

2 **Modeling Progressive Settlement of a Railway Bridge**  
3 **Transition Zone**

4  
5  
6 *TRB 18-03447*

7  
8 *TRB Committee AR050*

9  
10 *Transportation Research Board 97<sup>th</sup> Annual Meeting*

11 Submitted: November 15<sup>st</sup>, 2017

12  
13  
14 Stephen T. Wilk<sup>1,2</sup>, and Timothy D. Stark<sup>1</sup>

15  
16  
17  
18 *Department of Civil and Environmental Engineering<sup>1</sup>*  
19 *University of Illinois at Urbana-Champaign*  
20 *205 N. Mathews Ave., Urbana, IL 61801*

21  
22  
23  
24  
25  
26 6,302 Words, 5 Figures, 1 Table = 7,477 Total Word Count

27  
Stephen T. Wilk

(217) 333-7394

[swilk2@illinois.edu](mailto:swilk2@illinois.edu)

Timothy D. Stark

(217) 333-7394

[tstark@illinois.edu](mailto:tstark@illinois.edu)

28  
<sup>2</sup> Corresponding Author

## ABSTRACT

This paper models the progressive ballast settlement of a railway bridge transition using a three-dimensional dynamic numerical model that includes the train truck, rails, ties, ballast, subgrade, and bridge abutment. A ballast settlement model that relates tie load to ballast settlement is presented and demonstrated using an iterative procedure to evaluate bridge transition response up to 28 MGT. The results indicate transition zones attempt to reach a state of equilibrium in which the ballast settlement profile evenly distributes the wheel load to the underlying and surrounding ballast. This analysis scenario represents ideal transition zone behavior because it is assumed that the ballast is homogenous and has identical properties throughout the bridge approach. This assumption is challenged with simulations exploring heterogenous ballast conditions and the results suggest heterogenous ballast conditions may be a large contributor to differential settlement at transition zones.

**Keywords:** transition zone, approach, tie gap, progressive settlement, ballast

## 1 INTRODUCTION

2 Transition zones are railroad track locations experiencing rapid changes in stiffness, transient and  
3 permanent displacements, and support, which are often associated with accelerated ballast  
4 settlement and track geometry defects (1,2). For example, an instrumented bridge approach  
5 transition zone site located 4.5 m (15 ft.) from a bridge servicing high-speed passenger rail in the  
6 United States experienced a recurring ballast settlement rate of 14 mm/year while only 1 mm/year  
7 was experienced 18 m (60 ft.) from the same bridge in open track (3). Similar but less extreme  
8 situations have also been observed in Europe (4).

9 Multiple studies have investigated the root cause(s) of this differential settlement (3-6).  
10 Besides the inevitable problem that the approach track will naturally settle because it consists of  
11 earthen and ballast materials while the bridge will not because it is supported by deep foundations,  
12 the studies typically attribute increased wheel and tie loads in the approach as explanations for the  
13 significantly greater settlement in the approach as opposed to the open track, i.e. tangent track with  
14 no obstructions. Multiple sources of settlement in the approach are attributed to increased loads  
15 caused by differential stiffness, support, settlement, and damping between the bridge deck and  
16 approach (1,3-6). Undesirable ballast conditions are often observed in the approach compared to  
17 the open track and help explain the differential settlement because degraded, fouled, and poorly  
18 drained ballast will settle more than clean ballast, even with identical loadings (7). Other  
19 construction and maintenance practices such as inadequate ballast and subgrade compaction,  
20 tamping, and drainage are also influential on approach behavior. However, the exact mechanisms  
21 producing this differential settlement are often site specific and not properly understood so  
22 analytical, laboratory, and numerical predictions of transition zone performance typically do not  
23 represent measured field behavior.

24 Numerical techniques are becoming increasingly popular for track analyses because it  
25 provides users with a lower cost tool than physical track measurements and can isolate parameters  
26 influencing loading and settlement. Numerical techniques also serves as a digital laboratory to  
27 investigate conditions that may accelerate differential settlement and test the effectiveness of  
28 design and remedial techniques. To date, numerical analyses of transition zones have traditionally  
29 focused on investigating the significance of increased dynamic loads from differential stiffness  
30 and/or settlement between the bridge and approach to explain the accelerated settlement at  
31 transition zones. This typically involves analyzing track behavior at a single time-frame with the  
32 assumption of no approach settlement or uniform settlement in the approach and open track.

33 The majority of these single time-frame analyses use an idealized track geometry  
34 representing the ballast state immediately after track placement or tamping, i.e. isolating the effect  
35 of differential stiffness. For example, multiple studies (1,6,8,9,10) that investigated the effect of  
36 differential stiffness show that a 5 to 20% increase in dynamic wheel loads at: (1) the first few ties  
37 of the bridge (6,8) and (2) 2.5 to 3.7 m (8 to 12 feet) into the transition zone due to the coupling of  
38 the front and back axles of a truck or bogie (1,9,10). This increase in dynamic load in the approach  
39 is often cited as a possible reason for increased ballast settlement (1,9,10) but does not seem to  
40 explain the large settlement disparity, e.g., up to 14 times, between the transition zone and  
41 corresponding open track (3,6). For example, if a particular rail seat is expected to experience 40%  
42 of the wheel load (11), a 20% increase in wheel load would raise the rail seat load to only 48% of  
43 the wheel load; an insignificant amount because track stiffness and loading variations up to  $\pm 25\%$   
44 have been shown to routinely occur in track (12). However, these analyses omit the influence of  
45 ballast settlement so they cannot simulate the behavior of the majority of in-service track because  
46 loading conditions are expected to change with time as the track settles.

A couple of numerical studies (1,8) investigated the effect of transition zone settlement and show wheel and tie loads can increase up to 100% even if uniform ballast settlement occurs (1,8). Additionally, simulations investigating the effect of uneven ballast settlement in transition zones show increases in tie load up to 100% depending on the settlement geometry (10). While rail seat loads of 80% of the wheel load could potentially explain the observed settlement disparity, it is unclear whether the uniform ballast would actually settle in the manner that was simulated. For example, if a tie did experience a 100% increase in load, the ballast settlement under that tie is expected to be greater than surrounding ties resulting in local differential settlement. This settlement would therefore change the loading environment and likely reduce the load on that tie and distribute it to adjacent ties.

