Delft University of Technology

Railway ballast

Guo, Yunlong; Jing, Guoqing; Markine, V.L.

DOI
10.1016/B978-0-12-821042-0.00021-6

Publication date
2022

Document Version
Final published version

Published in
Rail Infrastructure Resilience

Citation (APA)
Guo, Y., Jing, G., & Markine, V. L. (2022). Railway ballast. In R. Calçada, & S. Kaewunruen (Eds.), *Rail Infrastructure Resilience: A Best-Practices Handbook* (pp. 295-317). Elsevier. https://doi.org/10.1016/B978-0-12-821042-0.00021-6

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' - Taverne project

https://www.openaccess.nl/en/you-share-we-take-care

Otherwise as indicated in the copyright section: the publisher
is the copyright holder of this work and the author uses the
Dutch legislation to make this work public.

Railway ballast

14

Yunlong Guo[a], *Valeri Marikine*[a], *and Guoqing Jing*[b]
[a]Delft University of Technology, Delft, The Netherlands, [b]Beijing Jiaotong University, Beijing, China

14.1 Introduction

14.1.1 Ballast definition

Railways play an important role in current transportation systems. The ballast bed (granular layer) is placed between the sleeper and the subballast as a shock absorber to reduce the stress from sleeper to an acceptable level (Fig. 14.1). Ballast bed is made of crushed rocks of certain size (in 20–60 mm range). Among the track components, ballast is the biggest part of the ballast track taking the largest volume.

As shown in Fig. 14.2, the ballast particles are placed between sleepers, under sleepers and on both sides of sleepers with certain profiles. The profiles include the ballast thickness (250–350 mm, from sleeper bottom), crib ballast (around 600 mm, between two adjacent sleepers) and shoulder ballast (300–500 mm).

14.1.2 Ballast function

The main purpose of ballast bed is to perform the following functions [1]:

- Providing an even load-bearing platform and supporting sleepers stably. Stable support and platform are necessary for safe train operation, furthermore, the track irregularity is mainly caused by unacceptable ballast bed deformation.
- Dissipating intense loads and reducing the stress magnitude at the subgrade surface. To avoid the stress concentration, the train loads from sleeper to the subgrade are minimized, dissipated, and uniformly distributed by the ballast. Nevertheless, ballast pockets are still developing due to high stresses on the ballast-soil interface.
- Keeping sufficient track stability by providing the sleeper resistance in vertical, longitudinal, and lateral directions. It needs to note that the lateral resistance is very important for continuous welded rail (CWR) track to reduce the buckling possibility. Ballast shear strength, influenced by ballast compaction and particle morphology, is the main characteristic affecting track stability.
- Providing necessary track elasticity and resiliency against dynamic loads. Losing the resiliency can lead to large differential settlements, and the proper elasticity can reduce damage to track components.
- Resisting sufficiently against biochemical contamination, mechanical contamination, and environment. The ballast disposes of not only the mechanical deterioration from the track structures (sleeper, ballast, and soil) and from the freight (coal, sands), but also the biochemical contamination (mostly the human excrement). Additionally, ballast needs to resist the weathering degradation (e.g., acid rain).

Rail Infrastructure Resilience. https://doi.org/10.1016/B978-0-12-821042-0.00021-6
Copyright © 2022 Elsevier Inc. All rights reserved.

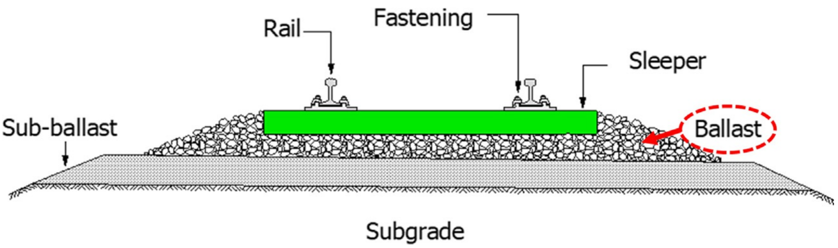

Fig. 14.1 Conventional ballast track.

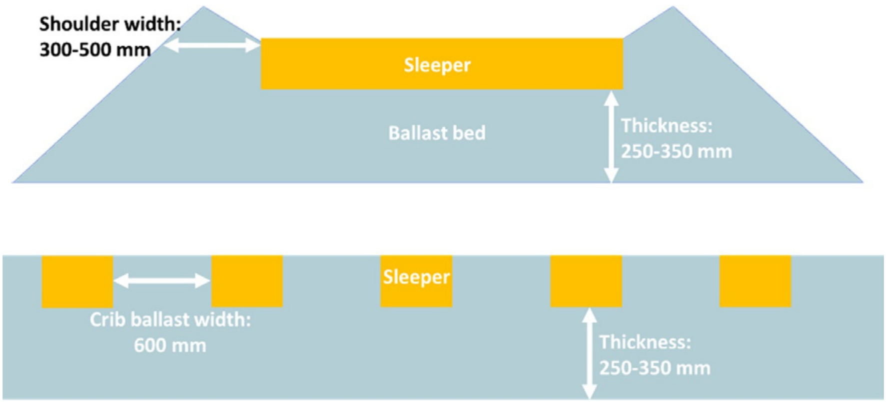

Fig. 14.2 Ballast bed profile size.

- Possessing adequate permeability for drainage. Newly built ballast bed can provide good drainage, and proper particle size distribution can increase the permeability. However, ballast fouling can reduce the permeability through jamming voids in ballast bed, and the fouling is inevitable.
- Absorbing noises. Compared with the slab track, the ballast layer can absorb noise and vibrations.
- Providing necessary electric insulation. The signaling needs the ballast layer to have enough electric insulation. Due to this, whether the steel slag can be used as railway ballast still remains a question.

14.1.3 Ballast research on current problems

With the development of high-speed railway and heavy haul railway, the main aspects in railway research are related to the development of new numerical methods, track evaluation standards, design philosophy, and maintenance strategies. For example, in the past two centuries, the design of ballast track almost remains the same, although the railway freight loads and speeds keep increasing [2,3].

Under cyclic loading due to passing trains, the ballast particles deteriorate due to breakage and abrasion, resulting in permanent plastic deformations of ballast bed. Accumulating the plastic deformation, the ballast bed cannot provide adequate performance.

The degradation becomes more severe due to the increasing axle loads (freight line) and train speed (passenger transport), which leads to frequent maintenance (e.g., tamping). More importantly, when the demand for higher speed and heavier haul is increasing, the unacceptable ballast bed performance can cause issues of passenger comfort and safety.

The current studies (research) on the ballast performed recently can be categorized into the four following issues [1,4].

14.1.3.1 Performance assessment

The performance characteristics of the ballast bed mainly contain durability, stability, shear strength, stiffness, and resilience [5]. In earlier studies, the factors influencing the performance (e.g., particle shape and size) were analyzed with the laboratory tests (e.g., direct shear test) or field tests (e.g., single sleeper push test, sleeper supporting stiffness measurement). Numerical models of the corresponding tests (e.g., direct shear test) were also applied. The studies for performance assessment of ballast bed have been relatively mature at both the basic knowledge and methodologies.

14.1.3.2 Ballast bed degradation mechanism

The mechanism of ballast bed degradation and the associated plastic deformations have not been revealed clearly, especially in some special railway structures, e.g., turnouts, transition zones. The problem becomes more complicated, due to the increasing train speed and heavier haul [6,7]. The main challenge for studying ballast bed degradation mechanism is that the factors are too much. For example, ballast particle degradation affects ballast bed degradation [1,4]. However, only a few factors are considered in one study in most cases, which causes the conclusions to be different.

14.1.3.3 Degradation mitigation and performance improvement of ballast bed

Using other materials in the ballast bed is an effective means for ballast degradation mitigation and performance improvement, e.g., using the under sleeper pads, geogrid, geocell, polyurethane [8], etc.

However, applying other materials changes the ballast bed properties, which possibly causes other issues of the ballast track. Therefore, the challenges are how to correctly use the new materials, reducing as much as possible their negative influence on ballast track.

14.1.3.4 Maintenance

Frequent maintenances to ballast lead to high costs. Earlier studies have shown that tamping (the most common maintenance) causes ballast particle degradation (breakage and abrasion) due to the impact from the insertion of the tamping tines into the ballast and the high squeezing force. Therefore, more studies should be performed toward more precise and correct maintenance.

14.1.4 Solutions to ballast problems

The solutions to the stressed ballast problems are summarized into three aspects, i.e., ballast degradation mitigation, ballast inspection improvement and better ballast condition assessment.

14.1.4.1 Ballast degradation

Ballast degradation usually describes the deterioration of ballast bed. Also, it has been used to describe the ballast particle degradation in recent studies. Ballast particle degradation mainly includes two mechanisms, namely breakage and abrasion [1]. Ballast particle degradation leads to ballast bed degradation ultimately influencing the performance of ballast bed and overall track performance. Therefore, it is necessary to study ballast particle degradation in order to better understanding the degradation mechanism and to improve the ballast bed performance.

