Construction and Building Materials 223 (2019) 629–642

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

High-speed railway ballast flight mechanism analysis and risk management – A literature review

Guoqing Jing[a], Dong Ding[b], Xiang Liu[c,*]

[a] Civil Engineering School, Beijing Jiaotong University, Beijing 10044, China
[b] Université de Technology de Compiègne, Laboratoire Roberval, Compiègne 60200, France
[c] Department of Civil and Environmental Engineering, Rutgers University-New Brunswick, Piscataway 08854, United States

HIGHLIGHTS

- Review of studies about ballast flight mechanism and influence factors.
- Recommendations of ballast aggregates selection and ballast bed profile were provided.
- Sleeper design and polyurethane materials solutions were presented.
- The reliability risk assessment of ballast flight is described for HSR line management.

ARTICLE INFO

Article history:
Received 16 March 2019
Received in revised form 19 June 2019
Accepted 24 June 2019

Keywords:
High speed rail
Ballast flight
Risk management
Structure optimization
Design

ABSTRACT

Ballast flight is a significant safety problem for high-speed ballasted tracks. In spite of the many relevant prior studies, a comprehensive review of the mechanism, recent developments, and critical issues with regards to ballast flight has remained missing. This paper, therefore, offers a general overview on the state of the art and practice in ballast flight risk management while encompassing the mechanism, influencing factors, analytical and engineering methods, risk mitigation strategies, etc. Herein, the problem of ballast flight is emphasized to be associated with the train speed, track response, ballast profile, and aggregate physical characteristics. Experiments and dynamic analysis, and reliability risk assessment are highlighted as research methods commonly used to analyze the mechanism and influencing factors of ballast flight. Technical solutions and risk management are furthermore presented as known strategies to mitigate the ballast flight problem. Through this review, researchers and practitioners are provided a reliable reference for investigating ballast flight and for developing implementation solutions to mitigate the associated risks.

Contents

* Corresponding author.
E-mail address: xiang.liu@rutgers.edu (X. Liu).

https://doi.org/10.1016/j.conbuildmat.2019.06.194
0950-0618/

Nomenclature

UIC	International Union of Railways (Union Internationale des Chemins de Fer)
SNCF	French National Railway Company (Socit nationale des chemins de fer français)
ADIF	Spanish national railway infrastructure company (Administrador de Infraestructuras Ferroviarias)
FS	Italian State Railways (Ferrovie dello Stato Italiane)
DB	German railway company (Deutsche Bahn AG)
CARS	China Academy of Railway Sciences
FRA	Federal Railroad Administration
KTX	Korea Train Express
AOA	Aerodynamics in Open Air project
CFD	Computational Fluid Dynamic
DEM	Discrete Element Method
LCC	Life-Cycle Costing
CWR	Continuous Welded Rail
RAMS	Reliability, Availability, Maintainability, Safety
HSR	High-speed Rail

1. Introduction

There are two generic choices of track structure type: ballasted and slab track [1]. As two common types of railroad track, ballasted track and slab track both have their merits. When it comes to application, the ballasted track is used on both normal and high-speed railways, while slab track is primarily adopted on high-speed railways. Both track types can meet the fast, safe, and comfortable operation conditions of high-speed railway, but slab track technology offers proven higher performance in service and longer life than traditional ballasted track, so slab track is increasingly becoming the norm for high-speed rail (HSR) [2,3]. Japan, Germany, and China are the most representative of slab track use [4–6]. However, because of the low price and easy maintenance of ballasted track, it is still used in many countries; for example, in France, Spain, Italy [7]. In particular, almost all French high-speed railways adopt the ballasted track type, which operation speed is over 320 km/h, and the maximum test speed of the eastern line is 574.8 km/h [8].

The disadvantage of ballasted track on high-speed railways is the potential for ballast flight, which is an important reason for restricting the development of ballasted track. At present, there is still a lack of in-depth research on ballast flight. This phenomenon occurs when a combination of both mechanical and aerodynamic forces, generated mostly by the passage of the train, cause one or more ballast particles to overcome gravity [9–15]. Ballast flight can cause damage to the railhead, train body, and adjacent structures, as well as injuries to maintenance workers and/or waiting passengers at through stations, which results in major maintenance costs and safety concerns for HSR systems with ballasted track [16,17]. The phenomenon of ballast flight is one of the major problems caused by the increase in railway speed over 300 km/h in terms of safety and the deterioration of both rolling stock and railway, and with high-speed train beginning to operate above 350 km/h, the aerodynamic load on the track induced by the passing of trains has caused ballast flight more frequently [18–20]. It should be noted that the ballast flight phenomenon can also be observed at low speeds, due to ice or snow in cold seasons, or other materials on the line [21].

Investigations have shown that both mechanical and aerodynamic forces are responsible for ballast flight and are related to both train operating conditions and track layouts [22]. On the other hand, the problem becomes extremely evident with increasing speed, when the ballast stones are lifted up due to the pressure and velocity field generated in the upper layer of ballast by the train. Ballast flight has been considered a problem in train aerodynamics since the 1980s, with reported damage like the well-known issues with the ICE 3 (inter-city express, German high-speed train) and another incident that occurred during 300 km/h test runs of the ETR 500 (Italian high-speed train) between Rome and Naples [23]. Furthermore, ballast flight is an important factor for high-speed ballasted track design as well, which correlates with ballast bed profile, ballast standard, track structure, etc. [24].

