

Evaluation of Tie Support at Transition Zones

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This paper discusses two instrumentation techniques, linear variable differential transformers (LVDTs) and accelerometers, used to monitor and evaluate track structure behavior with the goal of nondestructively and quickly identifying track structural problems that eventually cause track geometry problems. LVDT results at a poorly performing bridge approach and corresponding open track site are used to show a relationship between poor tie support and the observed permanent vertical displacements. The existence of a gap between the bottom of the tie and the top of the ballast is expected to increase permanent ballast vertical displacements because of increased loads and vibration applied to the underlying ballast. Similarly, accelerometers show larger peak tie accelerations at ties with tie-ballast gaps and suggest that poor tie support increases applied loads to underlying ballast. Collected field data show that the tie-ballast gap can increase with time, which results in progressive loss of tie support at that tie and an increasing load on adjacent ties because of redistribution of wheel loads. The results show the need for a nondestructive monitoring system to be used with existing track geometry detection systems to improve identification of poorly supported ties. This system will guide maintenance to reduce the gap, because even a small gap can decrease tie and ballast performance and thus require remediation of a track section rather than a single tie.

Recurring track geometry problems, especially at transition zones, require frequent maintenance by railroads. Although advancements in track geometry measurements with geometry cars and vehicle-track interaction (VTI) systems provide a quick and efficient method for identifying track geometry problems, these problem areas may not always manifest with actionable track geometry measurements, and these technologies do not identify the root-cause track structure problem of the poor track geometry. Hence it is difficult to select the appropriate remedial measure to address the track structure problem.

Some bridge approaches along Amtrak's Northeast Corridor (NEC) near Chester, Pennsylvania, were instrumented with linear variable differential transformers (LVDTs) and accelerometers for investigation of the cause of recurring track settlement (1–3). Analysis of the resulting field data led to the conclusion that these permanent vertical displacements are caused, or at least amplified, by an increase in applied loads to the ballast resulting primarily from poor tie support, that is, existence of a gap between the bottom of the tie and the top

of the ballast (3). A companion paper presents the analysis of those field data and a tie-ballast gap model for describing the data (4).

The development of a tie-ballast gap is attributed to ballast compaction immediately following tamping and is accentuated in transition zones (a) by transient differential movement between the bridge and the approach—that is, ballast, subballast, or subgrade—which results in an impact load when the front wheel of a single truck hits the bridge abutment because the wheel is below the abutment (5), and (b) by development of rail-fastener or tie-ballast gaps caused by the substructure settling while the rail on the abutment does not because it is well supported.

Existence of a tie-ballast gap leads to reduced support, increased rail deflections, redistribution of wheel loads to surrounding ties, and impact loads from the momentum of the moving tie contacting the ballast (3, 6). The increased applied loads at the instrumented and surroundings ties amplify increased permanent vertical displacements at the transition zone, resulting in the commonly observed bump or dip at the entrance and the exit of the bridge (5–10).

Although poor tie support is considered the primary cause of recurring track geometry issues at the instrumented bridge approaches on the NEC (4), the sites also have some track structural problems, such as damaged ties and broken rail joints, both of which were observed at the site investigated in this paper. These track structure problems also can lead to further increased loads on the track system and permanent track displacement.

This paper investigates railroad track behavior with nondestructive monitoring techniques, for example, accelerators, which are verified with LVDTs. Subsequent development of a nondestructive monitoring system would provide quantified insight into track structure performance and degradation with time, information that can guide future maintenance and remedial measures. This system can be used by track inspectors to identify quickly the type of track structure problems contributing to track geometry problems detected by current methods—track geometry car or VTI system—so remedial action can be chosen that addresses the specific track structure problem.

INSTRUMENTATION

The instrumentation initially installed at the investigated track transition sites consists of strain gauges and LVDTs for measuring wheel loads and track substructure displacements. The strain gauges were applied to the rail to measure wheel loads and tie reactions, and strings of five LVDTs measured displacement with depth. LVDT 1 measured from the top of the concrete tie to the bottom of the ballast layer (~0.3 m), LVDT 2 measured the subballast, and LVDTs 3, 4, and 5 measured the subgrade. Detailed explanations are available elsewhere (1, 2).