Ballast particle degradation mitigation can be achieved by applying new ballast materials, for example, steel slag [9] and Neoballast [10], as well as using new other materials, such as, rubber chips [11], under sleeper pads [12], geogrid [13] and polyurethane [14]. These applications are explained more in Section 14.2.3.2.

14.1.4.2 Ballast inspection

Ballast inspection is to check the ballast bed condition (e.g., ballast bed profile, geometry and hanging sleeper) in order to allow the vehicle safely rides on the track. It is closely related to ballast performance assessment and maintenance.

More focuses should be paid on ballast inspection. In the past, ballast inspection was not focused enough as much as other track components (inspected by gauging rules). However, most of the dangerous situations (e.g., buckling and mud-pumping) is resulted from ballast bed failure (low resistance to sleeper and ballast particle degradation). In addition, the track irregularity in most cases is contributed by the deformation of ballast bed.

More technical means have been developed and used for ballast inspection, such as, GPR, inspection train with camera, drones, SmartRock, and satellite. How these technical means have been applied for ballast inspection is explained in Section 14.3.

14.1.4.3 Ballast condition assessment

Ballast condition assessment is performed usually based on the data from ballast inspection or using numerical simulations. The assessment can be categorized into three aspects, data/signal processing, and numerical simulation.

For the data/signal process, it is to process the data that are mostly measured by some traditional instruments, for example, ballast acceleration (accelerometer), ballast bed settlement (displacement meter), ballast bed stress (pressure sensor), and ballast degradation (sieving).

For the numerical simulations, more and more assessment has been performed by building numerical models, among which the discrete element method (DEM) has clear advantages of simulating ballast particles. For example, using the DEM, some detailed parametric studies that are often not feasible in laboratory tests, can be performed, e.g., interparticle friction and distribution of contact forces (contact force chain).

14.2 Ballast degradation

In this section, ballast degradation mechanism is firstly introduced and discussed, with the subsections of

- degradation mechanism: introduction of ballast degradation reasons, types, and consequences,
- degradation factors: factors influencing ballast degradation, loading type, parent rock material, compaction, particle size, and shape,
- and degradation mitigation: solutions to mitigate ballast degradation (new materials and sleeper innovations).

14.2.1 Ballast degradation mechanism

14.2.1.1 Ballast degradation reasons

Several reasons cause ballast degradation, such as, train loading (cyclic loading, impact loading), maintenance (tamping, stabilization), weather (extreme weather, acid rain), geology (earthquake, desert) and biology (plants). Among these reasons, the train loading and maintenance are two main reasons. Nevertheless, other reasons are also critical when the ballast beds are in the extreme conditions, such as, special structure (transition zone), air pollution (acid rain), and cold region (freeze-thaw).

For the train loading, the degradation mechanism has been already demonstrated in depth. For example, in [1,15,16], many studies show that cyclic loadings cause ballast degradation (breakage) using laboratory tests. The laboratory tests are mainly the triaxial test, ballast box test, and improved ballast box test (e.g., movable side walls [17]). In addition, the impact loading is admitted widely as the reason for accelerating ballast degradation, which for example has been studied in the research on transition zone and switch and crossing [18,19].

For the maintenance, the degradation mechanism during the tamping have been studied, and more studies are still strongly needed to deepen the understanding. For example, in [20–22], laboratory tests were performed to study ballast degradation caused by tamping. in [23,24], ballast degradation in the field tests caused by tamping were examined. These studies demonstrated that the tamping operation causes serious ballast degradation, which was firstly proposed in the book [25].

For the other reasons, limited studies have been performed, which means more focuses should be paid to fill in the research gaps. Some advices on performing the related studies are given as follows.

- Weather: the cold region can be simulated using a refrigeration house. For example, the study in [26,27] tested the ballast performance. Further study can be performed on the ballast degradation in the low temperature.
- Geology: using ballast box test is possible to study the ballast degradation of the mixture of ballast particles and sands (desert area), e.g., [28]. For the earthquake, the shake table can be used to simulate earthquake loadings.
- Biology: the plant damages to the ballast is very small, but it is possible to be serious to the high-speed vehicle. Another possible reason is the plants improve the stiffness of ballast bed, which reduces the resilience (or elasticity) of ballast bed. This can cause more ballast degradation.

14.2.1.2 Ballast degradation types

Ballast particle degradation is generally classified includes two main types, breakage, and abrasion. However, it may not be sufficient to classify ballast degradation by two types, because ballast breakage can have various types, such as, corner breakage, splitting in the middle, and breaking into several parts. Particularly, until now, few methods were reported for ballast abrasion evaluation.

Most importantly, the current evaluation methods for the breakage and abrasion, which are still insufficient and need improvement, cannot present ballast degradation types.

For instance, all the breakage evaluation methods are based on sieving, analyzing the change of the PSD or the percentage of particles passing some certain sieve size, when performing laboratory tests, e.g., the Los Angeles Abrasion test, the triaxial test, and the prismoidal triaxial test [1,29]. The breakage index B_g (proposed in [30]) calculates particle sizes between the initial and final particle size distributions. To be more specific, it is the sum of the difference in percentage retained on sieves, having the same sign. However, it may not be sufficient to evaluate ballast breakage only by calculating the PSD, since the final PSD results are obtained based on various types of ballast breakage.

Most of the current methods that can study ballast abrasion are related to image analysis. For example, in [31], the abrasion is evaluated by the changes of ballast particle morphology. The University of Illinois aggregate image analyzer (UIAIA) and a second-generation aggregate imaging system (AIMS) are utilized to capture changes of individual particles before and after the micro-Deval test [31].

Consequently, among the previous methods, image analysis is the most potential and effective one, which can be a significant method to study the ballast degradation types. More studies based on that should be performed for better understanding of the ballast degradation mechanism and further its effects on the performance and deformation of ballast bed [1,32].

14.2.1.3 Ballast degradation consequences

The ballast degradation causes several consequences, including deformation (differential settlement), low capacity (lateral and longitudinal resistances), ballast bed harden and drainage failure (mud-pumping).

Deformation

Ballast degradation has great influences on the shear strength leading to big deformation of ballast bed, which was measured in triaxial tests [33] or other laboratory tests (e.g., direct shear test [34]). In addition, the ballast fouling, produced by ballast degradation, in most cases reduces the shear strength.

In addition, particle breakage significantly influences the performance (e.g., shear strength) and the deformation of any kinds of ballast material [1]. Particle size would be changed after crushing and generally cause the densification and the contaminations clogging the voids, which may further increase the shear strength [35]. The ballast abrasion is demonstrated in [36] that permanent settlement is related to the ballast abrasion.

Hanging sleeper is a mostly-seen issue due to differential settlement, which is closely related to rapid ballast degradation (due to impact loading).

Low capacity

The low capacity of ballast bed means that ballast degradation reduces the lateral resistance and longitudinal resistance to the sleeper, which causes unstable ballast track. The buckling is caused by the insufficient lateral resistance of ballast bed to the sleeper. The longitudinal resistance insufficiency is an unsolved issue of tracks that are built on the long steep slope (mountainous areas).

Ballast bed hardening

Ballast bed harden is caused by the fouling, which means the ballast bed becomes like a cemented concrete with the fouling as binder. The fouling, except some special line (e.g., Australian freight line for coal transportation), results from ballast degradation. Ballast bed harden means the ballast bed lost the elasticity and resilience with high stiffness. The geometry of the ballast track (with hardened ballast bed) is normally irregular, which leads to rapid track component degradation.

Drainage failure

The drainage failure would also induce dramatic ballast settlement. As reported in [37], saturation increased settlement by about 40% of that of dry ballast. The fouling jams the voids of ballast bed, blocking water flow. The mixture of fouling and water is a lubricant causing low capacity of ballast bed. In addition, the drainage failure also causes the mud-pumping, which is also an important reason of subgrade failure.

14.2.2 Ballast degradation factors

14.2.2.1 Loading type

The loading type includes cyclic loading from train and some impact loading at some special railway structures, such as, the transition zone and switch and crossing. In addition, the cyclic loading can be divided based on transportation types, such as freight line, passenger line, and mixed line. Due to the different vehicle types, the loadings are quite different, such as, the loading frequency and amplitude. For example, in some studies, the loading applied in the laboratory test simulates the normal speed train (e.g., 100km/h) [38]. For the high-speed train, the loading frequency and amplitude are quite different, whose effects to the ballast was studied in [39,40].

14.2.2.2 Parent rock material

Generally, the material of the parent rock is analyzed using the petrographic methods. Ballast is typically made of crushed (from quarry) rock particles, e.g., limestone, volcanic, granite, quartzite, and sandstone. The parent rock types are different in each country up to the quality and availability.

For the parent rock material, limited studies have been published, because the ballast materials in different countries are quite different, which means there is not a universal degradation growth/prediction for each ballast material. However, the parent rock material is in most cases tested before using the material to make the ballast bed. For example, in China, the China Academy of Railway Sciences tests if the parent rock materials are suitable to make ballast bed following the Chinese standard [41], for example, the magnesium sulfate value and water absorption as a screening test for freeze-thaw resistance. In the British standard, the parent rock material is also required to meet certain assessment [42]. Other examples on parent rock material can be found in [29,43].