Therefore, this paper incorporates a ballast settlement model in an existing dynamic three-dimensional numerical model to simulate the progressive settlement of a bridge approach transition zone. Ballast settlement is incorporated into the model using an iterative procedure and an empirical settlement model. The purpose of this model is to investigate transition zone behavior with time, to better understand how increased dynamic loads and ballast conditions affect ballast and transition zone settlement, and to help explain why bridge approaches often settle at greater rates than surrounding open track. This model is limited to investigating conceptual behavior and not prediction because the exact loading, track component conditions and interaction, and ballast settlement behavior are not known in physical track. By incorporating the basic mechanisms of transition zone degradation, the model can illustrate transition behavior and the impact of transition design and remedial measures on future differential displacements. This combined numerical model can be upgraded to include more track and ballast settlement mechanisms as more complexity is required and verification data becomes available.

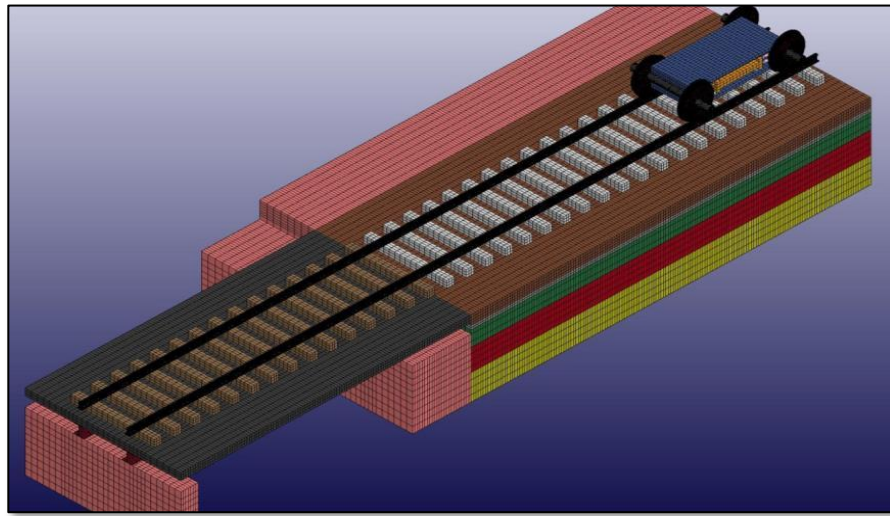
## NUMERICAL MODEL

The three-dimensional dynamic finite element software LS-DYNA was selected to numerically model the progressive settlement of a railway bridge transition zone because it specializes in non-linear transient dynamic finite element analyses. LS-DYNA is capable of modeling the entire track behavior along with inclusion of train cars, wheel systems, rail, tie, and substructure layers, allowing the creation of a track system model that can simulate the interaction of all track components and track response from a heterogeneous track system.

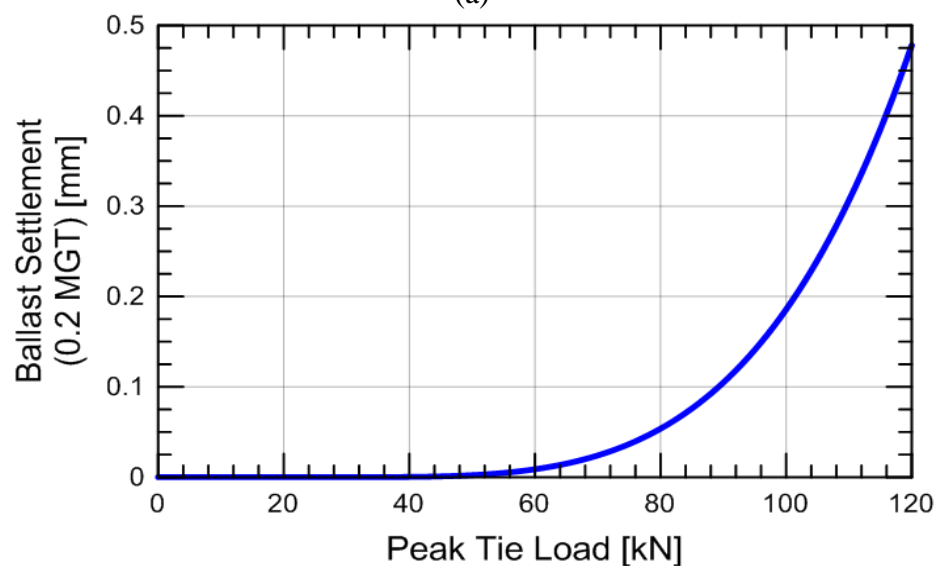
The finite element mesh for the bridge transition zone is shown in Figure 1(a) and consists of a cart replicating the secondary suspension system of an Acela power car, 136-RE rail, concrete crossties at 0.6 m (2-ft) spacing, a five layer substructure, and the bridge structure at Upland Street Bridge in Chester, PA. Table 1 presents the properties of the components used in the model (13) that was calibrated using field measurements (3,13). The dynamic model uses a cart to represent the secondary suspension system of a high-speed passenger power car. The cart consists of four wheels with the axles spaced 2.8 m (9.33 ft.) apart. The cart mass is contained in the cart center with a density such that each wheel applies a static wheel load of 100 kN to match an Acela power car. The axles and cart mass are connected with four sets of vertical and horizontal springs and vertical dampers. The velocity of the cart is set as 177 km/hour (110 mph) to replicate the operating speed of high speed trains along the Northeast Corridor (NEC). Pinned and non-reflective boundary conditions are used at all non-free surface boundaries and the distances are sufficient to prevent boundary effects from influencing the model. The non-reflective boundary conditions

absorb pressure and shear waves, preventing the pressure waves from reflecting back into the model.

To simulate ballast settlement, the tie and ballast surfaces are considered separate entities in the mesh and modeled as contact surfaces. This allows for physical separation between the tie and ballast and causes the ballast to elastically resist tie penetration. To simulate ballast settlement, the ballast element heights are decreased in the vertical direction as required underneath each tie. The application of gravity prior to train loading replicates how the rail and tie lay on the ballast. If the differential ballast settlement under its own weight is great enough, the rail and tie may not contact the ballast and cause a tie-ballast gap to form. While this model and paper assumes tie-ballast gaps are the only track defect, similar defects can arise in the physical track due to gaps between the rail and tie or any broken track component.