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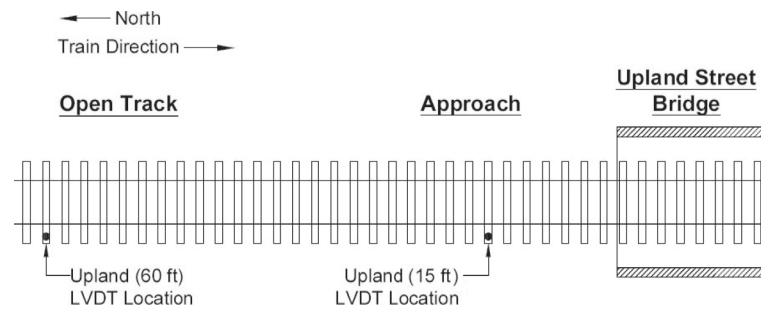


FIGURE 1 LVDT locations at NEC Upland Street bridge approach near Chester.

This instrumentation was used to determine the cause of recurring track geometry problems at two bridge approaches along the NEC in Chester and has proved to be useful because LVDT strings can measure the behavior of multiple substructure layers with depth. However, the LVDT strings are costly, time-consuming and difficult to install, unreliable over time, invasive to the rail and tie, and not durable. To provide a less invasive measurement technique for more widespread diagnosis of track support problems, accelerometers were subsequently attached to the top of concrete and timber ties to measure tie accelerations and movement. The LVDT data are used here to confirm the accelerometer data and interpretations.

This paper investigates the NEC bridge over Upland Street near Chester. The described instrumentation was installed near the west approach at concrete ties located 15 ft (4.57 m) and 60 ft (18.2 m) from the bridge abutment (Figure 1) for comparing transition zone and open track behavior. These sites are referred to as Upland 15 ft and Upland 60 ft throughout the paper.

The track at these locations is straight, elevated, and confined by large gravity retaining walls. One-dimensional vertical displacement was assumed in the interpretation and modeling of the LVDT measurements because of the lateral confinement provided by the retaining walls. The applied loading usually consists of high-speed passenger trains operating at 80 to 110 mph (129 to 177 km/h) from north to south (Figure 1).

Because initial LVDT results suggesting that poor tie support caused by ballast settlement is the primary cause of the transient and permanent vertical displacements at the Upland 15 ft site (3), alternative nondestructive methods were sought to identify and quantify tie support. A wide variety of instrumentation types and approaches was considered, and accelerometers were chosen for data collection and track assessment because they provide an inexpensive, quickly installed (eight accelerometers in 15 min), noninvasive, durable, and reusable means with which to nondestructively evaluate tie, rail, and track behavior by measuring tie and rail acceleration time histories. The accelerometers are only 0.5 in. long, weigh less than 0.1 oz (3 g), and are connected to the tie with a drop of superglue or epoxy, resulting in a quick and noninvasive monitoring system that does not interfere with train operations. This makes accelerometers suitable for short-term monitoring, that is, a single train pass or day, as well as long-term monitoring during wet and inclement weather because weather-resistant accelerometers are available.

Acceleration time histories are beneficial because they provide insight into the increased loading on the tie bottom and ballast, especially if a tie-ballast gap is present. Higher tie accelerations result in higher-impact forces on the bottom of the tie and the top of the ballast because of Newton's second law, indicating that the force increases with increasing acceleration given constant mass, and the impulse

momentum theorem, indicating that the force and duration of impact controls the transferred momentum. The acceleration time history can be converted to a frequency spectrum for determining the dominant frequencies of the tie deflection-vibration response, which gives insight into tie support conditions that can influence various vibration modes (11–14). Although support conditions were the motivation for use of accelerometers, tie accelerations also can be used to investigate the influence of damaged ties, fouled ballast, ballast rearrangement caused by applied loads and vibrations, moisture conditions, wheel-rail impacts, rail and wheel defects, substructure support on tie vibration and displacements, and the formation of a tie-ballast gap.

To correlate the LVDT and accelerometer results, accelerometers were temporarily installed at the Upland 15 ft and Upland 60 ft tie locations on September 4, 2013, and July 1, 2014. On both dates, all LVDTs and accelerometers recorded the same passing train. An accelerometer installed on a concrete tie at the Upland Street Bridge is shown in Figure 2. The grids attached to the rail and tie in Figure 2 were installed for use with a high-speed video camera that recorded their displacement time histories for comparison with the accelerometer derived displacements.



