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Dynamic train-track interactions over railway track stiffness transition zones using baseplate fastening systems

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Highlights

- Three-dimensional FE models of railway track transition have been developed.
- Using baseplate fastening system at railway track transition can potentially reduce the differential settlement.
- The new insights will help track engineers to make an appropriate decision on the design and usage of baseplate fastening systems at the transition zone.

Abstract: In railways, significant attention has been spent to solve transition zone problems as the railway tracks at these zones, especially at the transition between bridge and embankment, are prone to the significant degradation and they need extra maintenances and cost to ensure the safety and comfort of passengers. Despite all the efforts and researches, transition zone problems at the bridge transition zones are still not resolved. The application of baseplate fastening systems to fix the transition zone problem has not been fully investigated. The study proposed herein aims to fill the gap using numerical models to investigate the effect of baseplate pad stiffness and baseplate weight on the dynamic behaviour of the transition zone between slab track and ballasted embankment. The numerical models have been simulated using LS-DYNA software and validated by comparing with field measurements and other simulated results. The obtained results evidence that soft baseplate pads intensify the rail displacements and uneven track profile of the slab track. The results also show that the effect of baseplate weight is different for different stiffness. Overall, the optimal stiffness of baseplate can significantly reduce the differential settlement. However, the uses of heavier baseplates and softer baseplate pads together may cause negative effect by increasing the rail displacements and differential displacements. Hence, the use of baseplate fastening systems requires to carefully select pad stiffness, baseplate weight and their arrangement on the slab track. The new insights will help track engineers to make an appropriate decision on the design and usage of baseplate fastening systems at the transition zone.

Keywords: track transition; train-track interaction; dynamic response; resilient material; baseplate; fastening system.

1. Introduction

High-speed trains are usually developed with optimised structural designs to provide minimal environmental impacts and maximum economic and social gains. Despite that, the maintenance-related issues of high-speed trains have become more evident and severe by the cause of increased vehicle speeds [1, 2]. Nowadays, the maintenance issue at the transition zones of high-speed railway has become significantly important in the railway field and has received significant attention [3, 4]. The locations of the

transition zone are usually between tracks on the embankment (or other infrastructures such as tunnel) and the bridge end. However, the frequency of transition zone maintenance operations is 3 to 6 times higher than the maintenance operations at open tracks, and this results in faster degradation rates at the bridge transitions [5-7]. Therefore, bridge transition problems generally cause higher maintenance operation costs and disruptions in train services due to additional track maintenances are needed to ensure the safety and comfort of passenger [8, 9]. There are various factors that can cause degradation of the track components in the transition area, and even magnify them due to their combination. The major causes that accelerate track degradation at transition zones are [5, 10, 11]:

1. Abrupt changes in track stiffness: The different mechanical properties of the materials used in the railway track components has caused uneven track deflections under each wheel. As the train passes through these transition zones, the differential track deflections increase the dynamic wheel loads acting on the track and therefore increases the rate of track degradation.

2. Irregular railway track profile: Although the large settlements of bridge abutments are not likely to occur, the track bed layers often experience plastic deformations. This causes a differential deformation (e.g. a bump or dip) to occur at the transition zone. This situation also results in an increased rate of track degradation due to greater dynamic loads to create more damages to the track components.

In order to minimize the negative effects arising due to these causes, many mitigation measures have long been investigated and applied in transition zones. However, there is a lack of research on the use of baseplate fastening system on the bridge-embankment transition zone to provide a smooth transition. In addition, because of undesirable track degradation in transition zones is still frequently discovered after implementing other mitigation measures, more studies on the countermeasures are still required [9, 12].