(a)



(b)

Figure 1. (a) LS-DYNA finite element mesh showing Upland Street Bridge approach near Chester, PA with a rolling cart and (b) relation between peak tie load and ballast settlement from 10,000 load cycles for a 4th order settlement relation.

The four model outputs from the finite element mesh in Figure 1(a) are wheel-rail contact forces, tie-ballast contact forces, and tie and ballast displacements. These outputs will give insight into the transient and permanent performance of the transition zone.

Table 1 Model properties (13)

Layer	Color	Thickness [mm]	Modulus [MPa]	Poisson's Ratio
1 (Ballast)	Brown	305	207	0.3
2 (Subballast)	Grey	127	67	0.3
3 (Sandy Loam)	Green	508	33	0.3
4 Clayey Silt)	Red	721	32	0.3
5 (Sandy Loam)	Yellow	849	59	0.3
Component	Modulus [GPa]	Poisson's Ratio	Stiffness [N/m]	Damping [N*s/m]
Rail	200	0.28	-	-
Tie	21	0.15	-	-
Suspension System (Vertical)	-	-	7.3e5	7.3e6
Suspension System (Horizontal)	-	-	2.2e9	7.3e6

## SETTLEMENT RELATION

The first step in developing a progressive settlement analysis is to select an appropriate relation to represent ballast settlement under repeated loadings. To calculate ballast settlement within each iteration step, the empirical settlement relation proposed by Sato (14) and modified by Dahlberg (15) was used. Other available settlement models can be referenced in Dahlberg (15). This relation is well suited for differential loading environments, such as transition zones, because the calculated ballast settlement ( $y$ ) is only a function of the load applied at the tie-ballast interface ( $P$ ), which is the primary output of the numerical model. The original empirical settlement relation by Sato (14) was developed from laboratory ballast test data, which is preferred over continuum plasticity laws (16) built-in to existing numerical software because of greater control of the empirical relation and the ability to produce settlement in discrete load increments instead of every wheel pass. The notable exception is the use of discrete element modeling (DEM) but these methods are still in early development and the computational power to couple DEM ballast behavior with continuum track components and dynamic loads is beyond current capabilities (17,18). The empirical settlement relation from Dahlberg (15) is plotted in Figure 1(b) and displayed in Equation 2:

$$y = 5.87E^{-9} * (P - 25)^4 \quad (2)$$

where  $y$  is the ballast settlement in mm after 10,000 load cycles and  $P$  is the tie-ballast contact force in kN.

A simple settlement relation that is only a function of tie load is considered suitable for the initial analyses because the goal of the numerical simulation is to conceptually investigate changes

in loading environment from the progressive settlement of a transition zone and not replicating or predicting field behavior. Therefore, more complex models that vary with MGT and other factors are not considered. Physically, ballast settlement is a complex process that involves particle rearrangement, lateral movement, and degradation and is dependent on numerous factors, including ballast density, gradation, moisture content, rock type, angularity, hardness, confinement, rotation of principal stresses, loading material (concrete v. timber), and impact (19). These factors can later be incorporated into the settlement model as required, but for this current analysis, the ballast (Layer 1) is assumed to be homogenous.

## ITERATIVE PROCEDURE

Settlement is not built into the numerical model and is expected to change with time. This means the geometry of the mesh is updated prior to every iteration to reflect the predicted caused by the previously applied wheel loads. The four steps of the iteration procedure are described below:

1. A dynamic numerical simulation of the cart passing over the transition zone is completed with the model outputting the wheel loads, tie loads, tie displacement, and ballast displacements.
2. The peak tie loads from both the front and back axle of the cart are determined for Ties 1 through 10.
3. The ballast settlement under Ties 1 through 10 is calculated using the modified Dahlberg (15) settlement model described above for both the front and back axles independently. The settlement values from each axle are then summed. The settlement of Ties 11 and greater are assumed to be equal to Tie 10 and represent open track.
4. The calculated settlements from Step 3 are added to the existing cumulative settlements under each tie, i.e., Ties 1 through 10, and are incorporated into the numerical model geometry for the next iteration.

An important parameter in the iterative procedure is the representative MGT value of each iteration step, i.e. 0.4 MGT or 20,000 wheel passes. This is conceptually similar to a “time-step” and can significantly affect the simulation results because the transition zone loading environment is sensitive to local differential ballast settlements. This means large iteration steps can produce increased loads that could be avoided if using smaller iteration steps (10).

To show this, the maximum normalized tie load of a tie within a transition zone (Tie 6 in Figure 2) is determined using iteration steps of 0.2, 0.4, and 0.8 MGT. For the 0.4 to 0.8 MGT iterations, the settlement from Equation (2) was multiplied by either two or four. For 0.2 and 0.4 MGT iterative steps, the results are identical and the tie loading seems to be at a stable “equilibrium state”. However, the tie loads significantly deviate if assuming iteration steps of 0.8 MGT. This behavior indicates the progressive analysis has come out of “equilibrium” and is not representative of ballast incremental ballast settlement after each train pass. For this analysis, iterative steps of 0.4 MGT (20,000 load passes) are used.

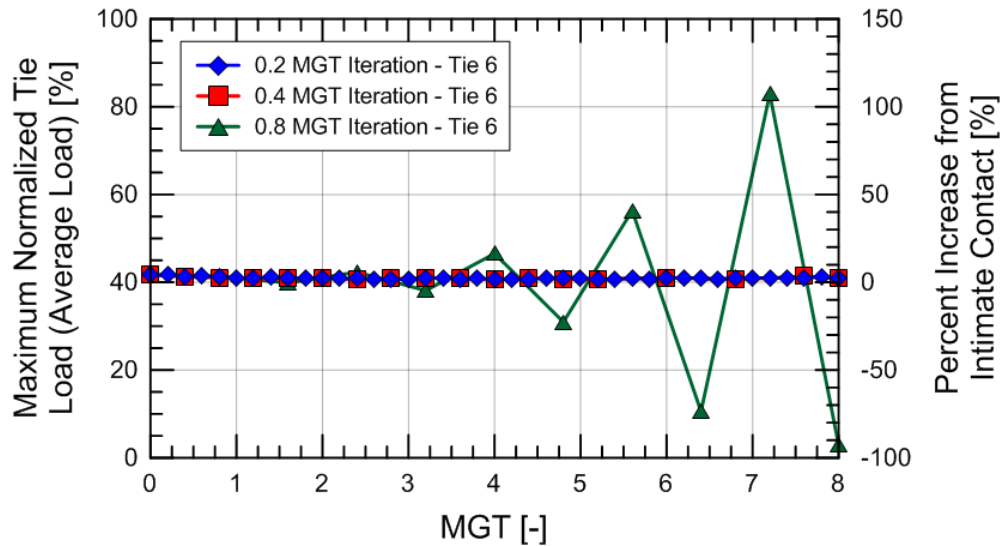


Figure 2. Comparison of maximum normalized Tie 6 load (front and back wheel average) with iterations steps of 0.2, 0.4, and 0.8 MGT.