FIGURE 2 Accelerometer on concrete tie at Upland Street near Chester.

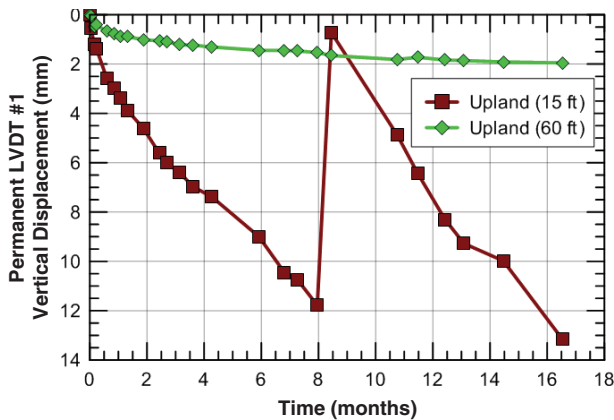


FIGURE 3 Permanent ballast (LVDT 1) vertical displacement at Upland 15 ft and Upland 60 ft.

PERMANENT VERTICAL DISPLACEMENTS

Figure 3 compares the measured permanent vertical displacements for LVDT 1 for about 16 months (August 2012 to December 2013) to illustrate track degradation with time. LVDT 1 measures the change in displacement from the top of the tie to 12 in. (0.3 m) into the ballast; LVDTs 2 through 5 measure deeper substructure layers. LVDTs 2 through 5 show little permanent vertical displacement, so most permanent movement is considered to be in the ballast or at the tie–ballast interface (LVDT 1) and hence is the focus of this study.

As expected, the permanent vertical displacements at Upland 15 ft are significantly greater than at Upland 60 ft, with a rate of 14 to 17 mm (0.55 to 0.70 in.) a year; Upland 60 ft experiences an average permanent vertical displacement of about 0.8 mm (0.03 in.) a year. The sudden decrease in permanent vertical displacements at Upland 15 ft after about 8 months was caused by tamping, which raised the rail to an elevation level with the surrounding track.

Figure 3 also shows that the rate of permanent vertical displacement in LVDT 1 at Upland 60 ft approaches zero, and the rate of permanent vertical displacement at Upland 15 ft remains about constant. This implies the ballast at Upland 60 ft is approaching an equilibrium condition or density with little additional particle rearrangement, crushing, or lateral movement required to support the applied loads. This behavior matches observations of laboratory tests (15), in which the rate of permanent vertical displacement decreased with increasing load cycles as ballast densified under repeated loading. However, the approximately constant rate of permanent vertical displacement, that is, the approximately constant loss of ballast or ballast rearrangement and breakage, at Upland 15 ft implies that the ballast has not been compacted to a density or shear strength to resist the applied loads. The equilibrium ballast density and strength have not been reached at Upland 15 ft yet, possibly because the applied loads are too high, ballast modulus or strength is reduced because of fouling and wetting, or there is ballast or tie breakage at this location.

BRIDGE APPROACH VERSUS OPEN TRACK BEHAVIOR

Tie or LVDT 1 Response

The reason for the greater permanent vertical displacements at Upland 15 ft than at Upland 60 ft was sought through analysis of the transient wheel loads and vertical displacements to explain track

behavior. Track behavior is often defined in terms of track geometry (Figure 3) or vehicle movements and accelerations, which are monitored by track geometry cars or VTI systems, respectively. These systems successfully detect rail position and track geometry issues (tamping in Figure 3) but not the structural aspect of track performance needed for describing the underlying causes of the geometry problems, for example, the tie–ballast gap. Through analysis of measured transient track behavior, the underlying causes of the geometry problems can be identified, facilitating selection of an appropriate remedial measure.

Investigation of possible causes of permanent vertical displacements at the Upland Street bridge approach, such as ballast stiffness, subgrade stiffness, fouling, or vibrations, shows that poor tie support leads to increased measured transient and permanent vertical displacements at Upland 15 ft (3). Poor tie support, or the existence of a tie–ballast gap, increases applied loads to the ballast through load redistribution and impact loads from the bottom of the moving tie contacting the top of the ballast. In other words, as the tie–ballast gap increases, the applied loading on the ballast, and hence permanent vertical displacement, increases.