Numerous researches on the countermeasures of the transition zones were conducted with the purposes to provide smooth changes in vertical stiffness between the approach to bridge, smooth settlement of the transition zone and smooth track modulus distribution along the bridge transition zone [12-14]. These countermeasures can be applied to either embankment or engineering structures (such as bridge, culvert and tunnel) to increase or decrease the track stiffness [12]. Many literatures presented embankment treatment solutions to prevent embankment settlement, such as backfilling with hot-mix asphalt (HMA) or cement bound granular mixtures (CBGM) [15-18] and strengthening embankment using piles or drilled displacement columns (DDC) [19-21]. Although HMA increases the allowable stress-bearing capacity of the track bed members and lowers the stress acting on subgrades, the performance of ballast on stiff subgrade is not enhanced [14, 22]. Furthermore, [15] stated that wedge shape backfills using CBGM has smoother changes in track stiffness at bridge end than when using hot-mix asphalt [14]. Nevertheless, wedge-shaped backfill with CBGM is complicated, risky, and time-taking to construct, and most importantly, the track stiffness issue at transition zone has not been fully settled. According to [19, 23], piles embankment and DDC provide gradual track stiffness changes at transition and restrain embankment settlement, but these two countermeasures are expensive, especially pile embankment [24]. The applications of ballast bonding can be found in [25]. This method may be too complicated for conventional lines due to application of bonding must satisfy certain preconditions (such as the ballasted trackbed layers need to be well-compacted, well-constructed and without mud) [26]. Despite that, the volume and cost of maintenance will be greatly decreased due to the tamping works are decreased significantly [27, 28]. Many different types of transition slab such as ribbed transition slab [29], precast prestressed transition slab [30], sloped transition slab [31] were created to accomplish superior performance with lower costs than the conventional approach slab. It is because the conventional transition slab has very expensive life-cycle costs and longer construction time [32, 33]. Furthermore, a transition zone construction in the Netherlands requires more maintenances after the use of transition slabs, and transition slabs also often crack under high impact loading and poor trackbed conditions [34, 35]. The application of countermeasures on engineering structure, such as under sleeper pad (USP), rail pad and ballast mat, helps to decrease track stiffness [12, 36, 37]. According to [38-40], the implementation of USPs may cause the track to behave worse on superstructure than without USPs because it increases the accelerations of rail and sleeper. However, some

literatures show that the use of USPs with varying stiffnesses can provide ideal track stiffness changes in the transition zone, thereby reducing the track degradation rate and sleeper bending strains [41, 42]. Both rail pads and ballast mats are also mainly used to lower track degradation rate [37] and rail pads are constructed in the same way as USPs to provide a smooth transition with optimal differential track stiffness [43, 44].

Baseplate is a type of rail-fastening system which is placed at the rail seat and consists of two resilient elements (rail pad and baseplate pad) with a cast-iron baseplate in between. Baseplate pad and rail pad are essential as they isolate the baseplate from railhead and supporting bridge structures such as sleepers or slab, thereby reduce bridge vibration and noise [45]. Baseplate system generally used to achieve lower stiffness and to reduce the lateral movement of the railhead, but such a low stiffness system may cause undesired high-amplitude vibrations of track components and increase the wheel rolling noise level [46, 47]. Among all the eight countermeasures, soft baseplate is the most economical and sustainable approach for short-span bridge [48]. In spite of that, most literatures focus for the use of baseplate to mitigate ground-borne noise and vibrations arise from the train, track and supporting structures [46, 49] and only little has focused on the application of baseplate as a measure for transition zone issues [25]. This paper aims to investigate the use of baseplate fastening system on slab track at the transition zone between slab track and ballast embankment to reduce the abrupt change in vertical track stiffness. The dynamic responses of transition zone subjected to 200km/h speed train are simulated using advanced three-dimensional train-track finite element modelling. Parametric studies considering different baseplate parameters are carried out.

2. Materials and Methods

The slab track and high-speed train models are constructed following [50, 51]. The 3D dynamic coupled vehicle-track models based upon the typical representative section of Wuhan-Guangzhou high-speed railway (HSR) are developed. The vehicles usually operating in this section of the high-speed railway line are China Railway High Speed (CRH) 2 Electric Multiple Unit (EMU) trains, which operates at a speed of 200 km/h [50]. The CRH 2 EMU train is modelled consisting of a one-car body, two bogies, four wheelsets, and two stage-suspension systems, as generally illustrated in Figure 1. The train components such as car body, bogies frames and wheelsets are modelled in 2D as rigid bodies using shell and beam elements. These train components are coupled via primary and secondary suspension systems using discrete elements (springs and dampers) which represents stiffness K and damping C . The CRH 2 EMU train geometry parameters and material properties are displayed in Table 1. In total, the FE model of the CRH 2 train contains 96 elements including beam, shell and discrete elements (springs and dampers).

Figure 1. Representative model of the simulated vehicle.

Table 1. Properties of the CRH 2 EMU train.