## PROGRESSIVE ANALYSIS RESULTS

The results of the progressive analysis indicate transition zones experience three distinct stages of behavior. Stage 1 is called the “Initial Stage” or “Pre-Equilibrium Stage” and represents the newly constructed track condition in which no substructure settlement has occurred and is within 0.0 to 0.4 MGT in this analysis. In this stage, differential loading is anticipated due to stiffness differences along the track. Stage 2 is called the “Equilibrium Stage” and represents the track response within 0.4 to 28 MGT in this particular analysis but this range will vary significantly or not even appear in physical track. This stage represents equalized loading amongst the ties in the track. Stage 3 is called the “Post-Equilibrium Stage” and represents the hypothetical track response at iterations greater than 28 MGT in this particular model. Increased tie loads are anticipated from load concentrations and impacts from tie-ballast gaps. Each stage and its unique characteristics are explained in the subsequent sections.

### Stage 1: First Iteration (0.0 MGT)

The first simulation of the cart passing over the bridge approach assumes newly laid and compacted ballast so no ballast settlement or tie-ballast gaps are initially present. This represents the most commonly simulated situation where increased dynamic loads are expected from: (1) the reaction force required to lift the front cart axle from the lower rail elevation in the approach to the higher rail elevation on the bridge deck and (2) the coupling effect of the front and back axles (1,9,10). This results in increased dynamic loads on: (1) the abutment and bridge deck and (2) at the location of the back axle when the front wheel is lifted to pass over the bridge abutment, which is about 3 meters (10 feet) before the abutment.

The simulation results show an increased load is distributed primarily to Ties 5 (10 ft.) and 6 (12 ft.). The normalized tie load, tie load divided by static wheel load, of the two ties are 47% and 43% respectively, which are increases of 20% and 7.5% from the assumption of intimate tie-ballast contact (normalized tie load = 40%).



While a normalized tie load of 40% would produce a ballast settlement of 0.11 mm at 0.4 MGT (see Figure 1b), the increased load at Tie 5 from the coupling of the front and back axles produces 0.18 mm of ballast settlement, almost doubling the “standard settlement”. This local differential settlement within the approach is a response to differential stiffness between the bridge and approach and also appears to initiate the process that results in the “dip” commonly observed about 1.8 to 3.2 m (6 to 12 feet) from the entrance bridge abutment (1,2). Of course, if there are differences in the ballast at or near Tie 5 the settlement will be greater than 0.11 mm at 0.4 MGT.

## Stage 2: Second Iteration (0.4 MGT)

The ballast settlement from the initial cart pass is incorporated in the numerical model for the second iteration analysis by decreasing vertical grid sizes of the ballast elements underneath each tie in the transition. The differential settlement within the transition zone is expected to change the wheel load distribution amongst the underlying ties and cause the load to shift from ties with the greatest ballast settlement to adjacent ties with lesser amounts of ballast settlement (10). This load redistribution mechanism is illustrated in Figure 3(a) with the second iteration analysis showing a reduction in load at Ties 5 and 6 and in increase in load at Ties 3, 4, and 7. For example, the normalized tie load at Tie 5 from the back wheel decreases from 47% (20% increase from intimate contact) to 44% (12% increase from intimate contact) and a similar reduction is observed for the front wheel. While this decrease in tie load may not seem significant, the non-linear tie load/ballast settlement relationship reduces the ballast settlement under Tie 5 from 0.18 mm between 0.0 to 0.4 MGT to 0.13 mm between 0.4 to 0.8 MGT (Figure 3b). This results in Tie 5 and 6 still experiencing the greatest dynamic loads and settlement but to a lesser degree than the Stage 1 analysis (0.0 MGT).

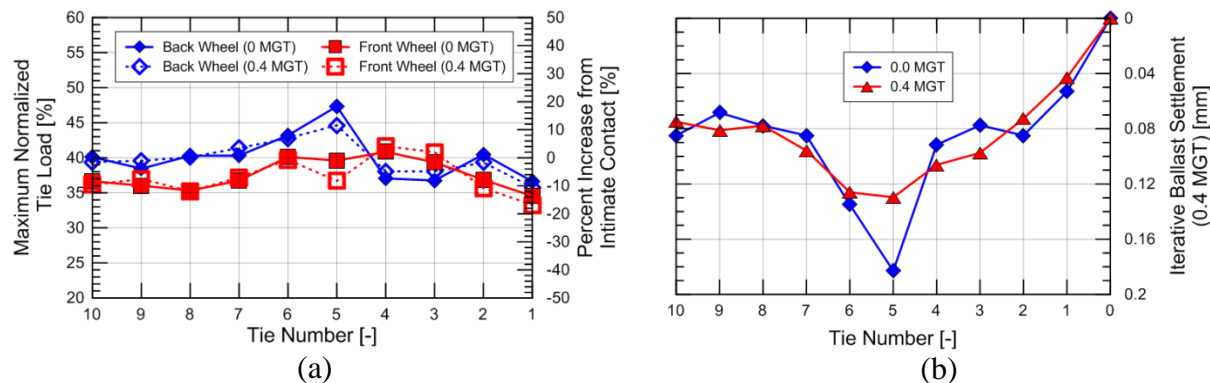


Figure 3. Analysis results showing: (a) Maximum normalized tie loads and resulting and (b) iterative ballast settlement from train passes at 0 and 0.4 MGT.