A tie–ballast interface behavior model developed with nonlinear and linear load–displacement portions was verified with strain gauge and LVDT 1 measurements (4). The strain gauges measured wheel loads, and LVDT 1 measured the peak transient displacement from the top of the concrete tie to 12 in. into the ballast layer. Because the displacements from LVDTs 2 through 5 are much smaller than that of LVDT 1, the LVDT 1 displacement is used here to approximate vertical tie displacement relative to the ballast. The following two parameters are used in the load–displacement model: mobilized stiffness of the ballast (k_{mob}) and the tie–ballast gap ($\delta_{P=0}$). Figure 4 shows the load–displacement behavior of the tie at both Upland 15 ft and 60 ft for the same passing train on July 1, 2014. The mobilized stiffness of the ballast (k_{mob}) is the slope of the lines in Figure 4 and is about the same for both locations. The tie–ballast gap is calculated by extrapolating the ballast stiffness to the zero load condition ($P = 0$), as indicated by Wilk et al. (4) and Sussmann et al. (16).

The load–displacement results in Figure 4 show a significant difference in the tie–ballast gap with values of 0.29 mm (0.01 in.) at Upland 60 ft and 6.74 mm (0.25 in.) at Upland 15 ft. The small gap at Upland 60 ft is indicative of good tie support, which results in good load distribution among adjacent ties so the instrumented tie is receiving 30% to 50% of the wheel load (17, 18). The larger tie–ballast gap at Upland 15 ft results in redistribution of load to

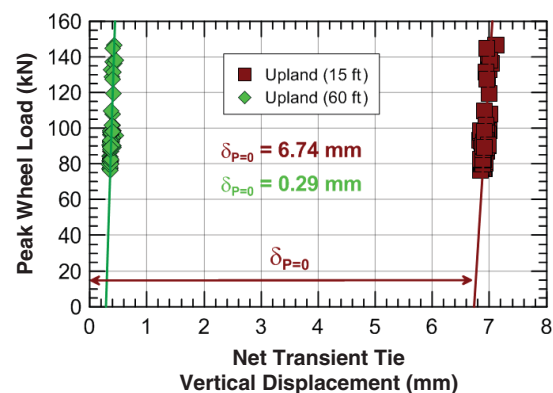


FIGURE 4 Tie load–displacement behavior at Upland 15 ft and Upland 60 ft on July 1, 2014.

adjacent ties (6) and impact loads from the momentum of the moving tie contacting the underlying ballast because of Newton's second law. Hence, the poor tie support at Upland 15 ft can result in greater loads applied to the underlying ballast, which results in the larger permanent vertical displacements shown in Figure 3.

Accelerometer Response

Tie transient and permanent vertical displacement support can be quantitatively measured with LVDTs, but accelerometers provide a quick (15 min to install eight accelerometers) and noninvasive means with which to evaluate tie support. Both peak accelerations and the behavior in the frequency domain offer insight for quick evaluation of tie support. An unsupported tie exhibits larger accelerations that correlate to larger impact loads because the force of impact equals the mass of the concrete tie and vehicle unsprung mass multiplied by tie acceleration. The frequency domain shows the dominant frequencies of tie response and their amplitudes, which can facilitate understanding of how the concrete ties at Upland Street Bridge are vibrating and of the tie support conditions associated with the different vibrations (11–14).

The acceleration time histories of two train bogies at Upland 15 ft and Upland 60 ft are compared in Figure 5. The tie accelerations at Upland 15 ft are consistently greater with peak accelerations of about -30 to -40 g, and the consistent accelerations at Upland 60 ft are less than or equal to -5 g. The greater accelerations at Upland 15 ft imply that a greater impact load is being applied to the tie bottom and ballast because of Newton's second law, which explains the observed broken adjacent tie and increasing transient and permanent vertical displacements over time at this location. For the Upland 60 ft site, previous instrumentation shows consistent peak accelerations of below -5 g is indicative of well-supported ties, which corresponds to a small tie-ballast gap and small transient and permanent vertical displacements with time.