Properties	Values	Units
Car body mass, M_c	3.96×10^4	kg

Bogie frame mass, M_b	3.5×10^3	kg
Wheelset mass, M_w	2.0×10^3	kg
Moment of inertia of car body about x axis, I_{cx}	1.132×10^5	$\text{kg} \cdot \text{m}^2$
Moment of inertia of car body about y axis, I_{cy}	1.94×10^6	$\text{kg} \cdot \text{m}^2$
Moment of inertia of car body about z axis, I_{cz}	1.615×10^6	$\text{kg} \cdot \text{m}^2$
Moment of inertia of bogie mass about x axis, I_{bx}	2.673×10^3	$\text{kg} \cdot \text{m}^2$
Moment of inertia of bogie mass about y axis, I_{by}	1.752×10^3	$\text{kg} \cdot \text{m}^2$
Moment of inertia of bogie mass about z axis, I_{bz}	3.3×10^3	$\text{kg} \cdot \text{m}^2$
Moment of inertia of wheelset about x axis, I_{wx}	0.949×10^3	$\text{kg} \cdot \text{m}^2$
Moment of inertia of wheelset about y axis, I_{wy}	0.118×10^3	$\text{kg} \cdot \text{m}^2$
Moment of inertia of wheelset about z axis, I_{wz}	0.967×10^3	$\text{kg} \cdot \text{m}^2$
Primary suspension stiffness, K_1	1.176×10^6	N/m
Primary suspension damping, C_1	1.96×10^3	N·s/m
Secondary suspension stiffness, K_2	1.89×10^5	N/m
Secondary suspension damping, C_2	4×10^3	N·s/m

According to [51], the Wuhan-Guangzhou HSR uses the China Railway Track System I (CRTS I) slab track which consists of two CN60 rails, rail pads, concrete slab, cement asphalt (CA) mortar layer and concrete base. The material properties of CRTS I slab track are presented in Table 2. The numerical model of CRTS I slab track contains 334 beams, 224 discrete and 8256 solid elements. The 3D and front views of train-track section with meshes are illustrated in Figure 2. The slab track model is then connected to the ballasted track to create the transition zone as shown in Figure 3. The dimension of the slab track model is set as 35.2 m x 3 m x 0.69 m since the focus is on the transition zone, and this also reduces computational time.

The FE model of a typical ballasted track is developed according to [52]. This FE model consists of UIC-60 rails, high-density polyethylene (HDPE) rail pads, concrete sleepers and ballast layer. To reduce the computational time and memory consumption, the numerical models of track components are simulated using 2D elements such as beam elements for the rails and sleepers, and spring-dashpot elements for rail pads and ballast layer. The material properties of this ballasted track are presented in Table 2. This FE ballasted track model is made of 1006 beam and 513 discrete elements and using the element mesh that is considered sufficient to recreate the ballasted track behaviour. The ballasted track model is simulated as 35.8 m x 2.5 m x 0.3 m and the transition zone is presented in Figure 3.

The computational applications for train and track modelling are developed using the available keywords in LS-DYNA. The material properties of the track and train components are defined using the keywords: *MAT_ELASTIC, *MAT_RIGID, *MAT_SPRING_ELASTIC and *MAT_DAMPER_VISCOUS. The contact between the wheel and rail is modelled using keywords: RAIL_TRACK and *RAIL_TRAIN. These keywords are also used to define wheel-rail contact stiffness ($K_H=1.325 \times 10^9$ N/m) and the properties of the train such as the nodes in contact with rail [53] (Li et al., 2020; LSTC, 2007). The vehicle is simulated to operate at a uniform velocity by adopting *DEFINE_CURVE and *BOUNDARY_PRESCRIBED_MOTION_RIGID modules to all the FE models of train components. The *DEFINE_CURVE keyword is first used to describe the relationship between motion value and time, where the function values are 1 when $t=0$ and $t>0$. Then the velocity (200 m/s) of the train model is defined using *BOUNDARY_PRESCRIBED_MOTION_RIGID module. The boundary conditions such as nodal set constraints at the rail, and the bottom and sides of the tracks are generated using *BOUNDARY_SPC_SET. The *CONTROL_DYNAMIC_RELAXATION module is used to simulate the induced stress and deformation, due to the preloading force caused by gravity, in the track model. Finally, a termination time of 0.255 s is required to stop the simulation using keyword: *CONTROL_TERMINATION. It is noted that this simulation time covers the whole travel time of train over both slab and ballasted tracks.

