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HIGH-SPEED PASSENGER RAIL TIE-BALLAST INTERACTION

SUMMARY

This Research Results Report presents evidence of poor tie support and increased applied loads that were used to determine the "root cause" of transient and permanent vertical displacements at two Amtrak bridge transitions.

These results are from a Federal Railroad Administration (FRA) study on differential movement at high-speed track transitions. Data from instrumented high-speed passenger bridge transitions along Amtrak's Northeast Corridor (NEC) near Chester, Pennsylvania show a relation between measured permanent vertical displacements of ballast and a gap between the bottom of the tie and top of the ballast. The existence of a gap at locations experiencing large permanent ballast displacements suggests that poor tie support amplifies the applied loads to the ballast which accelerates ballast and tie degradation. Therefore, the "root cause" of permanent vertical displacements at the instrumented high-speed passenger transition zone locations is concluded to be an increase of applied loads to the ballast and adjacent ties resulting from poor tie support at the instrumented tie.

BACKGROUND

Differential movement at railway track transitions is a safety and maintenance issue for railroads worldwide. One of the main examples of this differential movement is the existence of a "bump" or "dip" at the threshold entrance and exit of bridges as routinely observed at highway bridge transitions. These locations require frequent re-leveling because the differential movement is a safety concern especially for high-speed passenger trains. Several previous research studies have attempted to identify mitigation strategies to address this differential movement but none of these studies successfully measured, modeled, analyzed, or mitigated the issue.

OBJECTIVES

The objectives of instrumenting the NEC high-speed sites are to: (1) obtain field data to identify the "root cause(s)" of observed differential movement at selected bridge transitions, (2) use field data to calibrate a numerical transition model, and (3) use the calibrated numerical model to develop appropriate remedial, maintenance, and design measures to address the differential movement in a cost-effective manner.

METHODS

Six locations on the NEC where high-speed passenger trains operate were instrumented in July 2012 with strain gages on the rail to measure wheel and tie loads and five Linear Vertical Displacement Transducers (LVDTs) placed at different depths in the approach embankment to measure transient and permanent vertical displacements with depth under the measured wheel loads (see Figure 1). LVDT #1 is fixed to the tie to monitor tie behavior. Two bridge transition locations (12 and 15 feet from the bridge abutment) were selected for instrumentation because of permanent vertical displacement problems and their free track counterpart located about 60 feet from the bridge abutment for comparison purposes. Both sides of a single tie at a third bridge abutment were instrumented 80 feet from the bridge to investigate vertical displacements across a single tie.

ROOT CAUSE OF DIFFERENTIAL MOVEMENT

Measurements over a period of 185 days show the majority of permanent vertical displacement occurred between the bottom of the concrete tie and about 12 inches within the ballast layer for the two bridge transitions, which displayed the largest permanent vertical displacements. This focused the research on the tie-ballast interface and the ballast.

Figure 1. Photograph showing strain gages on rail and LVDT location on tie (see arrow)

Analysis of the transient vertical displacements suggest the primary "root cause" of the measured permanent ballast displacements at the instrumented bridge approaches is an increase in the applied loads to the ballast. The NEC field data suggest the main factor causing the increased applied loads to adjacent ties is the existence of a gap between the tie bottom and top of the ballast. Ongoing statistical analysis shows that the existence of this gap causes load redistribution to adjacent ties and can amplify wheel loads on the ballast. This redistribution of load can result in a progressive loss of tie support within a group of ties, leading to permanent vertical displacements, broken ties, and poor track geometry conditions over an area at the entrance and exit of bridges.

Figure 2 shows the transient tie displacements that must occur before the peak wheel load can be supported by the ballast, i.e., tie-ballast gap (δ_{gap}), seating displacement (δ_{seat}) to mobilize full ballast stiffness, and ballast displacement to resist the peak wheel load ($\delta_{mobilized}$).

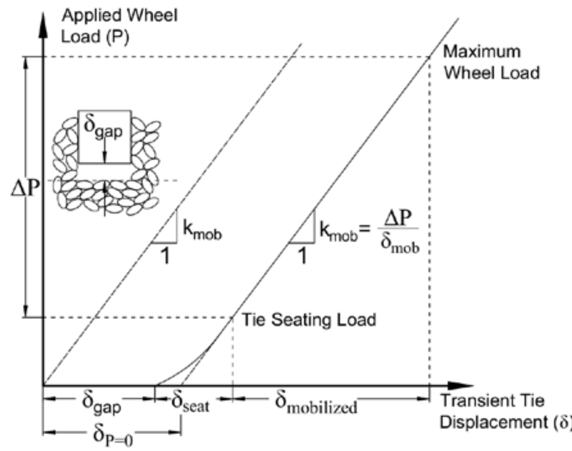

Figure 2. Theoretical tie-ballast interaction model

In other words, δ_{gap} and δ_{seat} must occur before the full support of the ballast is mobilized to resist the applied wheel load. Because measurements below the seating load are rarely obtained, the tie-ballast gap is estimated by extrapolating the linear relationship with a slope of k_{mob} (Figure 2) to the unloaded condition (P=0). This estimated "gap" is represented as $\delta_{P=0}$. While this method slightly overestimates the actual tie-ballast gap, the seating displacement (δ_{seat}) is small because the ballast is well compacted due to prior train passage and tie displacements.