This suggests the ballast will experiencing greater load will settle at larger magnitudes than surrounding ballast with lower loads. This will change the load distribution of subsequent train passes. Under ideal conditions, this will eventually result in a situation in which the load is evenly distributed amongst the underlying ties within the transition zone and allow the transition zone to enter a stage of “equilibrium” in which tie loads are minimized. Therefore, any track experiencing increased loads from differential stiffness, i.e. pre-equilibrium, will subsequently experience

1 differential ballast settlement that results in a better or more optimal wheel load distribution  
2 amongst transition zone ties, i.e. equilibrium.  
3

## 4 **Stage 2: Settlement**

5 To investigate the long-term settlement behavior of the transition zone, the cumulative ballast  
6 settlement profile, tie-ballast gaps, and transient displacements are recorded with increasing MGT.  
7 The track profile at 28 MGT with exaggerated vertical settlements is displayed in **Figure 4(a)** and  
8 illustrates how the rail hangs from the bridge deck and tie-ballast gaps develop within the approach.  
9 The analysis was discontinued at 28 MGT because: (1) the progressive analysis was continually  
10 requiring smaller iterative steps to remain in “equilibrium” and (2) the assumption of Ties 11 and  
11 greater having identical loading and settlement as Tie 10 did not hold as the load shifts farther  
12 away from the bridge abutment with increasing settlement and load redistribution.

13 Figure 4(b) shows increasing cumulative ballast settlement with increasing MGT and the  
14 gradual shifting of maximum cumulative ballast settlement from under Tie 5 (10 ft.) to Tie 7 (14  
15 ft.) during the duration of the analysis. This trend would be expected to continue as the load shifts  
16 farther from the bridge abutment. The maximum cumulative settlement at 28 MGT is 9.4 mm at  
17 Tie 7 (14 ft.) and the settlement at Tie 10 is 8.9 mm, both of which are close but slightly greater  
18 than the 7.6 mm for a normalized tie load of around 40%. Due to the differential settlement  
19 between the bridge deck and the transition zone, tie-ballast gaps develop in the transition zone.  
20 Initially, the tie-ballast gaps appear only under Ties 1 and 2 but gradually expand outwards and  
21 increase in magnitude as the bridge and open track rail elevations continue to deviate.

22 The transient displacement from the cart passing over the transition zone is displayed in  
23 Figure 4(c). This shows a deviation between the settlement and transient displacement profiles  
24 where the transition zone (Ties 1 through 8) experience significantly greater displacements than  
25 the open track (Tie 10). This behavior agrees with the measured results at multiple transition zone  
26 locations (3,4). The varying transient displacement in the transition zone is primarily explained by  
27 tie-ballast gap magnitudes because the ballast stiffness is assumed to be homogenous and loading  
28 is relatively similar across the transition zone. Therefore, in reality the transient displacements  
29 and tie-ballast gaps will be greater and more variable than shown in Figure 4(c) because ballast is  
30 not uniform and not compacted uniformly.

31 The development of a tie-ballast gap has implications on track behavior because track  
32 system discontinuities allow for more movement and impact loads between track components, and  
33 thus component degradation (21). For example, the freely moving tie will establish contact with  
34 the ballast during train loading and can result in increased tie wear and ballast degradation due to  
35 grinding and impact between the tie and ballast (3). This behavior is illustrated in ballast box  
36 testing performed by Selig and Waters (23), which shows significantly greater ballast settlement  
37 if a gap between the tie and ballast is present. This component degradation is not incorporated  
38 within the settlement model but is an important consideration, which is discussed in more detail  
39 below.  
40  
41  
42  
43

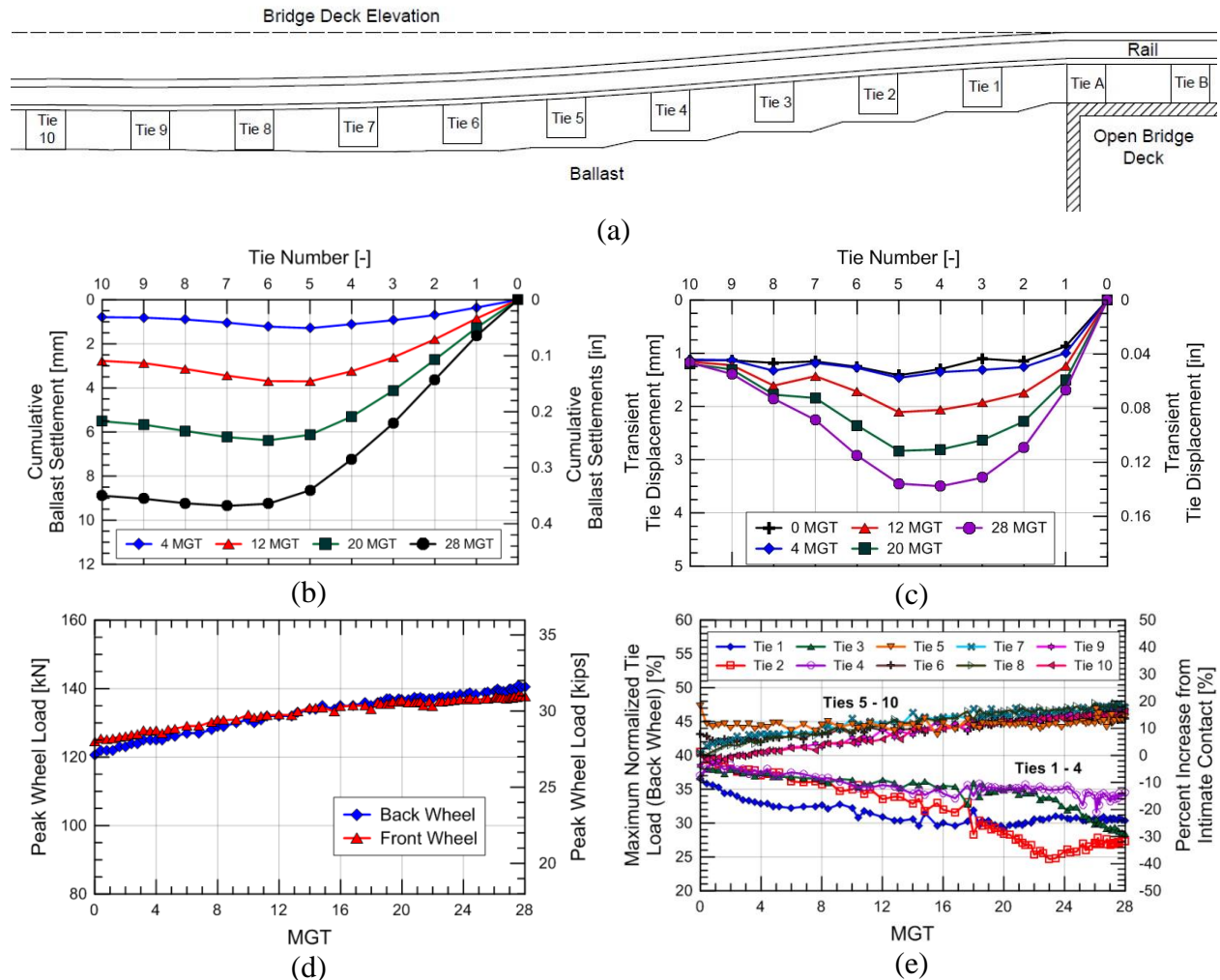


Figure 4. (a) ballast settlement profile at 28.0 MGT and cumulative (b) ballast settlement, (c) transient displacement with increasing MGT, (d) peak wheel loads and (e) tie loads from back wheel.

