William W. Hay Railroad Engineering Seminar

“Instrumentation and Performance Monitoring of Railroad Track Transitions Using Multidepth Deflectometers and Strain Gauges”

Dr. Erol Tutumluer
Professor and Director of International Programs

Date: Friday, October 3, 2014
Time: Seminar Begins 12:15
Location: Newmark Lab, Yeh Center, Room 2311
University of Illinois at Urbana-Champaign

Sponsored by
Instrumentation & Performance Monitoring of Railroad Track Transitions using Multidepth Deflectometers & Strain Gauges

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US High Speed Rail Depends on Shared Corridor / Shared Track Usage

Shared Track & Shared Right of Way

Adjacent track centers ≤ 25 feet (7.5 m)

HIGH SPEED RAIL

HEAVY AXLE LOADS

BALLASTED TRACK!!!
Erol Tutumluer – tutumluer@illinois.edu

Research on Track Geotechnics

- Railroad track substructure evaluation and condition assessment
- Aggregate size and shape influencing ballast performance using *Univ. of Illinois Aggregate Image Analyzer* & field imaging
- *Discrete Element Modeling (DEM)* of ballast strength and deformation behavior
- Polyurethane coated ballast behavior
- *Subgrade and ballast / subballast settlement at track transitions*
NEW JOURNAL
TRANSPORTATION GEOTECHNICS

Transportation Geotechnics is a new journal publishing high quality theoretical and applied papers on all aspects of geotechnics for roads, highways, railways, airfields and waterways.

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Professor Erol Tutumluer, University of Illinois, Urbana-Champaign, USA
Professor Yunmin Chen, Zhejiang University, Zhejiang, China
**Bridge Approach – Track Transition Problem**

- Differential settlement between the bridge deck and the approach often leads to “bump” development at bridge ends.

- $110 million/year is spent on transition zones in Europe (ERRI, 1999)

- Approximately $200 million is spent annually on track transition maintenance (Sasaoka et al., 2005)
Mitigation of Differential Movement at Railway Transitions for US High Speed Passenger Rail and Joint Passenger/Freight Corridors

PI: Erol Tutumluer

Co-PI: Timothy D. Stark

Research Engineer: Deb Mishra

Visiting Research Scholar: James P. Hyslip
Research Objective

Development of design and repair techniques to minimize and mitigate, respectively, differential movement at railway transitions to ensure safe high speed operation.


Scope

1. Monitor Railway Transitions for Differential Movement

2. Identify "Location" and Major Factors Causing Differential Movement at Monitored Railroad Transitions

3. Numerical Modeling of Monitored Railway Transitions and of Preferred Design and Rehabilitation Techniques for Rail Transitions
VISION for HIGH-SPEED RAIL in AMERICA

Partnership between public sector and private industry with Federal leadership

KEY
- Designated High-speed Rail Corridor
- Northeast Corridor (NEC)
- Other Passenger Rail Routes

[Map showing various regions and corridors]
Track Transitions Selected for Instrumentation

1 Amtrak – Northeast Corridor near Chester, PA

- **Recurrent differential movement** at several bridge approaches along the NEC
- **Three bridges** studied with Amtrak for detailed investigation
- Frequency of “bump appearance” suggests **ballast movement to be the primary mechanism**

2 Norfolk Southern – N Line

- **Eastern Megasite: Ingleside, West Virginia**
- Two bridge sites (MP352.2 and MP352.8) selected for performance monitoring
- Potential “far-surface” movement of **subgrade and fill material** under slow-moving freight trains
AMTRAK Northeast Corridor (NEC)

- The NEC is 457 miles long & has:
  - 17 tunnels
  - 1,186 bridges

- 2,220 passenger trains daily

- 70 freight trains daily (over 14 million car-miles of freight per year)

- 720,000 people ride along some part of the corridor each day.

- In 2011, 11 million passengers on Amtrak's Northeast Regional and Acela Express services
Three Bridge Approaches at Chester, PA Site

Recurring bridge approach settlement and geometry problems

Chester Amtrak Station Bridge Approach (January 2012)
 Installed **Multidepth Deflectometers (MDDs)** at 3 Bridge Approaches
Figure Source: DeBeer, 1989

Multidepth Deflectometer Module

Assembled MDD Module
Drilling and MDD Installation – Amtrak (night time)

Tripod Base for Drill Rig

Amtrak Chester, PA Bridges, July 2012

Custom-Designed Drill Rig being Mounted on Tripod Base

Hammer Drill Mounted on Drill Rig

Drilling through Concrete Tie for MDD Installation
Stabilizing the Ballast using Expandable Polyurethane Foam
Expansion of Polyurethane Foam Inside Drilled Hole
NS – MP 352.2 and MP 352.8 Bridges, Ingleside, West Virginia, Oct. 5 – Nov. 2, 2013
Anchor Installation
45-mm Diameter Hole for MDD Installation