Figure 6 compares the full measured acceleration time histories displayed in Figure 5 in the frequency domain. The acceleration time histories are converted to the frequency domain with fast Fourier transform techniques. Analysis of the acceleration responses in the frequency domain reveals greater amplitudes at Upland 15 ft both at low frequencies (<30 Hz) and for frequencies between 50 and 200 Hz. Low-frequency accelerations are attributed to displacement of the tie, and larger amplitudes at these frequencies are expected at sites displaying larger transient vertical displacements. This expectation is verified through analysis of the LVDT 1 transient displacement

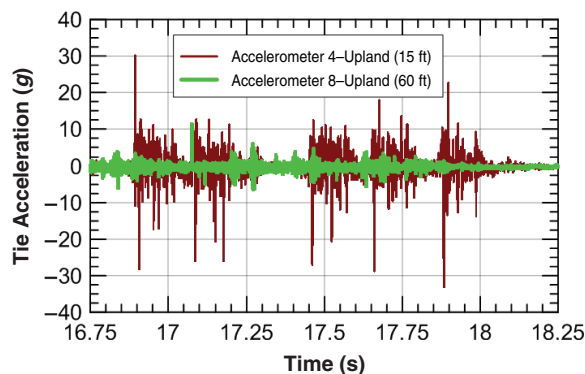


FIGURE 5 Measured tie accelerations of two bogies at Upland 15 ft and Upland 60 ft on July 1, 2014.

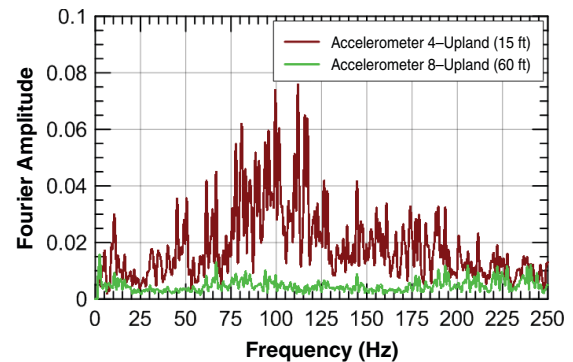


FIGURE 6 Measured tie acceleration time histories for Upland 15 ft and Upland 60 ft in Figure 5 converted to frequency domain for passing train on July 1, 2014.

time histories in the frequency domain, where the Upland 15 ft site shows larger amplitudes below 30 Hz. The large amplitudes for frequencies between 50 and 200 Hz are attributed to vibration within the tie and track system (11–14) because ties with poor support offer less damping and resistance to tie vibration than do well-supported ties.

These results show that accelerometers can be used to quickly distinguish ties with good and poor tie support conditions, and with LVDTs many ties can be simultaneously instrumented instead of only one tie. Greater peak accelerations and greater amplitudes at frequencies below 30 Hz and between 50 and 200 Hz indicate poor tie support. Table 1 summarizes the permanent vertical displacement, tie-ballast gap ($\delta_{p=0}$), and peak tie acceleration values for Upland 15 ft and Upland 60 ft. These results show that small permanent vertical displacements for tie accelerations less than or equal to -5 g and are being used to assess tie-ballast gap behavior at other railroad sites with concrete and timber ties.

DECREASING TIE SUPPORT WITH TIME AT UPLAND 15 ft

Tie support is one of the leading requirements to ensure good long-term performance of concrete ties. Changes in tie support with time must be understood because these changes influence tie life and frequency of track maintenance and repair. If the tie-ballast gap increases in size with time, not only do the impact loads increase with time but the wheel loads will be redistributed to surrounding ties (6), which leads to a progressive loss in tie support within a group of ties instead of just a single tie. Timely remediation of the initial tie support condition will reduce the potential for progressive degradation of a group of ties.

The change in tie support over time was investigated with accelerometers and corroborated with LVDT measurements. LVDT data

TABLE 1 Values of Permanent Vertical Displacement Rates, Tie-Ballast Gap Values, and Peak Accelerations

Site Location	Rate of Permanent Vertical Displacement [mm/year (in./year)]	$\delta_{p=0}$ [mm (in.)]	Peak Tie Acceleration (g)
Upland (15 ft)	15 (0.60)	6.74 (0.25)	-30 to -40
Upland (60 ft)	0.8 (0.03)	0.29 (0.01)	-5

were collected at the Upland Street Bridge in August and November 2012; January, June, and September 2013; and July 2014. Accelerometer data were collected at the same ties in September 2013 and July 2014 for comparison purposes.