14.2.2.3 Compaction (bulk density)

The bulk density characterizes the compaction state of ballast bed, similar to porosity of ballast bed. The bulk density is calculated as the ballast mass divided by the total volume (ballast particles and voids), while the porosity is calculated as the ratio of void volume to the total volume.

The compaction state of ballast bed has a significant influence on the performance (e.g., track stability, shear strength, and stiffness), thus, the bulk density (or porosity) is a key indicator for ballast bed quality during the ballast track construction, as well as when performing field and laboratory tests, and numerical simulations. The bulk density (porosity) is easy to obtain in the numerical simulations (e.g., using the discrete element method (DEM)).

Particularly, the compaction of ballast bed is a key factor influencing ballast degradation. Because low compaction leads to low confining stress to ballast, which causes more ballast degradation as explained in [44]. When the ballast bed is well-compacted, which means the ballast particles have enough contacts with the adjacent particles (named as coordination), then a stable degradation process is shown. More studies on the compaction (or confining stress/pressure) can be found in [20,45,46].

14.2.2.4 Particle size and shape

The particle sizes of ballast beds are presented by the particle size distribution (PSD), also known as gradation, which is obtained by sieving. The PSD measures the percentage (by weight) of the particles in a certain size range. For example, in the British standard, the fractions of the Gradation A are 22.4, 31.5, 40, 50, and 63mm.

The shape is normally evaluated roughly with the dimension ratio of the particles (elongation and flakiness) [47]. The flaky and elongated particles are calculated with the lengths of the three representative axes: the longest axis with the length *L*, the medium axis with the length *I* and the shortest axis with the length *S*. The ballast particles with *S*/*I* smaller than 0.6 or with *L*/*I* above 1.8 as the flaky or elongated ballast particles, respectively [48].

The particle shape is closely related to ballast degradation. For example, it was found that ballast specimens with flaky or elongated particles can cause lower resilience [35]. However, a limited percentage of flaky or elongated particles leads to higher shear strength and thus a lower rate of settlement accumulation [49]. Nevertheless, it was also reported that adding flaky or elongated particles results in more severe degradation and higher deformation of ballast bed [50].

Besides the elongation and flakiness, the angularity and surface texture are the other two main shape characteristics. However, limited studies on ballast degradation related to these two characteristics were found. Because the assessment of angularity and texture requires more accurate measurement tools than simply sieving, for example, laser scanning.

14.2.3 Ballast degradation mitigation

In this section, methods for ballast degradation mitigation are summarized from three aspects, ballast material, new geo-inclusion materials, and sleeper innovations.

- Ballast material: in these methods, solutions from the ballast bed itself are considered, for example, using high-density material and using more cubic ballast particles.
- New geo-inclusion materials: solutions from adding new materials in the ballast bed are considered, for example, geogrid, geocell, polyurethane, and ballast mat.
- Sleeper innovations: solutions from changing the sleeper material and shapes are considered, for example, ladder sleeper and plastic sleeper.

14.2.3.1 Ballast material

The ballast material is introduced in the Section 14.2.2, which has great influence on the ballast degradation, mainly the particle size and shape, as well as parent rock material. Therefore, optimizations on ballast material have been performed in many studies.

For example, in [51], different ballast materials are used for different sections of the bridge approach (transition zone) to balance the stiffness difference of the transition zone. The results show that using a smooth transition with different ballast materials at each section is effective to reduce or mitigate differential settlement, which can reflect the ballast degradation is mitigated.

Another example is using the steel slag as ballast particles. The densities of different steel slag are not always the same, but mostly higher than ballast material. Most importantly, it has higher resistance to degradation than rock, which was proved in [52]. More studies on the steel slag can be found in [53–56].

By bonding rubber chips to the ballast particles, the Neoballast is created. The degradation of the Neoballast particles was proved to be less than normal ballast in [57]. The shear strength and dynamic performance of Neoballast particles were studied in [10,58].

14.2.3.2 New geo-inclusion materials

The new geo-inclusions materials are able to reduce ballast degradation.

Under sleeper pads is a plastic pad attached between ballast particles and sleeper for softening their contacts and finally reducing ballast degradation [59]. It is a popular solution, which has attracted lots of studies, especially for the special structures, such as transition zone [60,61], switch and crossing [62,63], and joints [64].

Geogrid has been successfully applied to build railway tracks at weak subgrades, improve ballast layer stability, and reduce track settlement. However, to what extent it can reduce the ballast degradation has not been reported in any publications.

Geocell has been applied to improve the subgrade stability and reduce subgrade settlement [65]. In recent years, using it to enhance the performance of subballast was studied [66,67]. Some studies attempted to use the geocell in ballast layer to improve the ballast layer performance, such as [68,69]. However, until now the ballast degradation after using geocell has not been confirmed yet.

Polyurethane is also named as ballast glue, and in the review paper [14], studies on polyurethane-reinforced ballast bed are explained in details. Two types of polyurethane for now have been used, foam and glue. Polyurethane protects ballast particles and reduce the ballast degradation by reducing the relative motions between the contacted particles.

Ballast mat is rubber mat that is placed usually under the ballast layer (above subgrade/bridge). Ballast mat can absorb some energies from the vehicle, and dissipate the loadings more uniformly to the subgrade. It reduces the ballast degradation by storing some energies from the vehicle loading, then slowly giving part of the energies back to ballast. More studies about ballast mat can be found in [70–73].

14.2.3.3 Sleeper innovations

Sleeper innovations are new sleepers, which have been proposed to improve the CWR (continuous welded rail) track stability, such as, winged-shape sleeper [74,75], ladder sleeper [76], nailed sleeper [77], Y-shape sleeper [78], bi-block sleeper, sleeper anchor [79], and steel sleeper [80], as shown in Fig. 14.3. The innovative sleepers focus on improving the sleeper materials and shapes, and according to the results [74,75,77,78,81], they can provide larger lateral resistance. They can possibly also be used for ballast degradation mitigation. More studies can be performed in this direction.

For example, the winged-shape sleeper (Fig. 14.3E) was designed as a mono-block sleeper with wings on the bottom, end side, and middle side [82]. The sleeper was designed as "H-shape." The ladder sleeper is designed the shape as a "ladder." These two sleepers can reduce ballast degradation by increasing the contact area between ballast and sleeper, which can more uniformly dissipate the energies from cyclic loadings.