However, the issue of ballast flight is not regulated or defined by any international standard, and it is currently under investigation by the most important research groups, and it is currently under investigation by the most important research groups (University of Birmingham, University of Southampton, Polytechnic University of Milan, University of Madrid, Beijing Jiao tong university, University of Illinois Urbana-Champaign, SNCF, and DB) [14,25,21,26,27]. The research methods include wind tunnel tests and aerodynamic analysis, track dynamics, reliability risk assessment, and innovative tools and equipment. Yet the mechanism of ballast flight remains unclear, and the counteractive measures for ballast flight are still insufficient to handle the increasing speed of trains and complex operating conditions. Nowadays, newly operation or design ballasted track speed increased to 320–360 km/h, and some other even as high as 400 km/h, for example, the British High-Speed 2 (HS2) line design speed is 360 km/h and Russia's super high-speed maximum design value is 400 km/h [28]. The train speed increase is not only increasing Life-Cycle Costing (LCC), but also ballast flight risk and worsened track operation. Furthermore, HSR still confronts unsolved winter problems such as difficulties with switches, brakes, ballast pick-up, etc. [29].

This paper provides a review of research and practice regarding ballast flight risk management within the context of recent developments and experience initiatives. The main research content and the general framework of the paper are shown in Fig. 1. The first section briefly describes the mechanism and influencing factors of ballast flight. The following section studies recent developments on ballast flight, such as experiments and dynamic analysis, reliability risk assessment, and engineering measures. Finally it analyzes the mitigation management in technical solutions and risk management aspects.

2. Ballast flight

2.1. Ballast flight problem

2.1.1. Ballast flight phenomenon

Ballast flight is a phenomenon that is experienced across HSR systems throughout the world, and damage or problems are reported from railway and train companies [17,30]. This phenomenon is instigated due to train-induced mechanical and aerodynamic forces, where ballast particles detach from the railway ballast bed and cause damage to the railhead, train body, and adjacent structures, as well as causing injuries to maintenance workers and/or waiting passengers at through stations, which results in major maintenance costs and safety concerns [16,18,21], as shown in Fig. 2 and 3. The phenomenon of ballast flight is one of the major problems caused by the increase in railway speed over 300 km/h in terms of safety and deterioration of both rolling stock and railways. The phenomenon is quite recent and escalating due to the increasing velocities of high-speed trains on new high-speed lines and cross-border operations. Substantial knowledge gains have been made on this issue. The Aerodynamics in Open Air (AOA) project evaluated the problem in depth within a bilateral Franco-German scientific and technical research program (DEUFRAKO) and Aero-TRAIN project [21,31–33]. The Federal Railroad Administration (FRA) report [18] contains known occurrences of ballast flight which can be used for research and analysis. However, current ballast flight research and risk mitigation methods are not sufficient in the face of the increasing speed and complexity of operating conditions.

2.1.2. Ballast flight in extreme cold zone

Ballast flight is prone to happen in winter, when the consequences are also more serious. Former studies suggest that ballast impacts as a consequence of trains dropping ice and snow are one of the largest winter problems in Japan, the Nordic region, and northern China [34–36]. The occurrences of dry snow and temperature changes are two steps causing ballast flight due to collision with snow and ice fragments [29]. The dry and light snow can whirl around and cling to the train while running. This phenomenon causes snow packing, as shown in Fig. 4. The trains carrying snow then enter a warmer region and the heat and vibration cause the snow to melt. The frozen ice/snow then drops at high speed from the train, causing the ballast to fly up and seriously damage the car body and the environment along the track [37,38].

2.2. Ballast flight mechanism

Ballast flight is understood to be a combination of mechanical and aerodynamic effects [24], as illustrated by Fig. 5. Under high-speed train dynamics and aerodynamics, the ballast particles vibrate into loose contact or free of interlock, become detached from the ballast bed, and relocate to some extent. If the train speed, increased aerodynamic wind, and ballast vibration loads reach a critical state, it will result in sufficient momentum to lead to ballast flight. However, the individual contributions of particular

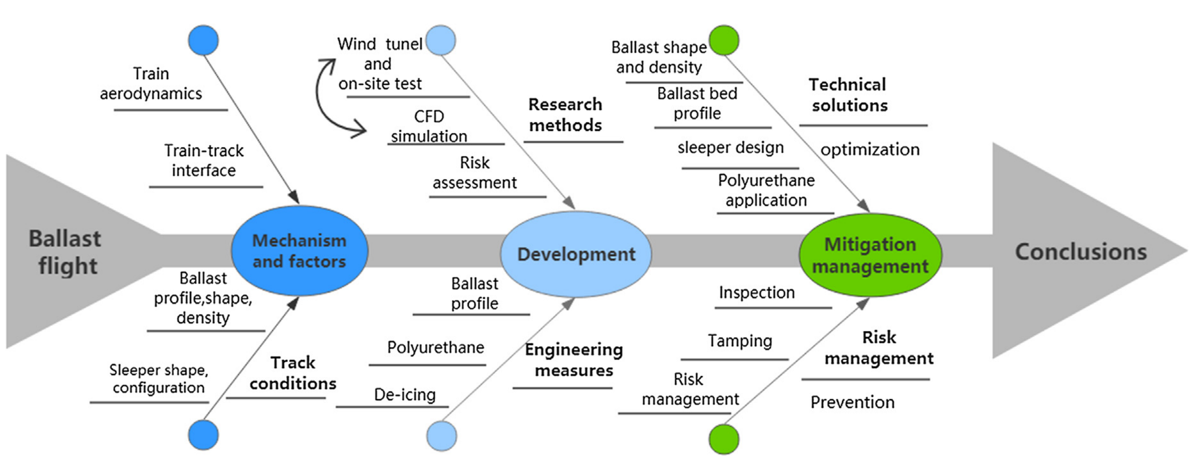


Fig. 1. Outline frame map.