Drilled Hole with Foam – Ballast Stabilization

Soil Removed from the Hole using the Spiral Drill Bit

2-Part Epoxy Grout used to “Bind” the Lining Tube

Lining Tube with Anchor

Lining Tube Installation

Amtrak Chester, PA Bridges, July 2012
Assembled MDD Module

Joining of Cores to Achieve Required Depths

Preparation & Completed Assembly of MDD String

1. Ballast
2. Fouled Ballast
3. Sandy Loam
4. Thin Sand Layer
5. Sandy Loam

Bottom of Tie
Core for Lowest MDD Ready for Installation on Top of the Anchor

MDD Module Mounted on Custom-Designed Installation Tool

MDD Installation into the Drilled Hole

Positioning of MDD at Layer Interface Corresponding to “Zero” Output Voltage from the Signal Conditioner
Collecting Cables Can Get Messy!!!
Installation Complete

• Each approach was tamped after installation of the bottom three modules

• Tamping Protectors were installed to prevent collapse of the holes
16 **Strain Gauges** Installed on Rail at Each MDD Installation
Strain Gauge Installation
Rail Marking for Strain Gauge Installation

Weldable Strain Gauges (Full Wheatstone Bridge Configuration)

Strain Gauges for Wheel Load and Tie Reaction Measurements

Rail Grinding

Spot Welding of Strain Gauges

Protecting Strain Gauges using Silicone
HBM Amplifier used for Data Acquisition

Caldwell East Rail

$y = 74.751x$

$R^2 = 0.9999$
Strain Gauge Calibration

MDD-1: 352.8 Far Hole

\[ y = 41.196x \]
\[ R^2 = 0.9999 \]
NS Bridge Approaches – W. Virginia

Train Passage Over Bridge 352.2
Way-Side Cable Connections

Amtrak Chester Bridges

Settlement data collected biweekly to monthly

Transient Track Response Collected in
- August 2012
- November 2012
- January 2013
- June 2013

Cable Connections from Way-Side Box to DAQ System

Signal Conditioner and DAQ System
Track Settlement Trends
Historical analysis of track geometry data clearly showed largest “dip” 15-ft. from the North abutment.

Second “dip” observed 60 ft. away from the North abutment was of significantly smaller magnitude.

MDD Positions: 15 ft. (4.6 m) and 60 ft. (18.3 m) from North Abutment.
Layer Settlements – Upland St.

15 ft. from North Abutment

Heavy rainfall leads to sudden changes in LVDT readings, which get restored to original trends after dissipation of excess moisture.

Upward movement of LVDT reading represents tamping effect.

Up to 12 mm of ballast settlement recorded before track resurfacing.
Layer Settlements – Upland St. (2)

60 ft. from North Abutment

No effect of tamping observed 60 ft. away from the abutment

Significantly less (2 mm) ballast settlement recorded 60-ft. away from the abutment
Madison Street Bridge-South Approach-Track 2

MDD Positions: 10 ft. (3.0 m) and 60 ft. (18.3 m) from South Abutment

Two “dips” located 12 ft. and 60 ft. away from the South abutment

Madison Avenue (MP 13.25)

R\textsuperscript{2} RP62 (50’ window)

Space Curve

Track 2 Traffic Direction
Layer Settlements – Madison St.

**12 ft. from South Abutment**

Approach was tamped ~25 days after instrumentation; after ~6 mm of ballast settlement.

Last set of measurement indicated a total ballast settlement of ~ 8 mm. Due for tamping?
Layer Settlements – Madison St. (2)

60 ft. from South Abutment

Madison 60 ft. location shows higher track settlement compared to Upland 60 ft. location.
Caldwell Street Bridge-South Approach-Track 3

MDD Positions: 80 ft. (24.4 m) from South Abutment

Significant “dip” 80 ft. from South abutment

R^2 RP62 (50’ window)

Space Curve

Track 3 Traffic Direction

Caldwell Street (MP 12.92)

Left

Center

Right

(a)

(b)

(c)
Layer Settlements – Caldwell St.

80 ft. from South Abutment West End of Tie

No tamping at this location even after 7 mm of ballast settlement
Layer Settlements – Caldwell St. (2)

80 ft. from South Abutment East End of Tie

Similar settlement amount on both sides of the tie
Selig et al. (1981) and Selig (1981) reported that more than 50% of the total track settlement was contributed by the ballast layer.