Figure 2. FE models of CRTS I slab track and CRH 2 EMU train.

Figure 3. Transition zone between slab track and ballasted track.

Table 2. Properties of the track (Wang et al., 2016; Liu et al., 2016).

Properties	Values	Units
Mass density of UIC60 rail	7.83×10^3	kg/m ³
Young's modulus of UIC60 rail	2.059×10^{11}	Pa
Possion's ratio of UIC60 rail	0.3	
Stiffness of rail pad	5.0×10^7	N/m
Damping of rail pad	7.5×10^4	N·s/m
Mass density of concrete (For slab and sleepers)	2.5×10^3	kg/m ³
Young's modulus of concrete (For slab and sleepers)	3.6×10^{10}	Pa
Possion's ratio of concrete (For slab and sleepers)	0.2	
Mass density of CA mortar layer	1.6×10^3	kg/m ³
Young's modulus of CA mortar layer	3.0×10^8	Pa
Possion's ratio of CA mortar layer	0.2	
Mass density of supporting layer	2.5×10^3	kg/m ³
Young's modulus of supporting layer	$.25 \times 10^{10}$	Pa
Possion's ratio of supporting layer	0.2	
Stiffness of subgrade	7.0×10^6	N/m
Stiffness of substructure in ballasted track	1.3×10^7	Pa

In this study, case iron baseplates and baseplate pads are added to the slab track in between the slab and rail pads of the FE model as beam and spring elements as shown in Figure 4. The material properties

of baseplates are presented in Table 3, and the stiffness of baseplate pads is simulated according to the typical values. The typical dynamic stiffness values of baseplate pads are obtained from a company, Tiflex Ltd, also known as Trackelast [54]. The thickness of baseplate is 15mm. The pad stiffness can be customized to provide an optimum transition zone. As the application of baseplate pads is typically for slab track, only the conditions of track components of slab track are modified according to the following list of parametric studies considering the pad stiffness presented in Table 3. In this study, the weight of baseplate is varied due to its size and thickness from the nominal value based on $0.37 \times 0.42 \times 0.015 \text{ m}^3$ plate. These studies assist in evaluating the effects of baseplate pad stiffness and baseplate weight on the track deflection by altering the material characteristics.

Figure 4. Baseplate modelling.

Table 3. Properties of baseplate and baseplate pad.

Properties	Values	Units
Cast iron baseplate ($0.37 \times 0.34 \text{ m}^2$)		
Density	7.4×10^3	kg/m^3
Young's modulus	1.7×10^{11}	Pa
Poisson's ratio	0.3	
Mass (Nominal value)	22.73	kg
Baseplate pad		
Stiffness	60, 400, 920, 1400	MN/m^2

In this study, the slab track and ballasted track are validated separately with the previous numerical results which have been validated already. The validation results are presented in Tables 4-5. As for slab track, validation of the established model for the train-track interactions includes three parts: wheel rail contact force, rail pad force and displacement of the rail [53]. Besides, the verification of the ballasted track model is performed by comparing the obtained simulation results of the wheel-rail contact force maximum displacements of rail and concrete sleeper at positions of rail seat and mid-span with [52]. The results appear to be within the acceptable range of 10%. Therefore, they exhibit an overall good agreement with other simulation results

Table 4. The validation results of train-track interaction on slab track.

Results	[53]	This study
Wheel-rail contact force (kN)	96.3	96.6
Rail displacement (mm)	0.863	0.829
Rail pad force (kN)	35.1	37.0

Table 5. The validation results of train-track interaction on ballasted track.

Results	[52]	This study
Wheel-rail contact force (kN)	100	98.4
Rail displacement at rail seat (mm)	2.606	2.596
Rail displacement at mid-span (mm)	2.604	2.415
Sleeper displacement at rail seat (mm)	2.576	2.522
Sleeper displacement at mid-span (mm)	2.511	2.352

3. Results

This paper investigates the parametric studies of baseplate parameters on the dynamic responses of track at transition zone. The rail displacement of transition zone is obtained. Firstly, only the stiffness of baseplate pad is considered and varied without cast iron baseplate. Secondly, the effects of weight of baseplate is carried out for different pad types. Lastly, the gradual changes in pad stiffness and baseplate mass on the slab track are considered to provide the progressively change in stiffness along the track.