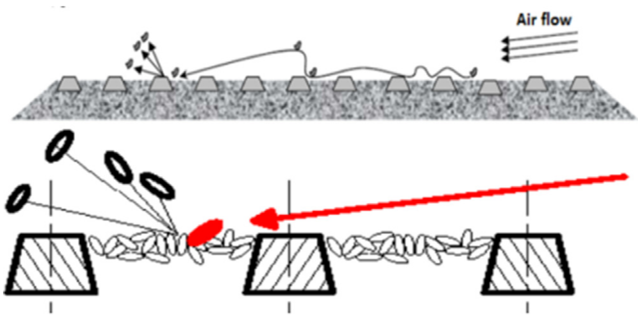


Fig. 2. Ballast flight caused by aerodynamics and/or melting ice.

Fig. 3. The consequences of ballast flight [23].

factors are hard to determine because there are so many interacting factors. For example, the risk of ballast flight is also affected by atmospheric conditions and ballast material effects.

Jing et al. [24] used a simplied equilibrium to detect the key parameters of ballast aerodynamic and dynamic effects. The relationship between particle acceleration a_T and gravity acceleration g, vertical vibration acceleration a, and wind loads $U(A)$ can be described by:

$$a_T = \frac{\alpha \int_0^A U(A)dA}{m} - (g - a) \tag{1}$$

where A is the effective area of wind loads on the ballast and α is the wind pressure coefficient. The state of ballast particles can be judged by the value of a_T. There are also several models that can be used to analyze the mechanism of ballast flight, which are summarized below in Table 1.

2.3. Influencing factors of ballast flight

The probabilistic occurrence of a ballast flight event can be modeled as a combination of two sub-events: the displacement of ballast particles from their rest positions, and the displaced ballast particles acquiring enough momentum to experience ballast flight. Fig. 6 shows an influence diagram that outlines the four major risk-frequency factors that can contribute to overall ballast flight risk. The chance that a ballast displacement will occur is affected by the atmospheric conditions, train aerodynamics, track responses, and ground effects. If ballast displacement occurs, the possibility of ballast flight is influenced by the train aerodynamics and track responses. Furthermore, some important relevant influencing factors are described in the below sections.

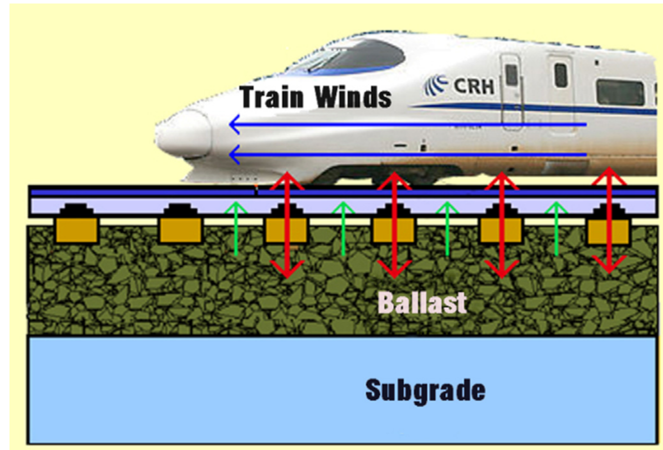


Fig. 5. Ballast flight mechanism.

2.3.1. Train speed

The key aerodynamic factor is speed since the aerodynamic force is proportional to the square of the speed of the train [42]. It is commonly held that ballast flight occurs beginning at speeds around 300 km/h [16,27,43]. However, there is a ballast flight was reported by the Federal Railroad Administration (FRA) with a speed of less than 160 km/h [14,18].

The effect of train speed was also evaluated by filed tests; for example, the wind pressure distribution of the CRH2-15C of China under different speed conditions. The results were similar to existing research: wind pressure which causes ballast particles moved increases with train speed [44]. Researchers at the Korea Rail-Road Research Institute developed a Kiel-probe array system and used it to investigate the actual wind characteristics [11]. The field measurement results showed that when the train runs at 300 km/h, a wind gust of about 25 m/s is induced just above the tie. If the

(a) (b)

Fig. 4. Snow flies up and sticks to the under floor equipment [29]: (a) The snow whirls around the train; (b) Resulting in snow packing.

Table 1
Summary of the ballast flight mechanism [24]

References	Theoretical basis	Formula	Comments	Results
Jing [24]	Newton's Second Law	$a_T = \frac{\alpha \int_0^A U(A)dA}{m} - (g - a)$	a_T: particle acceleration A: wind loads contact area $U(A)$: wind loads α : wind pressure coefficient g: gravity acceleration a: vertical acceleration	$a_T \leqslant 0$ stable $a_T > 0$ move
Navarro [39]	Particles Rotation Dynamic	$\ddot{\theta} = \frac{1}{I}\left[\frac{1}{2}\rho A_{FR} R U^2(t) c_m(\theta) - M_p g d_{cmA} cos\theta_{cm}\right]$	$\ddot{\theta}$: angular acceleration I: the moment of inertia ρ: air density A_{FR}: plan form area R: stone dimension cm: coefficient of aerodynamic d_{cmA}: distance between centre of mass and pivoting point A	$\ddot{\theta} \leqslant 0$ stable $\ddot{\theta} > 0$ rotate
G. Saussine [40]	Stress-strength interface analysis	Y(X) = 0.00239X-8.917 $X = \frac{1}{t_2 - t_1}\sum_{i=1}^{N}\int_{t_1}^{t_2} \|\|V(t)\|\|^2 dt$	$Y(X)$: displaced grains number X: total signal power V(t): air velocity	$Y(x) \leqslant 0$ stable $Y(x) > 0$ ballast flight
BJ. Lazaro [41]	Conservation of momentum	$(\mathrm{I})\rho_B d_B^3 \frac{dV_B}{dt} = -\rho_B d_B^3 g + F_a + F_c$ (II) $\rho_B d_B^5 I_B \frac{d\omega_B}{dt} - \rho_B d_B^5 (I_b \times \omega_B)\omega_B = M_a + M_c$	Eq(I): linear momentum Eq(II):: angular momentum	–

