cm of asphalt with 200 MPa modulus
- 30 cm of super compacted subgrade with 80 MPa modulus
- 35 cm of ballast on top
Italian Trackbed Construction – Improved Subgrade on left, prior to addition of Granular and Asphalt Subballasts on right
- Increased safety and structural reliability due to increased modulus and uniformity
- Reduced life-cycle cost on the infrastructure from reduced subgrade fatigue
- Increased homogenization of the track bearing capacity on the longitudinal profile and better ballast confinement
- Reduced ballast fouling due to improved drainage
- Reduced vibration levels throughout the track therefore reducing noise
- Reduced thickness compared to a conventional granular design

Advantages of Bituminous Subballast

Teixeira, 2005
Italian Railways Bituminous Trackbed Construction

Compacting Subgrade and Placing/Compacting Asphalt

Spreading and Compacting Ballast
Falling Weight Deflectometer for assessing Structural Competency

Station View of Completed Asphalt Trackbed
France

- Paris to Strasbourg high-speed line -- 2007
- 3 km asphalt subballast
- 574 km/hr (357mph) (test)
The test area for the LGV EE Case Study

- 3 Km Test zone with Asphalt under ballast
- Instrumentation:
  - Temperature Sensors
  - Accelerometers on the sleepers
  - Strain gauges at the base of the layer of asphalt
  - Pressure cells on subgrade support
Comparative Cross-Sectional Profiles

Figure 13. Traditional and Asphalt Cross Sections (Bitume Info, 2005)
Figure 1. Instrumentation of the EE HSL test zone with bituminous sub-ballast layer: Transversal plan (left) and top plan (right) (Not in scale)
<table>
<thead>
<tr>
<th>Matériaux</th>
<th>Module (MPa)</th>
<th>Coefficient de Poisson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rail : acier</td>
<td>210 000</td>
<td>0,29</td>
</tr>
<tr>
<td>Traverse : béton</td>
<td>35 000</td>
<td>0,25</td>
</tr>
<tr>
<td>Ballast</td>
<td>130</td>
<td>0,35</td>
</tr>
<tr>
<td>Grave-bitume ferroviaire</td>
<td>9 000</td>
<td>0,35</td>
</tr>
<tr>
<td>(Fatigue $\varepsilon_6 = 110 \times 10^{-6}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grave non traitée</td>
<td>$3 \times E_{\text{sol}} = 240$</td>
<td>0,35</td>
</tr>
<tr>
<td>Sol support (Plate-forme)</td>
<td>$E_{\text{sol}} = 80$</td>
<td>0,35</td>
</tr>
</tbody>
</table>

Une économie entre 0,30 et 0,45 cm
Testing

• Conduct tests for 4 years (2007-2011)
• Temperature sensors continuously recording air temperature
• Pressure Sensors and Strain Gages checked twice a year
• Accelerometers
**Context**

**The coated in the rail**

- **Benefits of bituminous mixtures in the railway track:**
  - Economies in *Materials*
  - *Equipment Traffic* During the yard
  - Increase of the *Stability of the structure*
  - Reduction of *Maintenance efforts*
  - Control of the *Vibration*

- **Special features of the rail:**
  - High speed → Dynamic efforts
  - Axle Loads High
  - Exposure to the *Humidity*
  - Effort of *Compression* Constant (weight of the superstructure)

Need to characterize the material for these conditions
The test area for the LGV EE REX

- **Vertical stiffness:**
  - **Comparable Values** To those areas utilize framing techniques
  - **Variation of stiffness** (Standard deviation of the signal EMW) **40% More low** That in the common areas (P. E. LAURENS PSIG-VERS-EVT)

- **Ground Pressure support:**
  - Approximately **50% More low** That in areas a classical structure

![Graph showing ground pressure comparison between Enrobé and Structure classique over time]
The test area for the LGV EE REX - Maintenance (2)

**Bituminous Structure** (Pk 110):
- More low rate of degradation
- Best effectiveness of maintenance work
  → Attenuation of the slope after Jam

**Classical Structure** (Pk 112):
- Degradation rate constant even after maintenance operations
Comments Relative to French Asphalt Track Section

Reduces overall cross-sectional thickness by 36 cm
Reduces quantity of fill material by 5,000 cubic meters/kilometer
Pressures under asphalt layer are one-half of granular sections
Deflections of asphalt track are one-third of allowable
Sleeper acceleration is not affected
Less maintenance is required on asphalt track
Asphalt track performs well
Based on performance, several more sections are planned

Source:
Bitume Info, 2005 & Robinette, 2013
Partial Findings

- The use of bituminous layers in structure of railway track allows you to reduce the efforts of maintenance.

- The complex module and the Poisson coefficient complex are strongly dependent on the frequency of solicitation and the temperature.

- In terms of rigidity, the trains running at high speed does not seem to be problematic for bituminous mixtures.

- The mold flow model 2S2P1D is a tool of great value for the study of bituminous materials.