Tie or LVDT 1 Response with Time

Figure 7 shows an increase of the tie–ballast gap with time at Upland 15 ft, which indicates a progressive deterioration of tie support. Starting with an initial tie–ballast gap of about 1.5 mm, the tie–ballast gap increased to 4.4 mm (0.17 in) within 10 months after installation. The gap continued to increase until the last recording of a value of 6.74 mm on July 1, 2014. Tamping at Upland 15 ft occurred before the first reading and after about 8 months (Figure 3), showing that tamping does not alleviate development of a tie–ballast gap because tamping loosens and reduces the density of the ballast (15). After a single train passes, the ballast will compress and densify, starting the gap formation process and load redistribution. In other words, tamping appears to be a short-term remedy for a tie–ballast gap. Other options for remediating tie support without loosening the ballast are shims under the tie, shovel packing, and stone blowing. These historically were used to adjust tie support layers by adding a small layer to the top of the ballast to correct the tie elevation after settlement.

These results show that tie–ballast gaps can increase with time. This gap increase can increase applied loads, that is, impacts and load redistribution, which can further increase the tie–ballast gap with time and degradation of the tie or underlying ballast. By identifying tie–ballast gaps in early stages, railroads may be able to remediate problematic regions and prevent the gap from increasing and affecting surrounding ties. These data suggest that a remedial measure other than tamping should be used to stop tie–ballast gaps from recurring and increasing.

Accelerometer Response with Time

Figure 8 compares tie accelerations at Upland 15 ft on September 4, 2013 (Figure 8a), and July 1, 2014 (Figure 8b), when the tie–ballast gap increased from 5.08 mm (0.2 in) to 6.74 mm, as shown in Figure 7. The measured tie accelerations also increased within this time frame, starting at about -20 g on September 4, 2013, and increasing to about -30 g on July 1, 2014. These results show not only that accelerometers can identify increased tie–ballast gaps but also that

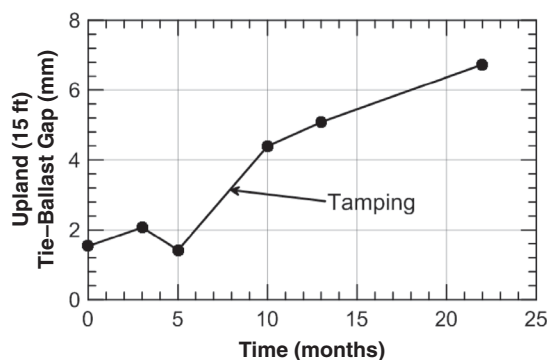


FIGURE 7 Calculated tie–ballast gap at Upland 15 ft over 22 months, August 2012 to July 2014.

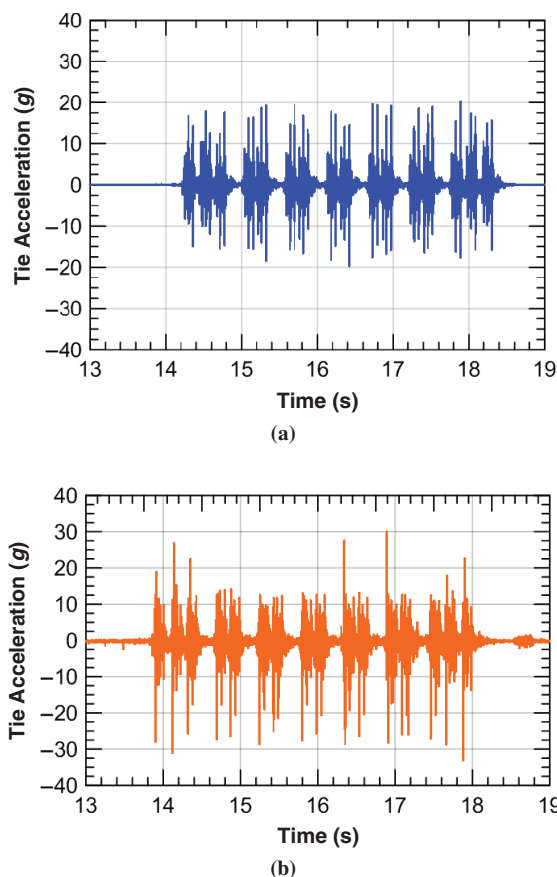


FIGURE 8 Measured tie accelerations at Upland 15 ft for passing train on (a) September 4, 2013, and (b) July 1, 2014.

larger tie–ballast gaps lead to increased loading on the tie bottom and underlying ballast because of impact loads.