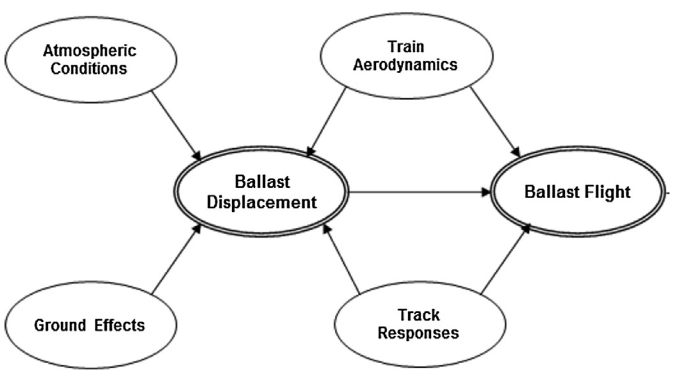


Fig. 6. Ballast flight risk influence diagram [18].

train runs at 350 km/h, the wind gust just above the tie increases to 30 m/s.

2.3.2. Train-track interface

Ballast flight can cause very serious damage to the train underframe due to the impacts of the ballast lifted by the under-hood flow generated by the train itself. Numerical and experimental approaches have been used to study the problem, giving special attention to the analysis of the under-body flow [16,21,31,45–48]. For example, the DB and Bombardier carried out experiments to measure the slipstreams at trackside behind a variety of high-speed trains (approximate speeds of 300 km/h) on the Madrid-Barcelona line using arrays of ultrasonic anemometers, together with measurements of ambient conditions. [31]. The research focuses not only on the streamline of the train, but on the underflow or underside of the brain's structure and its aerodynamics, especially the interaction with the ballasted track's shallow ballast particles. Further development and research interest could be developed by the Discrete Element Method (DEM) and Computational Fluid Dynamics (CFD) method to investigate the ballast particle aerodynamic effects under the underframe.

2.3.3. Ballast profile, size, shape, density

The aerodynamics of ballast profile should be considered for HSR ballasted track design. In recent research [49], the ballast bed cross-section aerodynamic effects were investigated by wind tunnel tests and CFD simulations, as shown in Fig. 7. The results show that the shoulder height and shape are correlated to aerodynamic effects, such that the smaller the shoulder height, the smaller the wind pressure. It should be noted that the shoulder height provides an important portion of the resistance force of the sleeper, up to 40% [50]. The above issue and findings result in a balance of ballast flight risk and Continuous Welded Rail (CWR) stability.

Ballast size and shape is also an influencing factor of ballast flight. Ballast particle size and shape not only influence the shear resistance and CWR stability, but also the ballast flight characteristics. Kwon et al. [11] performed an analysis of ballast particles being displaced in a wind tunnel setting. They found that the size of the particle had a direct relationship with its likelihood of being picked up by wind. Specifically, the less the ballast particle weighed, the higher the likelihood of the particle being picked up by aerodynamic forces.

Ballast material density has also proven to be a factor related to ballast flight. The theoretical calculation by Jing et al. [24] demonstrated that the higher the density of ballast particles, the less potential there is for ballast flight. Similar results were found by Qie et al. and Navarro et al. [44,51]. A similar research project of the ADIF [52] was carried out to analyze the on ballast flight on

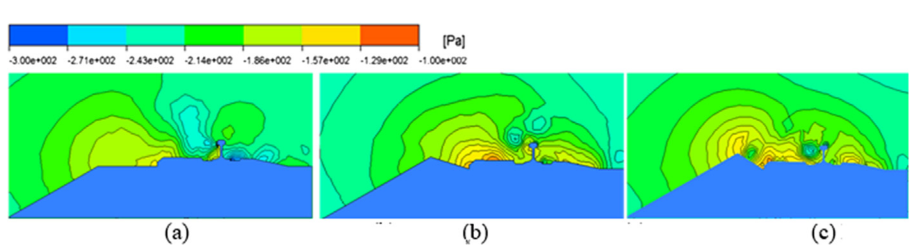


Fig. 7. Relationship between ballast aerodynamic and profile [49]. Ballast shoulder height: (a) 0 mm; (b) 100 mm; (c) 150 mm.

Fig. 8. HSR site test of ballast flight [52].

high-speed lines, as shown in Fig. 8. The movement of ballast particles were measured by high speed cameras and the optimal density and shape of the particles were studied by the research.

2.3.4. Sleeper shape and configuration

There is some research, like sleeper type and design, that are also related to ballast flight, for example, the risk of ballast flight for a bi-block sleeper is lower because there is no ballast on the mid of sleeper. ADIF has developed a new aerodynamic sleeper [53], as shown in Fig. 9a, which claims a 50% reduction in ballast flight risk. It should be noted that the aerodynamic sleeper not only reduces the wind vortex but also the possibility of ballast resting on the sleeper surface after the tamping work. Furthermore, there is also a popular method for ballast flight reduction. Lowering the ballast profile by 20 to 30 *mm* below the sleeper top, as shown in Fig. 9b, is a risk mitigation strategy adopted by several countries. As discussed previously, ballast particles are less prone to be picked up when there is a distance between the ballast and the sleeper top surface, where there is a high risk of ballast flight. There are also non-economical ballast flight measures based on changing sleeper configuration, like increasing sleeper numbers or the use of broad sleepers.