3.1. Baseplate pad stiffness

To study the influence of baseplate pad stiffness, four different cases of baseplate pad stiffness are considered. Figure 5 shows the vertical rail displacements of the slab track increase with decreasing baseplate pad stiffness. Especially the rail displacements of slab track with the use of lowest pad stiffness (60 MN/m/m^2) are even more significant than the rail displacements of the ballasted track. However, the use of lower stiffness baseplate pads has caused a more substantial disturbance in the slab track. These indicate the rail displacements profiles of slab track are greatly affected by the baseplate pad stiffness. As can be seen in Figure 5, although baseplate pads are applied only on the slab track, they also have provided with a smoother variation of rail displacements of ballasted track and the overall rail displacements profiles of ballasted track are smaller than the one without baseplate pad. Different pad stiffnesses generally do not affect the rail displacement on the ballasted track and only show minor effects near the bridge approach.

Figure 6 presents the differential settlement in percentage by calculating the percent difference in maximum rail displacement of slab track and ballasted track. The positive value indicates that the rail displacement of ballasted track is greater than that of slab track. It is clear that baseplate can potentially reduce the differential settlement at transition zone. The 400 MN/m/m^2 pad results in the better performance than others.

Figure 5. Rail displacement of transition zone.

Figure 6. Differential settlement (%) between slab track and ballasted track.

3.2. Baseplate weight

To investigate the effect of cast iron baseplate and its weight on the track displacement and how the impact may be varied under different baseplate pad stiffnesses, 3 different baseplate weight have been adopted for 4 different cases of pad stiffness.

The impact of baseplate weight on the track displacement under different baseplate pad stiffnesses is examined. Figures 7-10 show the rail deflections of slab track bridge are significantly affected by using baseplates. The effect of weight of baseplate on the rail deflections and their variations increase as the baseplate pad stiffness decrease. Nevertheless, the larger baseplate appears to slightly provide a smoother ride by reducing the variation of rail displacement. It is interesting that adding baseplate softens the slab track rather than using only baseplate pad. Moreover, as for very soft pads represented by the stiffness of 60 MN/m/m^2 , the baseplates clearly increase the differential stiffness between slab track and ballasted track. However, the weight of baseplate does not show the significant effects on track dynamic responses.

The differential settlements in percentage at transition zone are presented in Figure 11. It is clear that 400 MN/m/m^2 pads with cast iron baseplates provide the best results. The uniform settlements are likely to be observed since less than 5% differential settlements are noticed. Whereas the soft pads with stiffness of 60 MN/m/m^2 demonstrate an uneven deformation for all baseplate weight. It is noted that 400 MN/m/m^2 tends to be the optimum value of baseplate pad stiffness to reduce the differential settlement and track degradation.

Figure 7. Rail displacement at transition zone considering baseplate pad stiffness of 60 MN/m/m^2 varying baseplate weight.

Figure 8. Rail displacement at transition zone considering baseplate pad stiffness of 400 MN/m/m² varying baseplate weight.

Figure 9. Rail displacement at transition zone considering baseplate pad stiffness of 920 MN/m/m² varying baseplate weight.

Figure 10. Rail displacement at transition zone considering baseplate pad stiffness of 1400 MN/m/m² varying baseplate weight.

Figure 11. Differential displacement (%) between slab track and ballasted track considering various baseplates.

3.3 Optimal parameters

Figure 12 illustrates the variation of baseplate pad stiffness along the slab track. It is noted that the values of pad stiffness are decreased every 4 spans and values are based on the pad stiffness used in the previous section. However, the 330MN/m² pad stiffness is chosen for the last 4 spans since it provides the smoothest track stiffness in the transition zone. Also, weight of baseplate is increased every 8 spans from the slab end by two times and three times. The decreasing weight is also considered in the same sense.

Figure 12. Baseplate pad stiffness variation on slab track.

The results in Figure 13 show the study on using decreasing baseplate pad stiffness and varying baseplate weight along the bridge rather than using constant values allow the rail deflections of the bridge to increase which provides a smaller differential displacement. The overall rail displacements profile of the ballasted track also decreases. However, the use of increasing mass is better than using decreasing mass at decreasing the track stiffness and smoother transition from the bridge to embankment. From the results, the influence of baseplate pad stiffness is more effective than baseplate mass to provide lower track stiffness of bridge and lower differential settlement at the transition zone. It is important that track stiffness should be optimized. The variation of baseplate pad stiffness along the track should be taken into account to reduce the abrupt change in track stiffness and differential settlement resulting in reducing long-term track deterioration.