## Stage 2: Loading

The progressive settlement described above is related to the applied tie loads and ballast settlements at each iteration. The changes in wheel loads and tie loads with MGT are displayed in Figure 6(d) and (e). The results show the peak wheel loads increase from about 120 kN during the first iteration (0.0 MGT) to about 140 kN at 28 MGT. This increased wheel load is typically located over Tie 5 (10 ft.) and is caused by the coupling of the front and back axles as the cart passes from the lower elevation transition zone to the higher elevation bridge deck. The increase in wheel load from 20% to 40% is attributed to the effect of ballast settlement. However, it is lower than predicted from models in which ballast settlement is uniform throughout the transition zone (1,9) because of the “dip” in rail elevation around Tie 5 that results from the calculated uneven ballast settlement.

Figure 4(e) displays the normalized tie loads. A gradual increase in load is observed in Ties 6 through 10 while a gradual decrease in load is observed in Ties 1 through 4. The load experienced by Tie 5 remains essentially constant throughout the analysis excluding the initial run at 0.0 MGT. This load redistribution represents a shift of loading away from the bridge abutment because the ballast near the bridge settled resulting in poorly or unsupported ties. In particular, the tie loads did not increase significantly as the differential settlement increased. This result differs from previous analyses with assumed ballast surface profiles (9,13) and suggests the ballast surface profile from the progressive surface analysis is such to minimize tie loads.

### Stage 3: Post-Equilibrium

The model results show that the ballast profile continues to be such that the tie loads are minimized. However, certain transition zones in the field have shown evidence of increased loads and not the behavior observed in this model. This suggests that a “post-equilibrium” phase in which the increased loads do exist; however, is not obtained by the numerical model. This will be discussed in later sections.

## DISCUSSION

The results of this progressive settlement analysis does provide some insight to transition zone performance even with assuming the ballast is uniform. As expected, the near rigid bridge deck represents a restricting condition that produces differential settlement between the bridge deck and ballast in the approach, resulting in the gradual shifting of tie loads away from the bridge deck towards the open track. Tie-ballast gaps develop near the entrance side of the bridge abutment in reaction to the differential elevation between the rigid bridge and settling approach.

Comparisons between the results at 28 MGT and field observations show general agreement in behavior but the simulation does not replicate the field measured differential settlement between the transition zone and open track. For example, the difference between ballast settlement in the transition zone and open track in the numerical model (9.35 mm v. 8.89 mm) is less than some field measurements (12 mm v. 1.5 mm) at the modeled Upland Street Bridge (3,4). This suggests the numerical model is not simulating the increased load and dynamic environment in the transition zone and/or the ballast will settle at greater rates than the predicted settlement relation in Figure 1(b). This will be addressed in detail below.

Additionally, the numerical model results, along with field observations, suggest transition zones have three general stages within the resurfacing lifespan. The first stage is the “pre-equilibrium” stage, in which the transition zone is attempting to find balance within the materials itself and within the system. While not simulated, a loose ballast matrix immediately after tamping often result in initial settlements as the ballast recompacts to a more dense state (19,21,23). This post-tamping loose ballast state would also be considered a part of the “pre-equilibrium” stage because the ballast material will attempt to reach a density and gradation configuration that is in balance with the applied loading. Initial settlement of the subgrade or fill would also fall under the same category. The numerical results show how the transition zone system balances differential loading after the initial runs through differential settlement. Ideally, the time and settlement a transition zone experiences in this stage should be minimized.

1       The second stage is the “equilibrium” stage in which the transition zone system and  
2 materials have found a balance. Transition zones should ideally be within the stage for the majority  
3 of its lifespan. The third stage is the “post-equilibrium” stage is described with increased loads in  
4 the transition zone. This stage was not simulated using the numerical model and this may be due  
5 to the assumption of homogenous ballast. Future studies should investigate the effects of  
6 heterogenous ballast and whether differences in ballast degradation and fouling within the  
7 approach has a larger contribution to differential settlement than initially believed.  
8

## 9   **ADDITIONAL ANALYSES**

10   The base progressive analysis simulates the progressive settlement of a transition zone under ideal  
11 or uniform conditions in which the ballast is represented as a homogenous material with identical  
12 settlement behavior along the track. This is unlikely to physically occur because ballast will: (1)  
13 be tamped at various densities due to variations in the tamping process, (2) experience varying  
14 confinement conditions and moisture contents, and (3) eventually degrade due to ballast fouling,  
15 breakdown, and fatigue, tie-ballast contact, and tamping. This produces a condition in which the  
16 ballast is spatially and temporally varying and the ballast will not behave in a uniform manner as  
17 represented by the settlement model.

18       An additional analysis involves a sensitivity analysis to investigate the effects of  
19 heterogeneous ballast in bridge approaches. This analysis attempts to represent ballast that varies  
20 in density, gradation, fouling level and material, moisture, and other factors along the track that  
21 can lead to uneven settlements. This variation would not be known so an analysis that accounts for  
22 random variations is considered best suited for this particular analysis. To accomplish this  
23 randomness, the ballast settlement is randomly varied under each tie within ranges of +/- 0.125  
24 mm, 0.25 mm, and 0.5 mm at 16 and 28 MGT. For each situation (16 and 28 MGT), five analyses  
25 are conducted for a total of thirty (30) analyses. As improved and more detailed settlement  
26 measurements from physically monitored track is collected, more insight into a correct “random  
27 variation” value is anticipated. The purpose of this analysis is to determine the effect of randomized  
28 heterogeneity in track and its effect on increased loads.