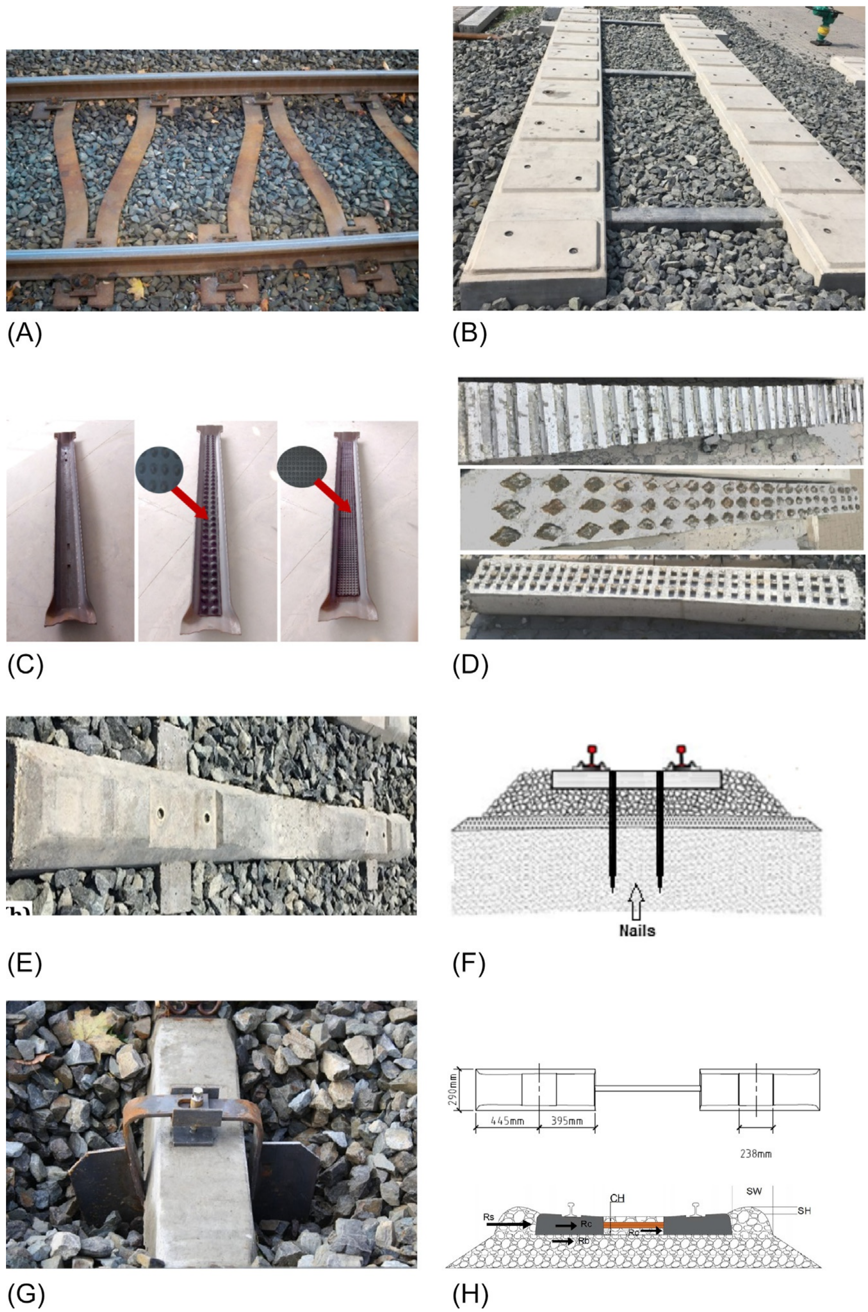

Fig. 14.3 Different types of innovated sleepers. (A) Y-shape sleeper (reproduced from G. Jing, H. Fu, P. Aela, Lateral displacement of different types of steel sleepers on ballasted track, Construct. Build. Mater. 186 (2018) 1268–1275). (B) Ladder sleeper (reproduced from G. Jing, P. Aela, H. Fu, The contribution of ballast layer components to the lateral resistance of ladder

(continued)

14.3 Ballast inspection and assessment

14.3.1 Ballast inspection

Ballast inspection provides guidance for ballast tamping. Because tamping breaks ballast particles, therefore, condition-based and predictive tamping are needed to reduce unnecessary tamping.

Ballast inspection with high-tech is the development trend toward achieving smart railway maintenance. Currently, many early-stage studies have been performed on smart monitoring, such as, structure health monitoring, smart sleeper, and smart rock [83,84]. More and more inspection methods are also developed, such as, using drones, inspection train, and satellite [85], as shown in Fig. 14.4.

Fig. 14.4A presents the SmartRock, which is made of a 3D printed plastic cover (ballast particle shape) and an accelerometer. The plastic cover has rock-similar characteristics, such as density and surface roughness. The accelerometer can measure the angular acceleration and axial acceleration (three orthogonal directions). The SmartRock can be used during the tamping to show the ballast accelerations, and comparing the acceleration of SmartRock with that of ballast particles in the DEM models. In addition, the acceleration of ballast particles can also show the ballast bed condition, such as the fouling, stiffness, which can be used as an indicator of maintenance. This is possible when the data of accelerations are well correlated with ballast bed conditions.

In addition, the drones with a camera to video the track has been studied. The track images are analyzed to assess the ballast bed condition and also the track geometry. This method has the advantage of less interruption to the train operation and safer to railway staffs. Because inspection train should be scheduled during the maintenance period (early in the morning usually), but the drones can operate and take videos at any time. In addition, some measurement of track geometry is operated by railway workers, which is a heavy work and also dangerous when trains are passing. Using the high quality (resolution) images can analyze not only the track geometry, but also

Fig. 14.3, cont'd sleeper track, Construct. Build. Mater. 202 (2019) 796–805). (C) Steel sleeper (reproduced from G. Jing, H. Fu, P. Aela, Lateral displacement of different types of steel sleepers on ballasted track, Construct. Build. Mater. 186 (2018) 1268–1275). (D) Frictional sleeper (reproduced from Y. Guo, H. Fu, Y. Qian, V. Markine, G. Jing, Effect of sleeper bottom texture on lateral resistance with discrete element modelling, Construct. Build. Mater. 250 (2020)). (E) Winged-shape sleeper (reproduced from T. Ichikawa, K. Hayano, T. Nakamura, Y. Momoya, Lateral resistance of ballasted tracks for various shapes of sleepers based on limit equilibrium methods, Jpn. Geotech. Soc. Spec. Publ. 2(46) (2016) 1632–1635). (F) Nailed sleeper (reproduced from M. Esmaeili, A. Khodaverdian, H.K. Neyestanaki, S. Nazari, Investigating the effect of nailed sleepers on increasing the lateral resistance of ballasted track, Comput. Geotech. 71 (2016) 1–11). (G) Sleeper anchor (reproduced from A. Zarembskis, *Survey of Techniques and Approaches for Increasing the Lateral Resistance of Wood Tie Track*, Department of Civil and Environmental Engineering, University of Delaware, Newark, DE). (H) Bi-block sleeper (reproduced from G. Jing, P. Aela, H. Fu, M. Esmaeili, Numerical and experimental analysis of lateral resistance of biblock sleeper on ballasted tracks, Int. J. Geomech. 20(6) (2020) 04020051).

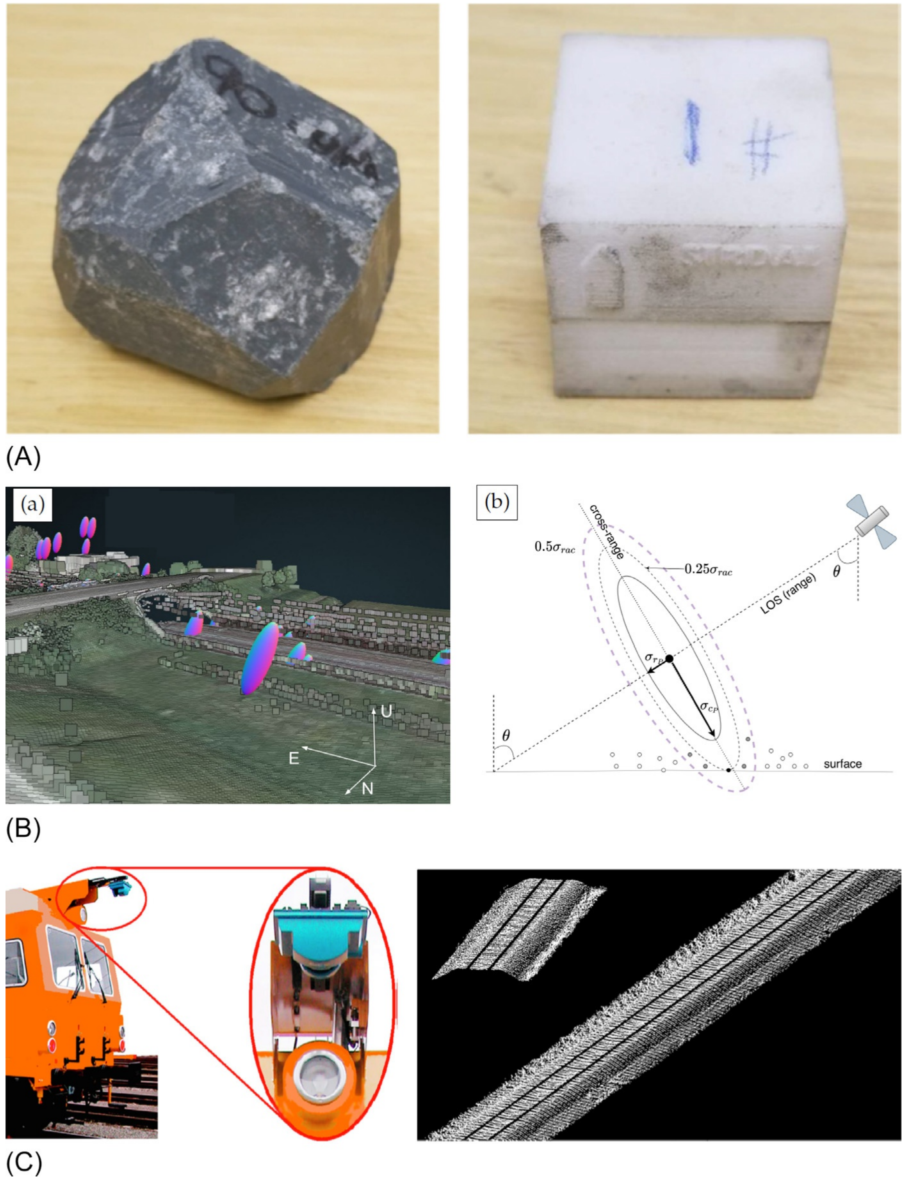

Fig. 14.4 Cutting-edge technique for smart monitoring. (A) SmartRock (reproduced from K. Zeng, T. Qiu, X. Bian, M. Xiao, H. Huang, Identification of ballast condition using SmartRock and pattern recognition, Construct. Build. Mater. 221 (2019) 50–59). (B) Satellite (reproduced from L. Chang, N.P. Sakpal, S.O. Elberink, H. Wang, Railway infrastructure classification and instability identification using sentinel-1 SAR and laser scanning data, Sensors (Basel) 20(24) (2020)). (C) Inspection train with laser scanner (reproduced from J. Sadeghi, M.E. Motieyan Najar, J.A. Zakeri, C. Kuttelwascher, Development of railway ballast geometry index using automated measurement system, Measurement 138 (2019) 132–142).

the rail, fastener and particularly ballast particles (particle size distribution, particle roughness, etc.).