Figure 3 illustrates estimation of the tie-ballast gap, i.e., δP=0, using transition (15 ft from bridge) and free field (60 ft from bridge) data from the Upland Street Bridge on the NEC. Upland (60 ft.) shows a small tie-ballast gap (~0.25 mm) which results in the smallest permanent vertical displacement of all six instrumented locations. Conversely, Upland (15 ft.) shows the largest tie-ballast gap (~1.4 mm) which resulted in the largest permanent vertical displacement. However, both locations exhibit similar ballast stiffness, k_{mob}, after the gaps are closed.

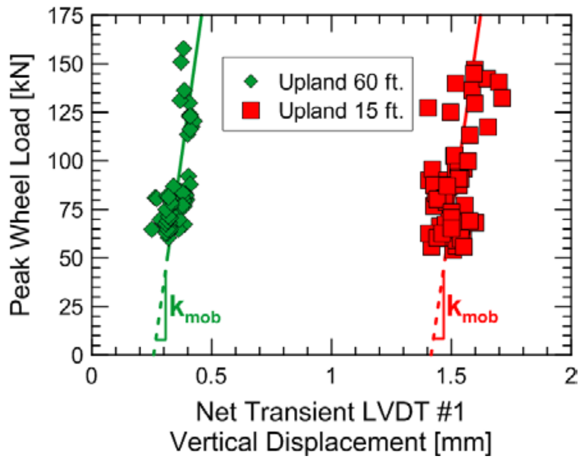

Figure 3. Comparison of transient vertical tie displacement behavior at Upland Street (15 ft.) and Upland (60 ft.) on 26 January 2013

Figure 4 shows a strong correlation between the average tie-ballast gap ($\delta_{P=0}$) obtained during four different data recordings and the accumulated permanent vertical displacement measured over the same time period. This data implies the tie-ballast gap is the primary cause of the observed permanent vertical displacements because the two bridge approach sites (red squares) exhibit excessive permanent vertical displacements while the four free track sites (green triangles) do not. As a result, the red vertical line separates sites with low and high permanent vertical displacements, which suggests a tie-ballast gap ($\delta_{P=0}$) greater than about 1.0 mm can lead to excessive permanent vertical displacements because of load redistribution among adjacent ties. While a gap of 1.0 mm seems unrealistically too small, this behavior of increased permanent vertical displacements from tie-ballast gaps of greater than 1.0 mm is also reported by Selig and Waters (1994) using experimental ballast box testing and field data from near Aberdeen, Maryland.

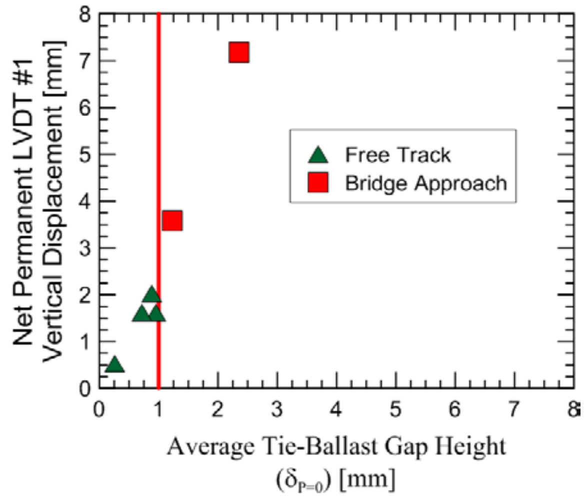

Figure 4. Correlation between tie-ballast gap height and permanent tie displacement.

The likely chain of events resulting in poor tie support and thus permanent vertical displacements is as follows: (1) ballast exists in an uncompacted state and compacts under the tie due to train passage, (2) after train passage the stiff rail pulls the tie back up producing a small gap between the ballast and bottom of the tie, (3) this gap results in increased applied loads and impact loads during subsequent train movements further reducing tie support, (4) some of the increased applied loads are distributed to adjacent ties and gaps start forming under adjacent ties, and (5) as the applied loads increase at a particular tie, transient and permanent vertical displacements of the tie and ballast increase causing further load redistribution.