29       An example of the randomly varying cumulative ballast profiles is displayed in Figure 5(a).  
30 The graph shows a random variation of +/- 0.5 mm at 28 MGT. As expected, the profiles show  
31 slight variations in settlement at each tie from the original simulation displayed in the previous  
32 section. The loading in Figure 5(b), however, displays a wide range of tie loads with the percent  
33 increase in tie load from the intimate tie contact condition exceeding 80%. This shows that slight  
34 settlement variations from the “equilibrium” state can significantly increase loads within the bridge  
35 approach due to significant load redistribution and may be a potential explanation for the increased  
36 loading and settlement observed in a transition environment.  
37  
38

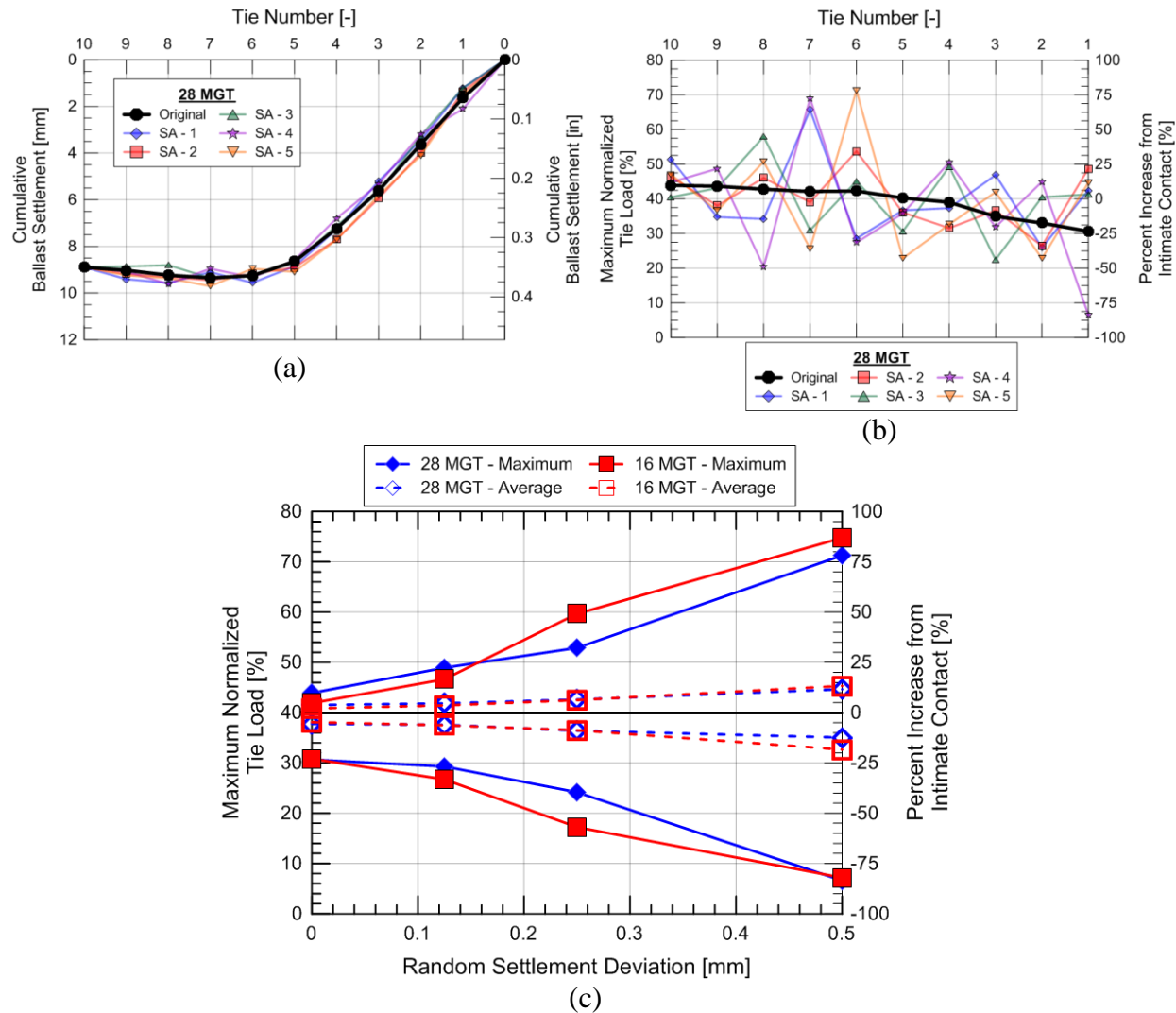


Figure 5. Figures showing: (a) ballast surface profile, (b) normalized tie loads for sensitivity analysis (SA) with  $\pm 0.5$  mm variation at 28 MGT, and (c) the maximum and minimum average tie load deviation from the sensitivity analysis.

Figure 5(c) displays the maximum and average normalized tie loads increase from the intimate tie contact condition for all of the analyses. The maximum trend lines for 16 and 28 MGT show the maximum and minimum normalized tie loads from all ten ties for all five analyses for each sensitivity analysis. The average trend lines take the average normalized tie load for all ties for all five analyses that are above 40% (percent increase from intimate contact) and that are below 40% (percent decrease from intimate contact). The results show that the maximum and average tie loads increase with increasing random settlement deviation. The results also did not show any meaningful difference between 16 and 28 MGT. This means the more random variation in settlement within a transition zone will lead to increased dynamic loads from load concentration more than increasing the applied wheel loads. This suggests that if good tie support is provided, the impact of higher wheel loads is not as significant or problematic than when poor tie support is present. Therefore, better design and remedial measures to reduce ballast settlement and tie-ballast gaps could be argued for in terms of greater revenue generation via higher wheel loads.

Noting that approach regions will likely experience greater levels of degradation and fouling and also tie-ballast gaps, which can increase the settlement, and the results of the sensitivity analysis, an explanation for increased settlement in the approach is: (1) reduced-performance ballast conditions, e.g. tie-ballast gaps, degradation, fouling, settlement, and (2) increased loads from ballast heterogeneity. However, further studies would be required to verify this hypothesis.