Fig. 14.4B presents that using the satellite analyses track geometry, for now, the settlement is mainly focused. Using the satellite can involve a lot of factors that are very important to the maintenance, for example, the geology (water, desert, and mountain) and weather (snow, rain). In addition, it can record the track geometry change (revolution) of the whole railway lines, which is very helpful to make the maintenance plans.

Fig. 14.4C is the inspection train with a camera to video track geometry. It is similar to using the drones. The advantage is that it can measure the track geometry when the track is loaded by the inspection train. A promising idea is to combine the dynamic responses (of the train-track) with the rail, sleeper and ballast performances. For example, the ballast bed profile has some defects (e.g., hanging sleeper), which possibly causes some acceleration abrupt change. This defect can also be reflected by the big displacements of ballast particles (seen through the video). The abrupt change means this part needs maintenance to repair the ballast bed profile (correcting the geometry).

The inspection data of the track have been collected for over 100 years. Using deep learning and machine learning to analyze the data is still on the early stage, which can be developed further for the condition-based and predictive ballast bed maintenance. In addition, this method can also be used for track quality prediction.

14.3.2 Ballast condition assessment

14.3.2.1 Data/signal processing

Data process

Through the ballast inspection, large amounts of data are obtained, for which rapid and accurate means for data process and analysis are required. The accuracy and efficiency of the data process is dependent on the quality of the labeled useful data. Specifically, the data have been collected from sensors (e.g., acceleration), manually the data are labeled in most cases. Therefore, using the data-driven algorithms to label the data automatically, e.g., unsupervised learning models, is able to contribute to data process accuracy and efficiency. Moreover, the data from inspection is highly imbalanced, which can be alleviated by using the data-driven algorithms by identifying more faulty samples.

Deep learning

Deep learning algorithms are the new trend of machine learning, which abstracts neural networks with more and more layers. Using the algorithms, it is not necessary to perform the data preprocessing, due to they can learn the representation directly. The algorithms have been applied to analyze many complicated data from all kinds of measurement, such as image, audio, and video [2]. The algorithms have been used for analyzing the data (railway track) measured during the inspection, which is also for railway ballast. The deep learning algorithms that have been applied in railway track include convolutional neural networks (CNNs), recurrent neural networks (RNNs), and long-short-term memory (LSTM) models. More explanations can be found in [86].

The convolutional neural network (CNN) is the most widely-used algorithms. The CNN has been used for the detection of track defects with computer-based vision. The CNN models can reach human-level ability (often used as a proxy for the Bayes error rate) in image recognition tasks [87].

Unsupervised learning models

Unsupervised learning aims to find patterns automatically from unlabeled data. Clustering methods and dimensionality reduction techniques are the most widely used unsupervised methods in railway track engineering [86].

Autonomous maintenance projects

Operational Technology, Canadian National Railway Company (CN) is moving out of the lab and into the field with new real-time technology platforms that increase the safety, execution and efficiency of our operations.

CN's Autonomous Track Inspection Program (ATIP) is a fully automated rail car that employs wireless communications to test and monitor real-time geometric track parameters without interrupting normal railroad operations. Powered by solar panels and a generator and traveling at revenue service track speed, our Autonomous Track Inspection Program uses the latest sensor and AI technology to deploy fully automated track inspections 24/7/365.

14.3.2.2 Numerical simulations—Discrete element method

The discrete element method (DEM) has been used in plenty of ballast-related studies and proved to be an effective numerical method [51,88–90]. The DEM is a numerical model or computer simulation approach that can simulate granular materials. It describes the mechanical behavior of assemblies of spheres (disks in 2D) or polyhedrons (polygons in 2D) and considers the individual particles in granular materials and their interactions (e.g., contacts, motions) [91,92]. Nowadays, it has become a powerful and efficient tool to reproduce the performance and deformation of granular materials [93]. Particularly, the DEM is widely applied in the ballast-related studies due to the advantage that an identical sample can be performed with various test conditions (e.g., loading). Moreover, using the DEM can perform some detailed parametric studies that are often not feasible in laboratory tests, e.g., interparticle friction and distribution of contact forces. More importantly, it can record the complete particle information (e.g., displacement, acceleration) during the numerical simulations, consider the characteristics of ballast particles (e.g., size, density), and understand the effects of ballast particle degradation (i.e., breakage and abrasion) on the performance and deformation of the ballast assemblies.

Regarding the above-mentioned research problems (Section 14.1.3), the DEM has been effectively applied to study them. For instance, the performance evaluation of ballast assemblies under various conditions (e.g., particle size distribution, fouling/

contamination) can be performed with the models of direct shear tests [94–101], ballast box test [36,90,102–104], or the triaxial tests [13,17,32,105–110]. Alternatively, the performance evaluation can be analyzed with the model of field tests, e.g., the single sleeper push test model [76,89,93,111–113] and the in-situ ballast track model [88,97,114–124].

When considering the particle degradation in the DEM models, setting the breakage and abrasion criterions is the first step [32,109,115,120,125–128]. With the criteria, the corresponding plastic deformation or fouled ballast bed performance can be presented, e.g., [36,116,122,129]. Particularly, the DEM models have also been applied in the dynamic performance and degradation study of ballast bed at the transition zone [51,130].

As for the ballast degradation mitigation and performance improvement, the under sleeper pads [90], the geogrid [13,104,130–137], the geocell [65,67], and the polyurethane [8,14] are the widely used geomaterials. Plenty of studies with DEM models have been performed to demonstrate their effectiveness and propose application advices.

Regarding the track maintenance, tamping is the most common means operated on ballast layer to restore the track elastic and geometry. Using the DEM models, the studies mainly concern the tamping frequency, compaction, and performance after tamping, etc. [113,138–144].

References

[1] B. Indraratna, W. Salim, C. Rujikiatkamjorn, Advanced Rail Geotechnology: Ballasted Track, CRC Press, London, 2011.

[2] Y. Guo, V. Markine, X. Zhang, W. Qiang, G. Jing, Image analysis for morphology, rheology and degradation study of railway ballast: a review, Transp. Geotech. 18 (2019) 173–211.

[3] Y. Guo, C. Zhao, V. Markine, G. Jing, W. Zhai, Calibration for discrete element modelling of railway ballast: a review, Transp. Geotech. 23 (2020), 100341.

[4] D. Li, J. Hyslip, T. Sussmann, S. Chrismer, Railway Geotechnics, CRC Press, 2002.

[5] W. Zhai, Vehicle–Track Coupled Dynamics Theory and Applications, Springer, Singapore, 2020.

[6] A. Danesh, M. Palassi, A.A. Mirghasemi, Evaluating the influence of ballast degradation on its shear behaviour, Int. J. Rail Transp. 6 (3) (2018) 145–162.

[7] W. Zhai, K. Wang, J. Lin, Modelling and experiment of railway ballast vibrations, J. Sound Vib. 270 (4) (2004) 673–683.

[8] D. Gundavaram, S.K.K. Hussaini, Polyurethane-based stabilization of railroad ballast—a critical review, Int. J. Rail Transp. 7 (3) (2019) 219–240.

[9] G. Jing, J. Wang, H. Wang, M. Siahkouhi, Numerical investigation of the behavior of stone ballast mixed by steel slag in ballasted railway track, Constr. Build. Mater. 262 (2020) 120015.

[10] Y. Guo, Y. Ji, Q. Zhou, V. Markine, G. Jing, Discrete element modelling of rubber-protected ballast performance subjected to direct shear test and cyclic loading, Sustainability 12 (7) (2020) 2836.

[11] Y. Guo, V. Markine, W. Qiang, H. Zhang, G. Jing, Effects of crumb rubber size and percentage on degradation reduction of railway ballast, Constr. Build. Mater. 212 (2019) 210–224.