When the permanent vertical displacements exceed a particular threshold, tamping or resurfacing is required to return the rail to its original elevation. With the previously compacted ballast now in a looser state due to tamping, the chain of events repeats because the ballast quickly compacts again under the first train. As a result, tamping will be required again in a short period of time to re-level the track and reduce the tie-ballast gap.

EVIDENCE OF INCREASED APPLIED LOADS

Increased applied loads at sites experiencing greater tie-ballast gaps are illustrated through measured wheel loads using strain gages on the rail and numerical results below. In Figure 5, each symbol represents the measured wheel loads at Upland (60 ft.) and Upland (15 ft.) for the same passing wheel at different times. Figure 5 shows measured wheel loads at Upland (15 ft.) are consistently greater than at Upland (60 ft.). This implies the transition zone is experiencing greater dynamic loads than the free field, which are reflected in greater permanent vertical displacements.

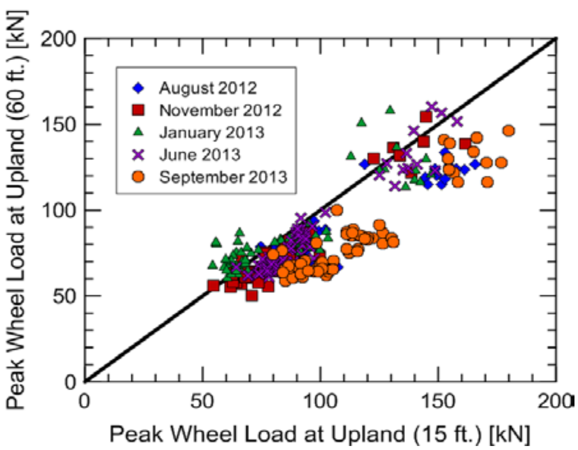

Figure 5. Comparison of Measured Peak Loads at Upland (15 ft.) versus (60 ft.)

Second, numerical analyses of the entire track system, i.e., train bogie, rails, ties, ballast, and substructure, with the dynamic software package LS-DYNA quantify the load redistribution. Modeling various gap heights at the instrumented and two adjacent ties, the force along the instrumented tie-ballast interface, e.g., tie load, is calculated as a percent wheel load where 40% is considered good load distribution (see tie gaps = 0.0 mm for all ties in Figure 6).

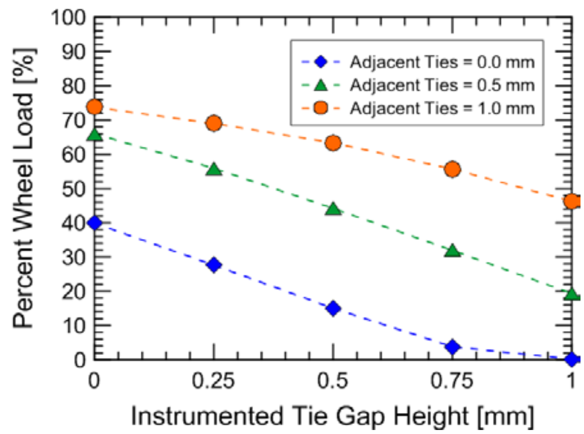

Figure 6. Numerically Calculated Tie Loads as Percent Wheel Load for Various Tie-Ballast Gaps

The results in Figure 6 show significant load redistribution as the tie-ballast gap increases. If the tie-ballast gap of the instrumented tie increases, the instrumented tie load decreases because the load on adjacent ties increases. If the tie-ballast gaps of the adjacent ties increase, the instrumented tie load increases. This implies the wheel load is redistributed from ties experiencing poor tie support to surrounding ties with good tie support. This progressively expands the range of poorly supported and damaged ties, leading to a progressive degradation and potential failure of the track section.

SUMMARY

The “root cause” of permanent vertical displacements at the two instrumented bridge approaches was determined to be an increase of applied loads on the ballast due to a tie-ballast gap caused by ballast compaction and settlement. Ongoing studies show that the existence of this gap redistributes wheel loads and can amplify contact forces on impact, leading to increased ballast compaction and degradation and tie damage.

FUTURE ACTIONS

Future actions include establishing quick non-destructive techniques for evaluating tie support for transitions and free field track and determining mitigation techniques using the results of field testing and various methods. Preliminary studies measuring tie accelerations on both well and poorly supported ties show that the latter experience greater tie accelerations, are dominated by low frequencies due to the lack of tie support, and large transient displacements obtained from double integration of acceleration time histories. High speed video cameras are being used with accelerometers to determine the optimal system for non-destructively evaluating tie-ballast support and thus track serviceability.

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KEYWORDS

Track transition, Differential movement, Tie-ballast interaction, Tie-ballast gap, Accelerometers, Cameras

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