3. Recent development on ballast flight

3.1. Test and dynamic analysis

3.1.1. Wind tunnel tests

Kwon et al. [11,54] conducted wind tunnel experiments that analyzed ballast flight as caused by strong winds from the passage of high-speed trains, as shown in Fig. 10. About 1000 ballast particles were collected from the high-speed line between Seoul and Busan, and 330 of them were classified according to their mass and shape. The particles were then placed in a wind tunnel, where the researchers analyzed the relationship between their mass and shape properties and the aerodynamic effect. During the tests, the researchers increased the wind speed and observed when particles started to move as a function of their ballast mass. Similar research was carried out by Jing et al. [15]. Their studies results indicated that non-cubic and small ballast particles are easily lifted by the wind. The larger the wind effect area, the higher the possibility of ballast flight for ballast particles of the same mass. This signifies that the flat ballast particles are more easily projected by wind, which requires further investigation into the shape index of ballast material specifications.

Saussine et al. [55] performed a full-scale laboratory test to reproduce a ballasted track, the geometry of the train underfloor, and the gust effect. To simulate the gust effect, a special shutter system was installed on the track model. The underbody design of the train is a significant parameter. Two aerodynamic effects that are important are the pressures generated by the train on the ballast and the induced airspeed under the train. The existence of cavities, such as those that occur near the bogies, and generalized underbody roughness with low clearances between the train and the track ballast exacerbate the ballast flight problem. Smoothing the train underbody profile permits lower clearances to the ballast level and reduces the likelihood of ballast flight, as well as beneficially reducing aerodynamic drag. Similar wind tunnel tests has also been carried out by Premoli et al. [21] and Kaltenbach et al. [56].

3.1.2. On-site tests

The railway aerodynamics project mainly addressed are open air pressure pulses, aerodynamic loads on track (ballast pick-up), crosswinds, train-tunnel interaction (loads on conventional trains and micro-pressure wave phenomena), and slipstream effects. A measurement campaign was carried out on the Spanish high-speed line between Madrid and Barcelona [31], as shown in Fig. 11.

Agretti et al. [23] was certifying the newly constructed high-speed line between Rome and Naples. Tests were conducted using a standard ETR 500 train set in its typical composition of 11 cars and two locomotives. At 270 km/h, damage occurred to the lateral car body and the rail. Sudden impacts to the train were felt at approximately the fourth or fifth car of the train set. Stones were found embedded in the nose of the locomotive. However, no damage was reported at speeds below 260 km/h.

Quinn et al. [14] measured air velocity and pressure at the underbody of a 20-car Eurostar Class 373 high-speed train in an inertial reference frame with sensors mounted to the tracks. The experiments also find the damage to the railhead when the trains running in excess of 160 km/h, as shown in Fig. 12.

In another study, Quinn et al. [57] observed an increase in pressure when the leading end of the train passes the location of the sensors followed by a decrease in pressure shortly after passing. They found no discernible variation in mean air speed lateral to the tracks. The mean measured airspeed was 5% of the train speed when the leading end of the train passed, and increased to stay between 30% and 40% of the train's speed after five car lengths. After the 20th car passed, the measured velocity decayed towards zero.

Kwon et al. [11] conducted a separate field investigation based on the track to measure the flows generated by the passage of Korea Train Express (KTX) trains at a speed of 300 km/h. The study concluded that geotechnical effects (ground accelerations) alone are insufficient to cause ballast flight: the cause is probably a combination of aerodynamic and ballast acceleration effects. Video recording showed a pulse of air, which is quite turbulent, traveling in front of the train, which may give rise to downward force into the ballast. Meanwhile, the pressure on the ballast particles and the displacement of ballast particles can be obtained by the wind pressure transducer and the displacement transducer respectively.

Ido et al. [58] measured air velocity in an inertial reference frame at the center of the underbody, i.e. halfway between the

(a) (b)

Fig. 9. (a) A new aerodynamic sleeper [53] and (b) a ballast flight preventive measure [18].

(a) (b)

Fig. 10. Ballast in wind tunnel [11]: (a) Before test; (b) After test.

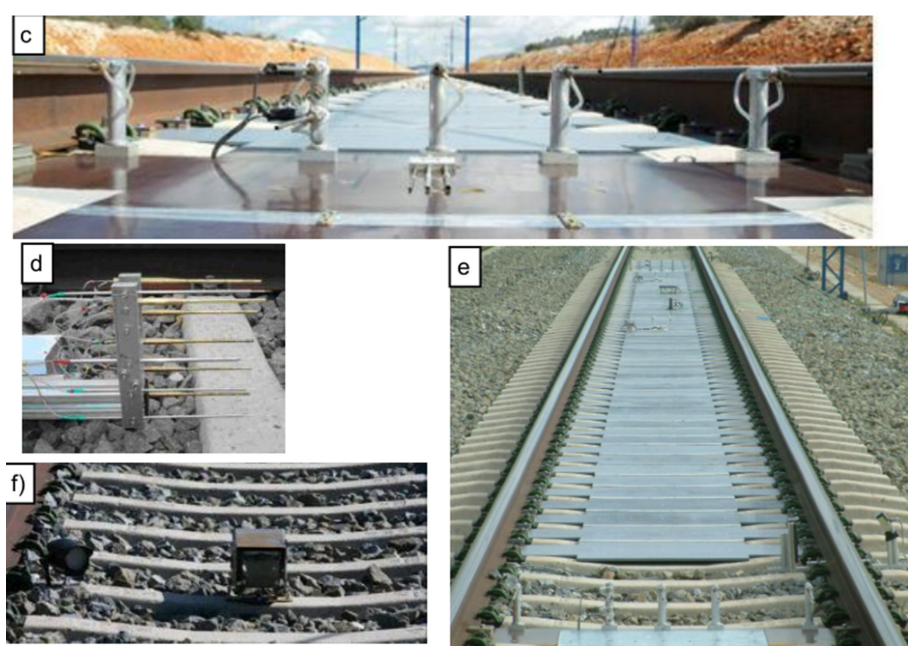


Fig. 11. Site test on the Spanish high line [31].