## SUMMARY

This paper introduces a three-dimensional dynamic numerical model that simulates the progressive settlement of railway bridge transition zone with the use of an empirical settlement model. The main findings of the analyses presented herein include:

- Progressive settlement analyses offer additional insight into track behavior as opposed to single-time frame analyses because the loading and settlement environment changes over time and can be compared to field track measurements, which reduces the need for assuming the initial ballast surface profile.
- Transition zone settlement occurs in the following three distinct stages: (1) initial/pre-equilibrium, (2) equilibrium, and (3) post-equilibrium.
- By assuming homogenous ballast properties and settlement rates, the approach track settles in a manner that reduces increased tie loads and evenly distributes the wheel load amongst underlying ties. This suggests that heterogenous ballast conditions may be a large contributor to increased loads and differential settlement.
- Heterogeneous ballast conditions can potentially produce increased loading within the approach. Random variations of ballast settlement under tie or 0.5 mm can increase loads up to about 80% due to the uneven distribution of wheel load throughout the approach.

## Acknowledgements

The authors acknowledge the funding provided by a Federal Railroad Administration (FRA) Broad Agency Announcement (BAA) research project titled: “Mitigation of Differential Movement at Railway Transitions for US High Speed Passenger and Joint Passenger/Freight Corridors” (DTFR53-11-C-0028) under the supervision of Cameron Stuart. The work of Tom Dehlin, Listen He, and Congyue Fang at the University of Illinois at Urbana-Champaign on the LS-DYNA analyses is gratefully acknowledged.

## References

1. Nicks J. (2009). “*The Bump at the End of the Railway Bridge*”. PhD Thesis, Texas A&M University, College Station, TX.
2. Mishra D, Tutumluer E, Stark TD, Hyslip JP, Chrismer SM, and Tomas M. (2012). Investigation of differential movement at railroad bridge approaches through geotechnical instrumentation. *J Zhejiang Univ-SciA (Appl Phys & Eng)*. 2012. 12(11), 814-824

3. Stark TD and Wilk ST. (2016). Root cause of differential movement at bridge transition zones. *Proc. IMechE. Part F: J. Rail Rapid Transp.* 2016. Vol 230(4), pp. 1257-1269
4. Coelho B, Hölscher P, Priest J, Powrie W, and Barends F. (2011). An assessment of transition zone performance. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.* 2011. Vol 225, pp. 129-139
5. Li D and Davis D. (2005). Transition of Railway Bridge Approaches. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, November, 2005. 131(11): pp. 1392–1398.
6. Plotkin D and Davis D. (2008). Bridge Approaches and Track Stiffness. *DOT/FRA/ORD-08-01*, February 2008.
7. Han, X. and Selig, E.T. (1997). Effects of Fouling on Ballast Settlement. *In Proceedings of 6<sup>th</sup> International Heavy Haul Railway Conference*. Cape Town, South Africa, April 6-10, 1997
8. Banimahd M, Woodward PK, Kennedy J, and Medero GM. (2011). Behavior of train-track interaction in stiffness transitions. *In: Proceedings of the institution of civil engineers-transport*. Vol. 165. Is. 3. Pp. 205 – 214.
9. Wang H, Markine VL, Shevtsov IY, and Dollevoet R. (2015). Analysis of the Dynamic Behavior of a Railway Track in Transition Zones with Differential Settlement. *Proceedings of the 2015 Joint Rail Conference*. March 23-26, 2015, San Jose, California.
10. Stark TD, Wilk ST, Thompson HB, and Sussmann TR. (2015). Effect of Unsupported Ties at Transition Zones. *Proceedings of Railway Engineering-2015 Conference*, June 30th – July 1st. Edinburgh, Scotland.
11. American Railway Engineering and Maintenance-of-Way Association (2013). AREMA Manual for Railway Engineering, Landover, Maryland. 2013
12. Fröhling RD. (1998). Low Frequency Dynamic Vehicle/Track Interaction: Modelling and Simulation. *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*. Vol 28. Pp. 30-46.
13. Wilk ST. (2017). “Mitigation of Differential Movement at Railroad Bridge Transition Zones”. PhD Thesis, University of Illinois at Urbana-Champaign, Urbana, IL.
14. Sato Y. (1997). Optimization of track maintenance work on ballasted track. *In proceedings of the World Congress on Railway Research (WCRR '97)*, Florence, Italy, 16-19 November 1997, Vol. B, pp. 405-411.
15. Dahlberg T. (2001). Some railroad settlement models – a critical review. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. Vol. 215. pp. 289 – 300. 2001.
16. Indraratna B, Thakur PK, Vinod JS, and Salim W. (2012). Semiempirical Cyclic Densification Model for Ballast Incorporating Particle Breakage. *International Journal of Geomechanics*. Vol 12, No 3, pp. 260-271.
17. Tutumluer E, Qian Y, Hashash YMA, Ghaboussi J, and Davis DD. (2013). Discrete element modelling of ballasted track deformation behaviour. *International Journal of Rail Transportation*. Vol. 1, Nos. 1-2. Pp. 57-73.
18. Chen C, Indraratna B, McDowell G, and Rujikiatkamjorn C. (2015). Discrete element modelling of lateral displacement of a granular assembly under cyclic loading. *Computers and Geotechnics*. Vol. 69. Pp. 474-484
19. Indraratna B, Salim W, and Rujikiatkamjorn C. (2012). *Advanced Rail Geotechnology – Ballasted Track*. CRC Press/Balkema Leiden. The Netherlands.
20. Sussmann TR, Ruel M, and Chrismer SM. (2012). Source of Ballast Fouling and Influence Considerations for Condition Assessment Criteria. *Transportation Research Record: Journal of the Transportation Research Board, Transportation Research Board of the National Academies*, No. 2289. Washington, D.C., 2012. Pp. 87-94.
21. Stark TD, Wilk ST, Rose JG, and Moorhead W. (2015). Effect of Hand Tamping on Transition Zone Behavior. *Proc: 2015 American Railway Engineering and Maintenance-of-Way Association Conference*. Minneapolis, MN.



- 1 22. Wilk ST, Stark TD, and Rose JG. (2016). Evaluating tie support at railway bridge transitions. *Proc.*  
2 *IMechE. Part F: J. Rail Rapid Transp.* 2015. Vol 230(4), pp. 1257-1269
- 3 23. Selig ET and Waters JM. (1994). *Track Geotechnology and Substructure Management*. London:  
4 Thomas Telford. 1994