Figure 13. Rail displacement at transition zone considering baseplate pad stiffness of 1400 MN/m/m² varying baseplate mass.

5. Conclusions

Baseplate is a captive assembled fastening system which has been applied to mitigate the noise and vibration for railways. However, only a few literatures have placed attention on the influence of baseplate pad stiffness to reduce the adverse effects that arise at the bridge embankment transition zone, and the influence of baseplate weight has been completely overlooked. Therefore, this report is the world's first to perform an investigation on the effects of weight of baseplate and pad stiffness on the transition zone between slab track and ballasted track to provide a smoother transition. The numerical models of train-track interaction established in this paper were developed using LSDYNA to investigate the dynamic responses and parametric studies. Based on the simulation results, the following novel insights can be drawn:

- The use of softer baseplate pads causes the rail displacements of slab track bridge to increase and amplify the uneven track profile. Baseplate pads with more elasticity reduce the vibrations transmitting through them, hence reduce the concrete slab displacements. The 400MN/m/m² pad is likely to be the best for use at typical transition zone.
- The rail displacements profiles of the transition zone are smoothened and with the least increase using heavier baseplate and higher pad stiffness that provides less displacement than the ballasted track. Low pad stiffness that possibly causes the rail displacement to exceed that of ballasted track would give the negative effects on transition zone.
- The effect of baseplate weight on the concrete slab displacements generally is imperceptible. However, it may cause an uplift displacement of concrete slab at the bridge-embankment transition.
- The results of using of gradual decreasing pad stiffnesses over the larger slab track area provide better smoothing effect on the transition zone.

The novel insights of these studies will provide railway engineers with a better understanding of the impact of pad stiffness and baseplate weight on the track displacement of the bridge embankment transition zone. Despite that, due to the limitations of the project, more research should be conducted based on the recommendations provided on the influence of baseplate weight to give more explicit, comprehensive knowledge. Lastly, it is suggested that the pad stiffness, baseplate weight and the arrangement of baseplate fastening systems should be carefully applied to maximize the benefit of baseplate at transition zone.

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References

1. Tan, P., Ma, J.-e., Zhou, J., and Fang, Y.-t. Sustainability Development Strategy of China's High Speed Rail. *Journal of Zhejiang University-SCIENCE A* **2016**, 17(12), 923-32.
2. He, G., Mol, A. P. J., Zhang, L., and Lu, Y. Environmental Risks of High-Speed Railway in China: Public Participation, Perception and Trust. *Environmental Development* **2015**, 14, 37-52.
3. Koch, E. Finite Element Analysis of Bridge Transition Zone for Investigating the Effect of Moving Loads. **2019**.
4. Koch, E., Hudacsek, P., SzepeshÁZi, R., and Kegyes-Brassai, O. 3d Modelling of Train-Track Interaction at Bridge Transition. *ce/papers* **2018**, 2(2-3), 695-700.
5. Fortunato, E., Paixão, A., and Calçada, R. Railway Track Transition Zones: Design, Construction, Monitoring and Numerical Modelling. *International Journal of Railway Technology* **2013**, 2(4), 33-58.