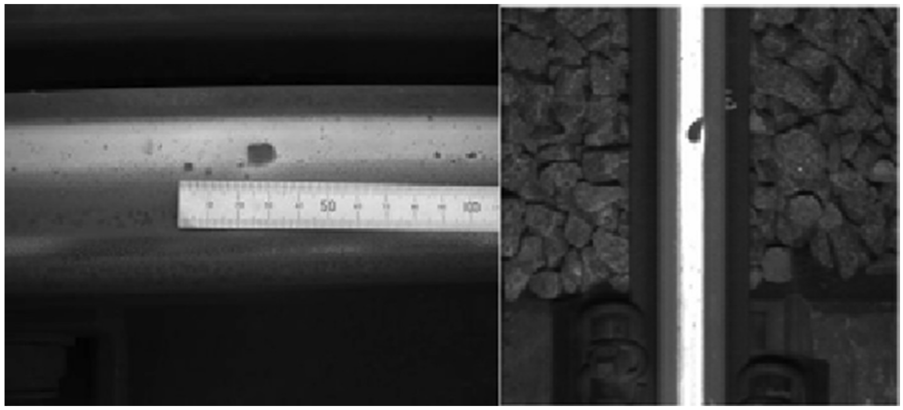


Fig. 12. Ballast pitting damage observed on UK's HS1 railhead [14].

wheels, of a 16-car Shinkansen high-speed train at different elevations relative to the undercarriage. They found that the velocity in the gap between the undercarriage and the ground has the characteristic S shape of a turbulent Couette flow, with a mean airspeed of about 50% of the train speed at a location halfway between the ground and the underbody. They also found that altering the underbody geometry can significantly alter the underbody air speeds.

3.1.3. Train aerodynamic analysis

Various researchers [9,42,59,60] used theoretical and CFD analysis to tackle unsteady flow phenomena related to high-speed trains, comparing with the experiments results, to achieve a better understanding of the physics behind ballast flight. C. Baker et al. [10,61] presents a wide-ranging review of train aerodynamics. In the study, they presented a detailed description of the flow field around the train and identified a number of flow regions. The effect of crosswinds and flow confinement was also discussed, and these include aerodynamic resistance and energy consumption, aerodynamic loads on trackside structures, the safety of passengers and trackside workers in train slipstreams, the flight of ballast beneath trains, the overturning of trains in high winds, and the issues associated with trains passing through tunnels. Brief conclusions are drawn regarding the need to establish a consistent risk-based framework for aerodynamic effects.

3.2. Reliability risk assessment

3.2.1. Ballasted track dynamic effects

It is clear that ballast flight is a sporadic phenomenon which is difficult to predict or to characterize under real conditions [58,62]. The relevance and accuracy of these results obtained under idealized conditions for the situation on the real track bed is not clear. However, characteristics of individual ballast particles vibration-tested in the ballast bed have proven to be a significant, direct, and simple index. Andres Lpez-Pita et al. [63–65] found that the increase in ballast acceleration is the aspect of most concern, and measures developed to reduce ballast acceleration could be used to reduce ballast flight, such as high elastic fastener and pad, sleeper optimization, asphalt sub-ballast layer, etc.

3.2.2. Reliability and risk evaluation

This sporadic and random ballast flight phenomenon is difficult to characterize by in-lab or in situ tests, however, the statistic or reliability methods are required to propose solutions to limit the phenomenon [14,24]. Some risk assessment analysis models have been developed, and these are summarized in Table 2.

Kwon et al. [11] developed a risk model based on the behavior of the ballast under high wind conditions. In this model, the Ballast Flight Probability Factor (BFPF) serves as a quantitative measure of the likelihood of ballast flight. The results showed the calculated probabilities for trains traveling at 300 and 350 km/h, and the mass of the ballast particle was also considered. Saussine et al. [27] further developed a risk assessment model that takes into account flow field measurements on commercial speeds, numerical development of ballast motion under an aerodynamic load using a discrete element approach, and the Stress Strength Interference Analysis approach, as shown in Fig. 13. The model was calibrated using different train types, leading to different experiences of flying ballast at operational speed. The method relies on pass-by line measurements of the aerodynamic field created by the train underneath the car-body and is calculated using a discrete element model of the probability of ejection of ballast grains.

Deng et al. [66] developed a Probabilistic Risk Analysis (PRA) model based on the information available from the field and the literature. The model enables a quantitative assessment of the probability of ballast particle displacement at a particular position on the track, as well as the probabilistic distribution of the total number of ballast particles that are expected to move. The model also accounts for various risk factors, such as train speed, ballast gradation, and track position. Shao et al. [67] conducted a probabilistic assessment of the ballast flight formation process using the Monte-Carlo approach. Similar probabilistic assessment of ballast flight has been developed by Rueter et al. [68] and Jing et al. [69].

3.3. Engineering measures

This section discusses engineering measures to reduce the ballast flight risk. It should be noted that different methods and materials result in different Reliability, Availability, Maintainability, and Safety (RAMS) results; therefore, the best choice depends on a comprehensive evaluation of speed, weather, and economic factors.