[12] Y. Guo, J. Wang, V. Markine, G. Jing, Ballast mechanical performance with and without under sleeper pads, KSCE J. Civ. Eng. 24 (11) (2020) 3202–3217.
[13] Y. Qian, D. Mishra, E. Tutumluer, H.A. Kazmee, Characterization of geogrid reinforced ballast behavior at different levels of degradation through triaxial shear strength test and discrete element modeling, Geotext. Geomembr. 43 (5) (2015) 393–402.
[14] G. Jing, L. Qie, V. Markine, W. Jia, Polyurethane reinforced ballasted track: review, innovation and challenge, Constr. Build. Mater. 208 (2019) 734–748.
[15] B. Indraratna, D. Ionescu, H. Christie, Shear behavior of railway ballast based on large-scale triaxial tests, J. Geotech. Geoenviron. 124 (5) (1998) 439–449.
[16] B. Indraratna, T. Ngo, Ballast Railroad Design: SMART-UOW Approach, CRC Press, 2018.
[17] C. Chen, B. Indraratna, G. McDowell, C. Rujikiatkamjorn, Discrete element modelling of lateral displacement of a granular assembly under cyclic loading, Comput. Geotech. 69 (2015) 474–484.
[18] H. Wang, V. Markine, X. Liu, Experimental analysis of railway track settlement in transition zones, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 232 (6) (2018) 1774–1789.
[19] X. Liu, V.L. Markine, H. Wang, I.Y. Shevtsov, Experimental tools for railway crossing condition monitoring (crossing condition monitoring tools), Measurement 129 (2018) 424–435.
[20] B. Aursudkij, A Laboratory Study of Railway Ballast Behaviour Under Traffic Loading and Tamping Maintenance, University of Nottingham, 2007.
[21] S.C. Douglas, Ballast quality and breakdown during tamping, in: Proceedings of the 2013 American Railway Engineering and Maintenance-of-Way Association Conference, Inidanpolis, IN, 2013.
[22] C. Paderno, Improving ballast tamping process, in: Proc., World Congress on Railway Research, 2011, pp. 1–6.
[23] Y. Descantes, R. Perales, G. Saussine, N. Milesi, On the damaging effects of the ballast tamping operation, AIPCR, 2011. p. sp.
[24] O. Barbir, D. Adam, F. Kopf, J. Pistrol, F. Auer, B. Antony, Development of condition-based tamping process in railway engineering, ce/papers 2 (2–3) (2018) 969–974.
[25] E.T. Selig, J.M. Waters, Track Geotechnology and Substructure Management, Thomas Telford, 1994.
[26] J. Liu, P. Wang, G. Liu, J. Dai, J. Xiao, H. Liu, Study of the characteristics of ballast bed resistance for different temperature and humidity conditions, Constr. Build. Mater. 266 (2021) 121115.
[27] J. Liu, P. Wang, G. Liu, M. Zhang, J. Xiao, H. Liu, Uniaxial compression characteristics of railway ballast combined with ice, Constr. Build. Mater. 263 (2020) 120554.
[28] M. Esmaeili, P. Aela, A. Hosseini, Experimental assessment of cyclic behavior of sand-fouled ballast mixed with tire derived aggregates, Soil Dyn. Earthq. Eng. 98 (2017) 1–11.
[29] R. Nålsund, Railway Ballast Characteristics, Selection Criterion and Performance, Department of Civil and Transport Engineering, Norwegian University of Science and Technology, Trondheim, 2014.
[30] R.J. Marsal, Mechanical Properties of Rockfill, Wiley (John) and Sons, Incorporated, 1973.
[31] M. Moaveni, E. Mahmoud, E. Ortiz, E. Tutumluer, S. Beshears, Use of advanced aggregate imaging systems to evaluate aggregate resistance to breakage, abrasion, and polishing, Transp. Res. Rec. 2401 (2014) 1–10.
[32] G.R. McDowell, H. Li, Discrete element modelling of scaled railway ballast under triaxial conditions, Granul. Matter 18 (3) (2016) 1–10.

[33] B. Indraratna, T. Ngo, C. Rujikiatkamjorn, Performance of ballast influenced by deformation and degradation: laboratory testing and numerical modeling, Int. J. Geomech. 20 (1) (2019) 04019138.

[34] W. Jia, V. Markine, Y. Guo, G. Jing, Experimental and numerical investigations on the shear behaviour of recycled railway ballast, Constr. Build. Mater. 217 (2019) 310–320.

[35] D. Ionescu, Evaluation of the Engineering Behaviour of Railway Ballast, University of Wollongong, Faculty of Engineering, 2004. https://ro.uow.edu.au/theses/421. (Doctor of Philosophy thesis).

[36] M. Lu, G. McDowell, Discrete element modelling of ballast abrasion, Géotechnique 56 (9) (2006) 651–655.

[37] B. Indraratna, D. Ionescu, D. Christie, R. Chowdhury, Compression and degradation of railway ballast under one-dimensional loading, Aust. Geomech. J. (1997) 48–61 (December).

[38] Y.L. Guo, C.F. Zhao, V. Markine, C. Shi, G.Q. Jing, W.M. Zhai, Discrete element modelling of railway ballast performance considering particle shape and rolling resistance, Rail. Eng. Sci. 28 (4) (2020) 382–407.

[39] X. Zhang, C. Zhao, W. Zhai, Importance of load frequency in applying cyclic loads to investigate ballast deformation under high-speed train loads, Soil Dyn. Earthq. Eng. 120 (2019) 28–38.

[40] Q.D. Sun, B. Indraratna, S. Nimbalkar, Deformation and degradation mechanisms of railway ballast under high frequency cyclic loading, J. Geotech. Geoenviron. 142 (1) (2016) 04015056.

[41] T.P.M.o. Railways, Railway Ballast, TB/T2140-2008, China Railway Publishing House, Beijing, 2008.

[42] B.s.p.B.E. British Standards Institution, Aggregates for Railway Ballast, British Standards Institution, London, 2013.

[43] A. Yitayew Alemu, Survey of Railway Ballast Selection and Aspects of Modelling Techniques, Trita-VBT, 2011. Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-87466. (Internet; Dissertation).

[44] B. Indraratna, J. Lackenby, D. Christie, Effect of confining pressure on the degradation of ballast under cyclic loading, Geotechnique 55 (4) (2005) 325–328.

[45] J. Lackenby, B. Indraratna, G. McDowell, D. Christie, Effect of confining pressure on ballast degradation and deformation under cyclic triaxial loading, Géotechnique 57 (6) (2007) 527–536.

[46] Z. Yu, D.P. Connolly, P.K. Woodward, O. Laghrouche, E. Tutumluer, Railway ballast anisotropy testing via true triaxial apparatus, Transp. Geotech. 23 (2020) 100355.

[47] L. Gates, E. Masad, R. Pyle, D. Bushee, Aggregate imaging measurement system 2 (AIMS-II): final report, Highway for Life Technology Partnership Program, Federal Highway Administration, US Department of Transportation, 2011.

[48] Y. Guo, V. Markine, J. Song, G. Jing, Ballast degradation: effect of particle size and shape using Los Angeles Abrasion test and image analysis, Constr. Build. Mater. 169 (2018) 414–424.

[49] C. Dunn, P. Bora, Shear strength of untreated road base aggregates measured by variable lateral pressure triaxial cell, J. Mater. 7 (2) (1972).

[50] Y. Gur, E. Shklarsky, M. Livneh, Effect of coarse-fraction flakiness on the strength of graded materials, in: Asian Conf Soil Mech & Fdn E Proc/Is/, 1967.

[51] Y. Qian, E. Tutumluer, Y.M.A. Hashash, J. Ghaboussi, D.D. Davis, Ballast settlement ramp to mitigate differential settlement in a bridge transition zone, Transp. Res. Rec. 2476 (2476) (2015) 45–52.

[52] A. Paixão, E. Fortunato, Abrasion evolution of steel furnace slag aggregate for railway ballast: 3D morphology analysis of scanned particles by close-range photogrammetry, Constr. Build. Mater. 267 (2021) 121225.
[53] S. Mehran Khoshoei, H. Mortazavi Bak, S. Mahdi Abtahi, S. Mahdi Hejazi, B. Shahbodagh, Experimental investigation of the cyclic behavior of steel-slag ballast mixed with tire-derived aggregate, J. Mater. Civ. Eng. 33 (2) (2021) 04020468.
[54] W. Jia, V.L. Markine, G. Jing, Analysis of furnace slag in railway sub-ballast based on experimental tests and DEM simulations, Constr. Build. Mater. 288 (2021) 123114.
[55] B. Guimarães Delgado, A. Viana da Fonseca, E. Fortunato, P. Maia, Mechanical behavior of inert steel slag ballast for heavy haul rail track: laboratory evaluation, Transp. Geotech. 20 (2019), 100243.
[56] Y. Qi, B. Indraratna, A. Heitor, J.S. Vinod, Effect of rubber crumbs on the cyclic behavior of steel furnace slag and coal wash mixtures, J. Geotech. Geoenviron. 144 (2) (2018) 04017107.
[57] V. Fontserè, A.L. Pita, N. Manzo, A. Ausilio, NEOBALLAST: new high-performance and long-lasting ballast for sustainable railway infrastructures, Transp. Res. Proc. 14 (2016) 1847–1854.
[58] M. Sol-Sánchez, F. Moreno-Navarro, M. Rubio-Gámez, N. Manzo, V. Fontseré, Full-scale study of Neoballast section for its application in railway tracks: optimization of track design, Mater. Struct. 51 (2) (2018) 43.
[59] T. Ngo, B. Indraratna, Mitigating ballast degradation with under-sleeper rubber pads: experimental and numerical perspectives, Comput. Geotech. 122 (2020), 103540.
[60] A. Paixão, C. Alves Ribeiro, N. Pinto, E. Fortunato, R. Calçada, On the use of under sleeper pads in transition zones at railway underpasses: experimental field testing, Struct. Infrastruct. Eng. 11 (2) (2014) 112–128.
[61] A. Paixão, J.N. Varandas, E. Fortunato, R. Calçada, Numerical simulations to improve the use of under sleeper pads at transition zones to railway bridges, Eng. Struct. 164 (2018) 169–182.
[62] L. Le Pen, G. Watson, A. Hudson, W. Powrie, Behaviour of under sleeper pads at switches and crossings – field measurements, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 232 (4) (2018) 1049–1063.
[63] H. Loy, Under sleeper pads in turnouts, Railw. Tech. Rev. 2 (2009) 35.
[64] S. Kaewunruen, A. Aikawa, A.M. Remennikov, Vibration attenuation at rail joints through under sleeper pads, Procedia Eng. 189 (2017) 193–198.
[65] Y. Liu, A. Deng, M. Jaksa, Three-dimensional modeling of geocell-reinforced straight and curved ballast embankments, Comput. Geotech. 102 (2018) 53–65.
[66] B. Indraratna, M.M. Biabani, S. Nimbalkar, Behavior of geocell-reinforced subballast subjected to cyclic loading in plane-strain condition, J. Geotech. Geoenviron. 141 (1) (2014) 04014081.
[67] N.T. Ngo, B. Indraratna, C. Rujikiatkamjorn, M. Mahdi Biabani, Experimental and discrete element modeling of geocell-stabilized subballast subjected to cyclic loading, J. Geotech. Geoenviron. 142 (4) (2016) 04015100.
[68] Y. Liu, A. Deng, M. Jaksa, Three-dimensional discrete-element modeling of geocell-reinforced ballast considering breakage, Int. J. Geomech. 20 (4) (2020) 04020032.
[69] S.K. Dash, A.S. Shivadas, Performance improvement of railway ballast using geocells, Indian Geotech. J. 42 (3) (2012) 186–193.
[70] G. Wettschureck, M. Heim, M. Tecklenburg, Long-term properties of Sylomer® ballast mats installed in the rapid transit railway tunnel near the Philharmonic Hall of Munich, Germany, Rail Eng. Int. 31 (4) (2002) 6–11.