In the frequency domain, the July 1, 2014, recording shows a greater response between frequencies of 50 and 200 Hz than the September 4, 2013, recording. A frequency of 100 to 150 Hz corresponds to the first bending mode of a concrete tie (11–14), so an increase in amplitude in this region implies more tie vibration is occurring because of less tie support (Figure 9).

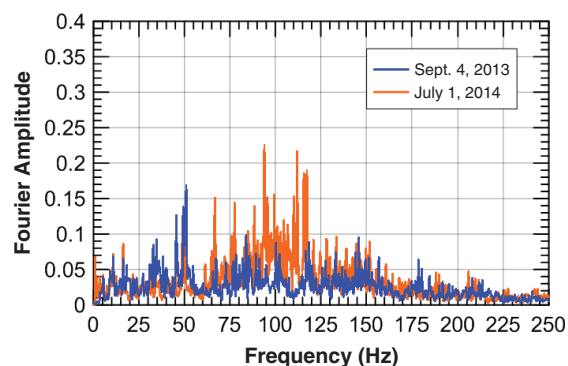


FIGURE 9 Measured tie accelerations in Figure 8 in frequency domain at Upland 15 ft for passing train on September 4, 2013, and July 1, 2014.

SUMMARY

This paper described the use of a nondestructive testing technique, that is, accelerometers, to evaluate track structure behavior by comparing the results with LVDT-derived displacement data. This system has been expanded to include high-speed video cameras used to measure transient displacement time histories of both the rail and the tie nondestructively. After track structural problems are identified, remedial measures can be selected that address the cause of the track geometry problem so that the problem does not progress to a larger and more expensive track geometry issue or track structural deterioration problem.

A bridge approach experiencing track geometry problems on the NEC (Upland 15 ft) along with its well-performing open track counterpart (Upland 60 ft) were instrumented with accelerometers to correlate with data from previously installed LVDTs. These field measurements resulted in the following observations:

- The bridge approach (Upland 15 ft) exhibits a faster rate of permanent vertical displacement, 15 mm (0.6 in.) a year, than the nearby open track location (Upland 60 ft), at only 1 mm (0.04 in.) per year.
- The faster rate of permanent vertical displacement at the bridge approach is associated with a greater tie–ballast gap (6.74 mm) than the open track site (0.29 mm). The greater tie–ballast gap causes increased applied loads because of the impact of the tie hitting the ballast and load redistribution among adjacent ties.
- The rate of permanent vertical displacement at the open track site (Upland 60 ft) is approaching zero because the underlying ballast has compacted to a density that is sufficient to resist the applied loads and applied load, and it is not being displaced by impact loads while the rate of permanent vertical displacement at the bridge approach site (Upland 15 ft) increases with time at a constant rate.
- The bridge approach site also shows significantly greater peak accelerations (~30 g) than the corresponding open track location (~5 g). Similar behavior is observed in the frequency domain with greater tie vibrations at the bridge approach (Upland 15 ft) at frequencies of 50 to 200 Hz; the open track site shows little response, at frequencies of 0 to 200 Hz. Hence, increased peak accelerations and greater tie vibrations can be used as indicators of poor tie support and the success of remedial measures in reducing the tie–ballast gap.
- The field LVDT and accelerometer data show that the tie–ballast gap can increase with time. The bridge approach site (Upland 15 ft) shows an increase in tie–ballast gap from about 1.5 mm to 6.74 mm in 16 months. As expected, the greatest increase in tie–ballast gap occurred after tamping. This implies that tamping only temporarily reduces the tie–ballast gap, and other remedial actions should be explored to provide a longer-term correction of the tie–ballast gap.
- The increase in peak accelerations between the September 4, 2013, and July 1, 2014, readings (~20 to ~30 g) at the bridge approach site shows an increase in applied force to the ballast in agreement with Newton's second law.

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