3.3.1. Ballast profile

Track engineering measures could be developed to reduce the risk of ballast flight. Some measures are often used in engineering: compacting and stabilizing the top layer of ballast; ensuring that ballast aggregates are washed and free of dust; reducing shoulder ballast height while maintaining CWR stability; and decreasing the ballast airflow interaction to diminish the aerodynamic effects. The crib ballast top should be 2–4 cm lower than the sleeper top level and larger ballast aggregates are preferred on top of the ballast bed surface (as this affects ballast tamping); moreover, ballast should

Table 2
Summary of the ballast flight risk assessment methods.

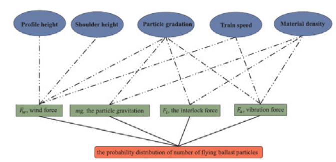
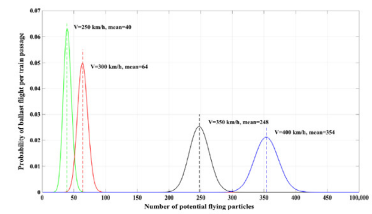
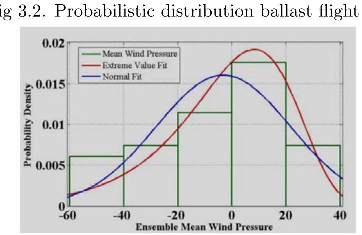
<table>
<tr><th>Reference</th><th>Models</th><th>Contents</th><th>Results</th></tr>
<tr><td>Kwon et al. [11]</td><td>Ballast Flight Probability Factor (BFPF)</td><td>(1)$Vtrack < Vmin$,BFPF = 0,no ballast flight;
(2)$Vtrack > Vmax$,BFPF = 1, ballast flight;
(3)$Vmin \leq Vtrack \leq Vmax$
$BFPF = \int_{m_1}^{m_2} \frac{Vtrack-Vmin}{Vmax-Vmin}\frac{1}{m_2-m_1}dm$</td><td>Table 3.1. BFPF related to train speed and ballast mass<table><tr><th rowspan="2">Train speed</th><th colspan="4">Ballast mass (g)</th><th rowspan="2">Total</th></tr><tr><th>0-50</th><th>50-100</th><th>100-150</th><th>150-200</th></tr><tr><td>300</td><td>39.80%</td><td>19.70%</td><td>11.50%</td><td>14.70%</td><td>24.20%</td></tr><tr><td>350</td><td>64.30%</td><td>43.30%</td><td>32.80%</td><td>33.60%</td><td>46.10%</td></tr></table></td></tr>
<tr><td>G.Saussine et al. [27]</td><td>Stress-Strength Interference Analysis</td><td>R: strength and C: stress
$P_d = P(R < C) = P(R - C < 0)$
$P_d = \int_0^{\infty} f_c(x)F_R(x)dx$
where P_d is the failure probability.</td><td>Table 3.2. The risk levels based on Stress-Strength Interference<table><tr><th rowspan="2">Stress</th><th>300 km/h</th><th>320 km/h</th><th rowspan="2">Strength</th><th rowspan="2">Ejected grains</th></tr><tr><td>22967 / 772</td><td>26000 / 1041</td></tr><tr><td rowspan="2">Risk</td><td>5,46E-05</td><td>1,44E-02</td><td>30544 / 1800</td><td>5</td></tr><tr><td>1,38E-08</td><td>8,02E-05</td><td>33848 / 1800</td><td>15</td></tr></table></td></tr>
<tr><td>Deng et all. [66]</td><td>Probabilistic Risk Analysis (PRA) model</td><td>
Fig.3.1 PRA model</td><td>
Fig 3.2. Probabilistic distribution ballast flight number</td></tr>
<tr><td>Shao et all. [67]</td><td>Monte Carlo Method</td><td>$P_f = \int_{g(X)<0} f_X(x)dx$
f_x is the probability distribution of x,
it means the random variable.</td><td>

Fig 3.3. Ballast flight probabilistic distribution of wind force.</td></tr>
</table>

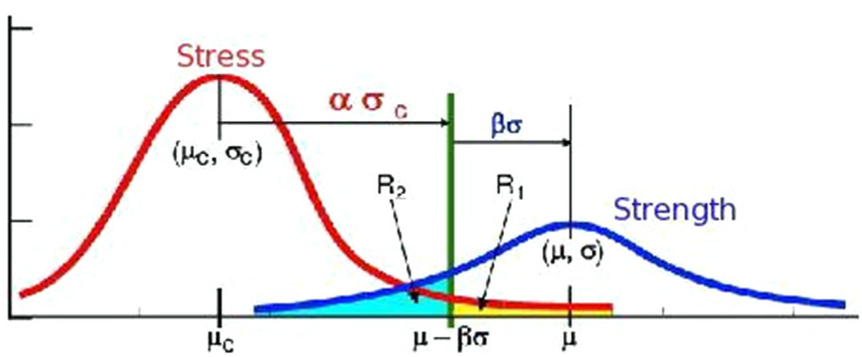


Fig. 13. Generic Stress Strength Interface Analysis [27].

be swept off the sleeper top surface, where the ballast can easily be picked up due to the higher vibration of the sleeper [24].

Lowering the ballast profile by 2–4 cm below the sleeper top is a risk mitigation strategy adopted by several countries, such as Japan, China, France, and Spain [7,70,26,71]. As discussed previously, ballast particles are more prone to be picked up if on the surface of the sleeper. This solution has appeared to have good results, but in France, this solution caused an increase in the tamping frequency. This could be explained by the fact that a lower ballast profile also implies a lower lateral resistance. It should be noted that the ballast shoulder height reduction leads to a tamping maintenance frequency increase, and results in a potential lack of lateral resistance for the Continuous Welded Rail, as well as the crib ballast reduction. All the potential ballast profile engineering methods should be tested with reference to Le et al. [50], which investigates ballast-sleeper interactions.