6. Wang, H., Chang, L., and Markine, V. Structural Health Monitoring of Railway Transition Zones Using Satellite Radar Data. *Sensors* **2018**, 18(2), 413.
7. Hsi, J. Bridge Approach Embankments Supported on Concrete Injected Columns. In *Geocongress 2008: Geosustainability and Geohazard Mitigation*, 612-19, 2008.
8. Nicks, J. E. *The Bump at the End of the Railway Bridge*. Vol. 71, 2009.
9. Stark, T. D., and Wilk, S. T. Root Cause of Differential Movement at Bridge Transition Zones. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* **2016**, 230(4), 1257-69.
10. Wang, H., Silvast, M., Markine, V., and Wiljanen, B. Analysis of the Dynamic Wheel Loads in Railway Transition Zones Considering the Moisture Condition of the Ballast and Subballast. *Applied Sciences* **2017**, 7(12), 1208.
11. Paixão, A., Fortunato, E., and Calçada, R. Transition Zones to Railway Bridges: Track Measurements and Numerical Modelling. *Engineering Structures* **2014**, 80, 435-43.
12. Wang, H., and Markine, V. Corrective Countermeasure for Track Transition Zones in Railways: Adjustable Fastener. *Engineering Structures* **2018**, 169, 1-14.
13. Gallage, C., Dareeju, B., and Dhanasekar, M. State-of-the-Art: Track Degradation at Bridge Transitions. 2013.
14. Li, D., and Davis, D. Transition of Railroad Bridge Approaches. *Journal of Geotechnical and Geoenvironmental Engineering* **2005**, 131(11), 1392-98.
15. Paixão, A., Fortunato, E., and Calçada, R. Design and Construction of Backfills for Railway Track Transition Zones. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit* **2015**, 229(1), 58-70.
16. Yenigalla, R. V. An Overview of Mitigation Strategies for Settlements under Bridge Approach Slabs. **2012**.
17. Dupont, B., and Allen, D. L. Movements and Settlements of Highway Bridge Approaches. **2002**.
18. Setiawan, D. M. Worldwide Hot Mix Asphalt Layer Application and Scrap Rubber and Bitumen Emulsion Studies on Railway Track-Bed. *Semesta Teknika* **2018**, 21(2), 166-77.
19. Li, W., and Bian, X. Dynamic Performance of Pile-Supported Bridge-Embankment Transition Zones under High-Speed Train Moving Loads. *Procedia Engineering* **2016**, 143, 1059-67.
20. Woldringh, R. F., and New, B. M. Embankment Design for High Speed Trains on Soft Soils. 1999.
21. Wong, P., and Muttuvel, T. Support of Road Embankments on Soft Ground Using Controlled Modulus Columns. 2011.
22. Rose, J., and Souleyrette, R. Asphalt Railway Trackbeds: Recent Designs, Applications and Performances. 2015.
23. Ejjaouani, H., Lambert, S., and Jean, L. Tramway De Rabat-Salé, Amélioration De Sol Par Colonnes Ballastées Sous Remblais. 2011.
24. Larisch, M. D., Kelly, R., and Muttuvel, T. Improvement of Soft Soil Formations by Drilled Displacement Columns. **2015**.
25. Kaewunruen, S. Dynamic Responses of Railway Bridge Ends: A Systems Performance Improvement by Application of Ballast Glue/Bond. 2014.
26. Lakušić, S., Ahac, M., and Haladin, I. Track Stability Using Ballast Bonding Method. 2010.
27. Luangboriboon, N., Kaewunruen, S., and Sussman, J. M. Lifecycle Cost Analysis for Operations and Maintenance Planning of Railway Bridge Transition. 2018.
28. Gundavaram, D., and Hussaini, S. K. K. Polyurethane-Based Stabilization of Railroad Ballast—a Critical Review. *International Journal of Rail Transportation* **2019**, 7(3), 219-40.
29. Shi, X. M., Cai, C. S., Voyiadjis, G., and Zhang, Z. Design of Ribbed Concrete Approach Slab Based on Interaction with the Embankment. *Transportation Research Record* **2005**, 1936(1), 181-91.
30. Merritt, D. K., Miron, A. J., Rogers, R. B., and Rasmussen, R. O. "Construction of the Iowa Highway 60 Precast Prestressed Concrete Pavement Bridge Approach Slab Demonstration Project." 2007.