[71] S. Mohammadzadeh, A. Miri, M. Nouri, Enhancing the structural performance of masonry arch bridges with ballast mats, J. Perform. Constr. Facil. 31 (5) (2017) 04017089.
[72] S.K. Navaratnarajah, B. Indraratna, Use of rubber mats to improve the deformation and degradation behavior of rail ballast under cyclic loading, J. Geotech. Geoenviron. 143 (6) (2017) 04017015.
[73] A.D.O. Lima, M.S. Dersch, Y. Qian, E. Tutumluer, J.R. Edwards, Laboratory fatigue performance of under-ballast mats under varying loads and support conditions, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 233 (6) (2019) 606–613. 0954409718795920.
[74] Y. Koike, T. Nakamura, K. Hayano, Y. Momoya, Numerical method for evaluating the lateral resistance of sleepers in ballasted tracks, Soils Found. 54 (3) (2014) 502–514.
[75] T. Ichikawa, K. Hayano, T. Nakamura, Y. Momoya, Lateral resistance of ballasted tracks for various shapes of sleepers based on limit equilibrium methods, Jpn. Geotech. Soc. Spec. Publ. 2 (46) (2016) 1632–1635.
[76] G. Jing, P. Aela, H. Fu, The contribution of ballast layer components to the lateral resistance of ladder sleeper track, Constr. Build. Mater. 202 (2019) 796–805.
[77] M. Esmaeili, A. Khodaverdian, H.K. Neyestanaki, S. Nazari, Investigating the effect of nailed sleepers on increasing the lateral resistance of ballasted track, Comput. Geotech. 71 (2016) 1–11.
[78] V. Ungureanu, A. Mariş, Y shape railway sleepers from fiber reinforced foamed urethane, Bull. Transilv. Univ. Bras. CIBv 6 (55, Special Issue No. 1) (2013).
[79] G. Jing, Y. Ji, P. Aela, Experimental and numerical analysis of anchor-reinforced sleepers lateral resistance on ballasted track, Constr. Build. Mater. 264 (2020) 120197.
[80] J.A. Zakeri, R. Talebi, F. Rahmani, Field investigation on the lateral resistance of ballasted tracks with strengthened steel sleepers using the multi sleeper push test, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 234 (9) (2020) 969–975. 095440971987777.
[81] J. Ali Zakeri, M. Esmaeili, A. Kasraei, A. Bakhtiary, A numerical investigation on the lateral resistance of frictional sleepers in ballasted railway tracks, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 230 (2) (2014) 440–449.
[82] L.M. Domingo, J.I.R. Herraiz, C. Zamorano, T.R. Herraiz, Design of a new high lateral resistance sleeper and performance comparison with conventional sleepers in a curved railway track by means of finite element models, Lat. Am. J. Solids Struct. 11 (7) (2014) 1238–1250.
[83] K. Zeng, T. Qiu, X. Bian, M. Xiao, H. Huang, Identification of ballast condition using SmartRock and pattern recognition, Constr. Build. Mater. 221 (2019) 50–59.
[84] G. Jing, M. Siahkouhi, J. Riley Edwards, M.S. Dersch, N.A. Hoult, Smart railway sleepers – a review of recent developments, challenges, and future prospects, Constr. Build. Mater. 271 (2021) 121533.
[85] L. Chang, R.P. Dollevoet, R.F. Hanssen, Nationwide railway monitoring using satellite SAR interferometry, IEEE J. Sel. Top. Appl. Earth Obs. and Remote Sens. 10 (2) (2017) 596–604.
[86] J. Xie, J. Huang, C. Zeng, S.-H. Jiang, N. Podlich, Systematic literature review on data-driven models for predictive maintenance of railway track: implications in geotechnical engineering, Geosciences 10 (11) (2020) 425.
[87] C. Szegedy, A. Toshev, D. Erhan, Deep neural networks for object detection, Adv. Neural Inf. Process. Syst. 26 (2013).
[88] X. Zhang, C. Zhao, W. Zhai, Dynamic behavior analysis of high-speed railway ballast under moving vehicle loads using discrete element method, Int. J. Geomech. 17 (7) (2016) 04016157.

[89] G. Jing, H. Fu, P. Aela, Lateral displacement of different types of steel sleepers on ballasted track, Constr. Build. Mater. 186 (2018) 1268–1275.
[90] H. Li, G.R. McDowell, Discrete element modelling of under sleeper pads using a box test, Granul. Matter 20 (2) (2018) 1–12.
[91] P.A. Cundall, O.D. Strack, A discrete numerical model for granular assemblies, Geotechnique 29 (1) (1979) 47–65.
[92] C. O'Sullivan, Particulate Discrete Element Modelling: A Geomechanics Perspective, CRC Press, 2014.
[93] J.I. González, Numerical Analysis of Railway Ballast Behaviour Using the Discrete Element Method, Universitat Politècnica de Catalunya, 2017.
[94] B. Suhr, S. Marschnig, K. Six, Comparison of two different types of railway ballast in compression and direct shear tests: experimental results and DEM model validation, Granul. Matter 20 (4) (2018) 70.
[95] D. Mishra, S.N. Mahmud, Effect of particle size and shape characteristics on ballast shear strength: a numerical study using the direct shear test, in: 2017 Joint Rail Conference, American Society of Mechanical Engineers, 2017. V001T01A014.
[96] Z. Wang, G. Jing, Q. Yu, H. Yin, Analysis of ballast direct shear tests by discrete element method under different normal stress, Measurement 63 (2015) 17–24.
[97] H. Huang, E. Tutumluer, Discrete Element Modeling for fouled railroad ballast, Constr. Build. Mater. 25 (8) (2011) 3306–3312.
[98] B. Suhr, K. Six, Parametrisation of a DEM model for railway ballast under different load cases, Granul. Matter 19 (4) (2017) 64.
[99] B. Indraratna, S.S. Nimbalkar, N.T. Ngo, T. Neville, Performance improvement of rail track substructure using artificial inclusions – experimental and numerical studies, Transp. Geotech. 8 (2016) 69–85.
[100] B. Indraratna, N.T. Ngo, C. Rujikiatkamjorn, J. Vinod, Behavior of fresh and fouled railway ballast subjected to direct shear testing: discrete element simulation, Int. J. Geomech. 14 (1) (2012) 34–44.
[101] X. Bian, W. Li, Y. Qian, E. Tutumluer, Micromechanical particle interactions in railway ballast through DEM simulations of direct shear tests, Int. J. Geomech. 19 (5) (2019) 04019031.
[102] S. Laryea, M. Safari Baghsorkhi, J.F. Ferellec, G.R. McDowell, C. Chen, Comparison of performance of concrete and steel sleepers using experimental and discrete element methods, Transp. Geotech. 1 (4) (2014) 225–240.
[103] M. Lu, G.R. McDowell, The importance of modelling ballast particle shape in the discrete element method, Granul. Matter 9 (1–2) (2006) 69–80.
[104] C. Chen, G.R. McDowell, N.H. Thom, Discrete element modelling of cyclic loads of geogrid-reinforced ballast under confined and unconfined conditions, Geotext. Geomembr. 35 (2012) 76–86.
[105] J. Harkness, A. Zervos, L. Le Pen, S. Aingaran, W. Powrie, Discrete element simulation of railway ballast: modelling cell pressure effects in triaxial tests, Granul. Matter 18 (3) (2016) 1–13.
[106] M. Lu, G.R. McDowell, Discrete element modelling of railway ballast under monotonic and cyclic triaxial loading, Géotechnique 60 (6) (2010) 459–467.
[107] J. Xiao, D. Zhang, K. Wei, Z. Luo, Shakedown behaviors of railway ballast under cyclic loading, Constr. Build. Mater. 155 (2017) 1206–1214.
[108] S. Ahmed, J. Harkness, L. Le Pen, W. Powrie, A. Zervos, Numerical modelling of railway ballast at the particle scale, Int. J. Numer. Anal. Methods Geomech. 40 (5) (2016) 713–737.