Selig and Waters (1994) noted that the contribution from the ballast layer will be even higher for track that has been in service for a significant period of time.
Transient Response Trends
Dynamic Data Acquisition under Train Loading

Upland Street Bridge Approach (Train 1)

60-ft. from North Abutment
Percent of Total Transient Deformations Contributed by Individual LVDTs

Upland Street 15 ft. Location

LVDT 1 accounts for a majority of the total track transient deformations
Better support conditions at the 60 ft. location leads to less transient deformations in the ballast layer.
LVDT 1 accounts for 45-95% of the total transient deformations.
Percent of Total Transient Deformations Contributed by Individual LVDTs

Similar trends as Upland Street 15 ft. location
LVDT 1 movement at Madison 60 ft. location more significant than that at Upland 60 ft. location
LVDT 1 accounts for 40-75% of the total transient deformations.
Strain Gauge Layout – Wheel Loads
Measured (a) Wheel Loads; (b) Ballast Layer Displacements; and (c) Ballast Accelerations

Acela Express Wheel Loads
Acela Express Axle Layout

Last 2 Wheels of Trailing Locomotive Used for Geotrack Analysis
Using GEOTRACK to **Backcalculate Layer Moduli**

**Rails**
- Linear elastic beams
- Span eleven ties
- Free to rotate and ends and at each tie
- Linear spring between rail and tie

**Ties**
- Linear elastic beams
- Supported at 10-equally spaced circular locations by the underlying ballast

- 3-Dimensional, Multilayer
- Up to 5 layers
- Infinite horizontal extent
- No slip at layer interfaces
- Only vertical loading considered

Li and Selig (1998)
Peak displacements for last two locomotive wheels plotted
Measured vs Calculated Deflections
(Upland St. Bridge, 60 ft. Location – 2 mm settlement)

Example: Day 97 Values Used in Backcalculation
Layer Moduli Backcalculated from Matching Deflections at MDD Positions

<table>
<thead>
<tr>
<th>Layer</th>
<th>Modulus (MPa)</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Day 0</td>
<td>Day 97</td>
<td>Day 178</td>
</tr>
<tr>
<td>Ballast</td>
<td>45</td>
<td>69</td>
<td>56</td>
</tr>
<tr>
<td>Fouled Ballast</td>
<td>17</td>
<td>55</td>
<td>48</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>32</td>
<td>31.5</td>
<td>30</td>
</tr>
<tr>
<td>Clayey Silt</td>
<td>34</td>
<td>32</td>
<td>31</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>66</td>
<td>69</td>
<td>60</td>
</tr>
</tbody>
</table>

Overall Track Modulus:
- Day 0: 3.310 kips/in./in. = 22.818 N/mm/mm
- Day 97: 3.838 kips/in./in. = 26.460 N/mm/mm
- Day 178: 3.398 kips/in./in. = 23.425 N/mm/mm

Modulus changes most significant in the ballast and fouled ballast layers

Typical Values for Bridge Approaches: 14 - 41 N/mm/mm (Plotkin et al., 2006)
Analyses of Tie Support Conditions
Percent Load Carried by Instrumented Tie

Upland Street

60 ft. Location

Less than 2 mm settlement
Percent Load Carried by Instrumented Tie

Caldwell St.  ~ 7 mm settlement

Similar support conditions under both ends of the tie
Gradual increase in % load carried by instrumented tie indicates inadequate support conditions.
Summary and Recommendations

- **MDD and strain gauge instrumentation technologies** were successfully employed to measure deformations of ballasted track substructure layers, wheel loads and tie reactions under high speed passenger traffic at AMTRAK NEC in the US.

- **Most of the deformations** at the instrumented bridge approaches at the AMTRAK NEC appear to be occurring in the **ballast layer**.

- **“Near-surface” remedial measures** are recommended to mitigate the differential movement problem by arresting excessive ballast reorientation and movement.
Selected Remedial Measures
## Remedial Measures & Implementation Details

<table>
<thead>
<tr>
<th>Bridge / Approach</th>
<th>Track</th>
<th>Remedial Measure</th>
<th>Approximate Length of Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upland / North</td>
<td>3</td>
<td>Chemical Grouting</td>
<td>40 ft.</td>
</tr>
<tr>
<td>Upland / South</td>
<td>2</td>
<td>Under-Tie Pads</td>
<td>60 ft.</td>
</tr>
<tr>
<td>Madison / North</td>
<td>3</td>
<td>Reduced Tie Spacing</td>
<td>60 ft.</td>
</tr>
<tr>
<td>Madison / South</td>
<td>2</td>
<td>Stone blowing</td>
<td>Based on Void Measurements</td>
</tr>
</tbody>
</table>
Polyurethane Grouting / Injection of Ballast

XiTrack GeoComposite

Thompson and Woodward, 2004
Installation of Under Tie Pads

Without Under-Tie Pads

With Under-Tie Pads

Figure Source:
### Stoneblowing

- **A** Initial condition
- **B** Ties raised
- **C** Stoneblowing tubes driven next to tie
- **D** Compressed air used to blow stones
- **E** Stoneblowing tubes withdrawn
- **F** Ties lowered to rest on freshly inserted stone

Selig and Waters, 1994

McMichael and McNaughton, 2003
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