- 369 31. Wong, H. K. W., and Small, J. C. Effect of Orientation of Approach Slabs on Pavement
370 Deformation. *Journal of Transportation Engineering* **1994**, 120(4), 590-602.
- 371 32. Hoppe, E. J. Guidelines for the Use, Design, and Construction of Bridge Approach Slabs. **1999**.
- 372 33. Ma, S. Bridge Approach Slab Analysis and Design Incorporating Elastic Soil Support. **2011**.
- 373 34. Nassif, H., Abu-Amra, T., and Shah, N. Finite Element Modeling of Bridge Approach and
374 Transition Slabs. 2002.
- 375 35. Fara, A. Transition Zones for Railway Bridges: A Study of the Sikån Bridge. 2014.
- 376 36. Mottahed, J., Zakeri, J. A., and Mohammadzadeh, S. A Field Investigation on the Effects of Using
377 Usps in Transition Zone from Ballasted Track to Bridges. *International journal of civil engineering*
378 **2019**, 17(9), 1421-31.
- 379 37. Lund, H., and Åswärdh, A. Transition Zones between Ballasted and Ballast Less Tracks. *Lund:*
380 *LTH School of Engineering at Campus Helsingborg, Department of Technology and Society, Lund*
381 *University* **2014**.
- 382 38. Sañudo, R., Dell'Olio, L., Casado, J. A., Carrascal, I. A., and Diego, S. Track Transitions in
383 Railways: A Review. *Construction and Building Materials* **2016**, 112, 140-57.
- 384 39. Jayasuriya, C., Indraratna, B., and Nimbalkar, S. Analysis of the Performance of under Sleeper
385 Pads-a Critical Review. 2015.
- 386 40. Ngamkhanong, C., and Kaewunruen, S. Effects of under Sleeper Pads on Dynamic Responses of
387 Railway Prestressed Concrete Sleepers Subjected to High Intensity Impact Loads. *Engineering*
388 *Structures* **2020**, 214, 110604.
- 389 41. Witt, S. The Influence of under Sleeper Pads on Railway Track Dynamics. Master, Linköping
390 University, 2008.
- 391 42. Schneider, P., Bolmsvik, R., and Nielsen, J. C. O. In Situ Performance of a Ballasted Railway Track
392 with under Sleeper Pads. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal*
393 *of Rail and Rapid Transit* **2011**, 225(3), 299-309.
- 394 43. Zakeri, J.-A., and Ghorbani, V. Investigation on Dynamic Behavior of Railway Track in Transition
395 Zone. *Journal of mechanical science and technology* **2011**, 25(2), 287-92.
- 396 44. Aggestam, E. Simulation of Vertical Dynamic Interaction between Railway Vehicle and Slab
397 Track. **2018**.
- 398 45. Herron, D., Jones, C. J. C., Thompson, D. J., and Rhodes, D. Prediction and Measurement of
399 Vibration on a Modern Concrete Railway Bridge Fitted with Resilient Rail Fasteners. In *Noise and*
400 *Vibration Mitigation for Rail Transportation Systems*, 201-09: Springer, 2012.
- 401 46. Wang, A., and Cos, S. Advantage of Baseplate with Two Resilient Layers for Railway Slab.
402 *Pandrol Rail Fastenings I, td* **2000**.
- 403 47. Thompson, D., Squicciarini, G., Ntotsios, E., and Baeza, L. Noise and Vibration from Railway
404 Vehicles. In *Handbook of Railway Vehicle Dynamics, Second Edition*, 521-78: CRC Press, 2019.
- 405 48. Setsobhonkul, S., Kaewunruen, S., and Sussman, J. M. Lifecycle Assessments of Railway Bridge
406 Transitions Exposed to Extreme Climate Events. *Frontiers in Built Environment* **2017**, 3, 35.
- 407 49. Bewes, O. G. The Calculation of Noise from Railway Bridges and Viaducts. **2005**.
- 408 50. Liu, D., Liu, Y.-f., Ren, J.-j., Yang, R.-s., and Liu, X.-y. Contact Loss beneath Track Slab Caused
409 by Deteriorated Cement Emulsified Asphalt Mortar: Dynamic Characteristics of Vehicle-Slab
410 Track System and Prototype Experiment. *Mathematical Problems in Engineering* **2016**, 2016.
- 411 51. Zhai, W., Liu, P., Lin, J., and Wang, K. Experimental Investigation on Vibration Behaviour of a
412 Crh Train at Speed of 350 Km/H. *International Journal of Rail Transportation* **2015**, 3(1), 1-16.
- 413 52. Kaewunruen, S., Ngamkhanong, C., and Ng, J. Influence of Time-Dependent Material Degradation
414 on Life Cycle Serviceability of Interspersed Railway Tracks Due to Moving Train Loads.
415 *Engineering Structures* **2019**, 199, 109625.
- 416 53. Li, T., Su, Q., and Kaewunruen, S. Influences of Piles on the Ground Vibration Considering the
417 Train-Track-Soil Dynamic Interactions. *Computers and Geotechnics* **2020**, 120, 103455.
- 418 54. Trackelast. Plain Line Rail Pads. <http://www.trackelast.com/plain-line-pads.html>.

- 419 55. Kaewunruen, S., Sussman, J. M., and Matsumoto, A. Grand Challenges in Transportation and
420 Transit Systems. *Frontiers in Built Environment* **2016**, 2, 4.
421