Reference:
Characterization of Thermomechanical Properties of Coated Bituminous Rail
By: Diego Ramirez Cardona
SNCF – French National Railways
October 31, 2014
Rail Experiences with bituminous mixtures:

- **LGV is European** Phase 1:
  - 3 Km Test Area

- **Large Project proponents:**
  - LGV EE phase 2
  - LGV Bretagne Country-de-Loire
  - LGV Atlantic southern Europe-atlantic
  - Workaround
  - Nimes-Montpellier

Large rail projects in France (www.rff.fr)
<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Layer</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Ballast</td>
<td>200</td>
</tr>
<tr>
<td>20</td>
<td>Unbound granular material</td>
<td>200</td>
</tr>
<tr>
<td>30</td>
<td>Unbound granular material</td>
<td>200</td>
</tr>
<tr>
<td>700</td>
<td>Soil</td>
<td>80</td>
</tr>
</tbody>
</table>

**Configuration 1 - Reference zone**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Layer</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Bituminous mixture</td>
<td>9600</td>
</tr>
<tr>
<td>30</td>
<td>Treated soil (TS)</td>
<td>10000</td>
</tr>
<tr>
<td>700</td>
<td>Soil</td>
<td>50</td>
</tr>
</tbody>
</table>

**Configuration 3 - GB+TS**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Layer</th>
<th>Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Bituminous mixture</td>
<td>9600</td>
</tr>
<tr>
<td>20</td>
<td>Unbound granular material</td>
<td>200</td>
</tr>
<tr>
<td>700</td>
<td>Soil</td>
<td>80</td>
</tr>
</tbody>
</table>

**Configuration 2 - GB zone**

Figure 2. Parameters of the three studied track configurations (Not in scale) and extract of the mesh for FE calculations (Not in scale).
Austrian Railways

LEGEND

- Two tracks or more
- Single track
- Electrified with 15kV 16.7Hz
- 15kV 16.7Hz under construction
- Electrified with other current types
- Project
- Operated as tramway
- Freight only
- Non-electrified
- Electrified Narrow gauge
- Non-electrified
- Non-electrified lines with freight only are not included
- Tourist lines

Feel free to use this map for non-commercial purposes, but please send a notice or your comments to maps@tourex.org.

Situation 2-2000
- Closed due to flood damages (Aug 2002)
Reasons for Implementing Asphalt Layers

How to install an Asphalt Layer?

Targets of an Asphalt Layer

– to allow road vehicles running on the sub-layer during construction phase independently from weather and sub-soil situation

– clear separation of sub- and superstructure during the whole service life

Advantages

– drainage effect for raining water hindering it penetrating the substructure
– avoiding the pumping up of fines into the ballast
– delivering a certain amount of elasticity
– homogenising the stresses affecting the substructure
Long Term Experiences
Jauntal, Carinthia

Maintenance free asphalt layer since 1963
Austrian Railways Conclusions

Asphalt layers improve the quality of track in defining a clear and long lasting separation between superstructure and sub-structure. This separation results in less maintenance demands of track and (thus) longer service lives.

These benefits must be paid by an additional investment of 10€/m² within the initial construction.

*Life cycle cost analyses show that it is worth to implement asphalt layers on heavy loaded lines (> 15,000 gt per day and track), as then the annual average track cost can be reduced by 3% to 5%.*

However, implementation of asphalt layers cannot be proposed for branch lines carrying small transport volumes.

Asphalt Layers must be understood as an additional investment in quality, then it pays back its costs. It must not be implemented in order to reduce quality in sub-layers, by for example reducing the thickness of the frost-layers.
Austrian Railways Implementation

Consequently asphalt layers of 8 cm to 12 cm form a **standard element** for new high capacity and high speed lines in Austria.

Due to the long interruption of operation installing of asphalt layers are not proposed within track re-investment and maintenance operations.

Reference:
Dr. Peter Veit
University of Graz
November 24, 2014

**Picture a to c:** new Koralm link

**Picture d:** Schoberpass-line, built in 1991
Concluding Comments

The majority of Railroad Trackbed and Roadbed Designs on the U.S. Railroad System Evolved mainly through Trial and Error; later based on Empirical Measures.

Essentially all U.S. Trackbed/Roadbeds are composed of All-Granular Support Layers.

Periodic Maintenance (surfacing) of the track is necessary to maintain the required Track Geometric Features.

Each Trackbed Support Layer provides specific Qualities; Combined the Layers represent a System.

Computer Systems (finite element/layered analysis) can be used to Design and Analyze Layered Track Structures – Kentrack was the featured Rational Procedure herein.

Using the Computer System, the Relative Effects of Various Layer Compositions (Properties) andThicknesses can be Evaluated – Sensitivity Analysis.
There is considerable interest presently by selected International Railway Agencies to develop Innovative Trackbed Structural Design Programs

Recent Innovative Trackbed Structural Designs and Construction Techniques for Italian, French and Austrian Railways were featured

The Incorporation of a Constituent Layer of Asphalt within the Track Structure and Follow-Up Performance Evaluations for the three Western European Railway Agencies were highlighted

The Asphalt Layer augments or replaces a portion of the Traditional Granular Support Layers providing documented Enhanced Properties to the Track Support Structure
Thank You for **Your** Attention Questions ????