[109] B. Indraratna, P.K. Thakur, J.S. Vinod, Experimental and numerical study of railway ballast behavior under cyclic loading, Int. J. Geomech. 10 (4) (2009) 136–144.
[110] S. Liu, T. Qiu, Y. Qian, H. Huang, E. Tutumluer, S. Shen, Simulations of large-scale triaxial shear tests on ballast aggregates using sensing mechanism and real-time (SMART) computing, Comput. Geotech. 110 (2019) 184–198.
[111] F. Khatibi, M. Esmaeili, S. Mohammadzadeh, DEM analysis of railway track lateral resistance, Soils Found. 57 (4) (2017) 587–602.
[112] Z. Zeng, S. Song, W. Wang, H. Yan, G. Wang, B. Xiao, Ballast bed resistance characteristics based on discrete-element modeling, Adv. Mech. Eng. 10 (6) (2018). 1687814018781461.
[113] E. Tutumluer, H. Huang, Y. Hashash, J. Ghaboussi, Aggregate shape effects on ballast tamping and railroad track lateral stability, in: AREMA Annual Conference, Loisville, KY, September 2006, 2006, pp. 17–20.
[114] D. Nishiura, H. Sakai, A. Aikawa, S. Tsuzuki, H. Sakaguchi, Novel discrete element modeling coupled with finite element method for investigating ballasted railway track dynamics, Comput. Geotech. 96 (2018) 40–54.
[115] B. Dahal, S.N. Mahmud, D. Mishra, Simulating ballast breakage under repeated loading using the discrete element method, in: 2018 Joint Rail Conference, American Society of Mechanical Engineers, 2018. V001T01A003.
[116] E. Tutumluer, Y. Qian, Y.M.A. Hashash, J. Ghaboussi, D.D. Davis, Discrete element modelling of ballasted track deformation behaviour, Int. J. Rail Transp. 1 (1–2) (2013) 57–73.
[117] S. Ji, S. Sun, Y. Yan, Discrete element modeling of dynamic behaviors of railway ballast under cyclic loading with dilated polyhedra, Int. J. Numer. Anal. Methods Geomech. 41 (2) (2017) 180–197.
[118] N.T. Ngo, B. Indraratna, C. Rujikiatkamjorn, Simulation ballasted track behavior: numerical treatment and field application, Int. J. Geomech. 17 (6) (2016) 04016130.
[119] E. Mahmoud, A.T. Papagiannakis, D. Renteria, Discrete element analysis of railway ballast under cycling loading, Procedia Eng. 143 (2016) 1068–1076.
[120] S. Lobo-Guerrero, L.E. Vallejo, Discrete element method analysis of railtrack ballast degradation during cyclic loading, Granul. Matter 8 (3–4) (2006) 195–204.
[121] S. Liu, H. Huang, T. Qiu, L. Gao, Comparison of laboratory testing using SmartRock and discrete element modeling of ballast particle movement, J. Mater. Civ. Eng. 29 (3) (2017) D6016001.
[122] I. Deiros, C. Voivret, G. Combe, F. Emeriault, Quantifying degradation of railway ballast using numerical simulations of micro-deval test and in-situ conditions, Procedia Eng. 143 (2016) 1016–1023.
[123] H. Huang, S. Chrismer, Discrete element modeling of ballast settlement under trains moving at “Critical Speeds”, Constr. Build. Mater. 38 (2013) 994–1000.
[124] W.T. Hou, B. Feng, W. Li, E. Tutumluer, Ballast support condition affecting crosstie performance investigated through discrete element method, in: Pr ASME Joint Rail C, 2018.
[125] B. Wang, U. Martin, S. Rapp, Discrete element modeling of the single-particle crushing test for ballast stones, Comput. Geotech. 88 (2017) 61–73.
[126] P. Thakur, J.S. Vinod, B. Indraratna, Effect of particle breakage on cyclic densification of ballast: a DEM approach, IOP Conf. Ser.: Mater. Sci. Eng. 10 (1) (2010) 012229. IOP Publishing.
[127] J. Qian, J. Gu, X. Gu, M. Huang, L. Mu, DEM analysis of railtrack ballast degradation under monotonic and cyclic loading, Procedia Eng. 143 (2016) 1285–1292.
[128] Z. Hossain, B. Indraratna, F. Darve, P. Thakur, DEM analysis of angular ballast breakage under cyclic loading, Geomech. Geoengin. 2 (3) (2007) 175–181.

[129] E. Tutumluer, H. Huang, Y. Hashash, J. Ghaboussi, Discrete element modeling of railroad ballast settlement, in: AREMA Conference, 2007.
[130] C. Chen, G.R. McDowell, An investigation of the dynamic behaviour of track transition zones using discrete element modelling, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 230 (1) (2014) 117–128.
[131] C. Chen, G.R. McDowell, N.H. Thom, A study of geogrid-reinforced ballast using laboratory pull-out tests and discrete element modelling, Geomech. Geoengin. 8 (4) (2013) 244–253.
[132] B. Indraratna, S. Nimbalkar, C. Rujikiatkamjorn, From theory to practice in track geomechanics – Australian perspective for synthetic inclusions, Transp. Geotech. 1 (4) (2014) 171–187.
[133] S.N. Mahmud, D. Mishra, D.O. Potyondy, Effect of geogrid inclusion on ballast resilient modulus: the concept of 'geogrid gain factor', in: 2018 Joint Rail Conference, American Society of Mechanical Engineers, 2018. V001T01A005.
[134] Y. Qian, E. Tutumluer, H. Huang, A validated discrete element modeling approach for studying geogrid-aggregate reinforcement mechanisms, in: Geo-Frontiers 2011: Advances in Geotechnical Engineering, 2011, pp. 4653–4662.
[135] N.T. Ngo, B. Indraratna, C. Rujikiatkamjorn, Modelling geogrid-reinforced railway ballast using the discrete element method, Transp. Geotech. 8 (2016) 86–102.
[136] N.T. Ngo, B. Indraratna, C. Rujikiatkamjorn, DEM simulation of the behaviour of geogrid stabilised ballast fouled with coal, Comput. Geotech. 55 (2014) 224–231.
[137] C.-x. Miao, J.-j. Zheng, R.-j. Zhang, L. Cui, DEM modeling of pullout behavior of geogrid reinforced ballast: the effect of particle shape, Comput. Geotech. 81 (2017) 249–261.
[138] J.-F. Ferellec, R. Perales, V.-H. Nhu, M. Wone, G. Saussine, Analysis of compaction of railway ballast by different maintenance methods using DEM, in: EPJ Web of Conferences, EDP Sciences, 2017, p. 15032.
[139] G. Saussine, E. Azéma, P. Gautier, R. Peyroux, F. Radjai, Numerical modeling of the tamping operation by Discrete Element Approach, in: World Congress Rail Research, 2008, pp. 1–9.
[140] T. Zhou, B. Hu, J. Sun, Z. Liu, Discrete element method simulation of railway ballast compactness during tamping process, Open Electr. Electr. Eng. J. 7 (2013) 103–109.
[141] R. Perales, G. Saussine, N. Milesi, F. Radjai, Numerical investigation of the tamping process, in: 9th World Congress on Railway Research, 2011.
[142] X.J. Wang, Y.L. Chi, W. Li, T.Y. Zhou, X.L. Geng, The research of the numerical simulation on the granular ballast bed tamping, Adv. Mater. Res. (2012) 1395–1398. Trans Tech Publ.
[143] T.M.P. Hoang, P. Alart, D. Dureisseix, G. Saussine, A domain decomposition method for granular dynamics using discrete elements and application to railway ballast, Ann. Solid Struct. Mech. 2 (2–4) (2011) 87–98.
[144] D.S. Kim, S.H. Hwang, A. Kono, T. Matsushima, Evaluation of ballast compactness during the tamping process by using an image-based 3D discrete element method, Proc. Inst. Mech. Eng. F J. Rail Rapid Transit 232 (7) (2018). 0954409718754927.