3.3.2. Polyurethane or bagging

The polyurethane system is a conventional method applied for HSR, especially for the transition zone. The ballast polyurethane is currently used in China, which is proving to be effective but lacks longtime application data, such as tamping maintenance. D. Ding. [49] demonstrated ballast settlement using polyurethane bonding. A half-structure 1:1 mode is tested in a wind tunnel. Results show, after bonding, ballast displacement did not occur when wind speed were increased to 30 m/s, corresponding to a 350 km/h train passing. The China Academy of Railway Sciences (CARS) conducted the first site test of the 350 km/h speed class polyurethane track bed on the Ji-Qing high-speed railway line, as shown in Fig. 14. The highest test speed reached 385 km/h, yet without ballast flight [72].

Furthermore, Jing et al. [73] used full-section surface bonding in order to prevent ballast flight, considering maintenance availability, spraying at the surface to a depth of 60 *mm*, as shown in Fig. 15. This method aims to solve the ballast flight problem by bonding the ballast particles to the surface so that they cannot move. At the same time, the method can increase the lateral resistance by 17%, which is enough to maintain track stability. The test showed that full-section surface bonding does not influence tamping maintenance because of the lower bonding depth.

Ballast bagging is another risk mitigation strategy tested in Japan on those sections of the Shinkansen with ballasted track [71,74]. If this solution is employed, the ballast particles are contained within the bag and no ballast flight can occur. However, the bags need to be removed and replaced for track maintenance.

3.3.3. Train body streamline design

The structure of the bottom of the train directly affects the safety and performance of the high-speed train. The bottom of the train, especially the raised parts such as the bogie, squeezes the air, causing high-speed turbulence, which can easily cause ballast flight [31,33]. Current developments in train design for ballast protection and reduction of ballast flight include: reducing the gaps between cars; minimizing the cavities in the bodies and the underfloor antenna region; designing underfloor components with integrated armor; and installing intercar deflectors and additional deflectors at the bogie cavities to reduce air turbulence.

3.3.4. De-icing operations at snow zone

Snow dropping from high-speed trains can have negative effects: the dispersion of ballast by the impact of falling ice lumps, damage to places along railway tracks, glass breakage in vehicles, and damage to ground equipment [29,37,38].

Speed reduction is the most effective measure to reduce ballast flight in winter. For example, on the HA-DA railway across northern China, the minimum temperature is $-40^{\circ}C$, so the rail maintains a winter maximum speed of 200 km/h and a summer speed of 300 km/h. By combining vehicle side measures and ground side measures, the amount of snow adhesion can also be minimized. Such measures include [29]:

- Expansion of ballast screen installations.
- Protection of ground equipment.
- Snow removals by hand and by hot water jet device.
- On-train measures, such as electric heaters and air conditioners.

3.3.5. In practice

In France, the turbulent zones occurring between the power car and end trailer were reduced (this was achieved on the V150 train), and the front and rear shapes of the interface between two trains coupled in multiple was also researched to alleviate this highly turbulent zone. The ballast's behavior at this level on a line or section of the line given the following two modifications and upgrades [27,75]:

- Lowering of the ballast level between sleepers by 50 *mm*.
- Blowing or bushing off of ballast from the sleepers.

After employing these methods, Claus (2008) [30,76]reports that SNCF did not record any ballast flight incidents over the past 20 years, and no ballast flight was observed or recorded during 2007 test runs performed by the TGV V-150, when it successfully achieved the world speed record 574.8 km/h.

In order to prevent ballast flight, further measures were taken on China's Hefu HSR with a maximum speed of 330 km/h, as follows [77]:

- Ballast washed, cleaned, and meeting gradation requirements;
- A ballast shoulder width of not less than 0.5 m, with the ballast shoulder flush with the top surface of the sleeper;
- Lowering of the ballast level based on position: In the middle of the sleeper: a ballast level 20 *mm* below the top surface of the sleeper; at the bottom of the rail: a level 40–50 *mm* below the rail bearing surface; and in the turnout area: a level 40–50 *mm* below the top surface of the sleeper.

4. Mitigation management

4.1. Technical solutions

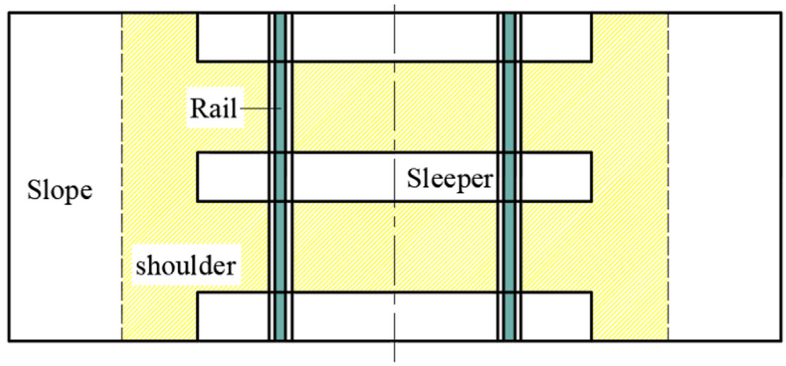
4.1.1. Ballast bed profile

Ballasted track with ballast above sleeper levels contributes to the ballast flight problem. It is acknowledged that reducing clearances between the ballast and train, and increasing air speeds under the train make ballast stones more vulnerable to aerodynamic effects [11,14,21]. There is thus a trend to reduce the ballast shoulder and crib level with speed increase; for example, the China HSR ballasted track standard presented in Table 3. However, this solution comes with a tradeoff for CWR and lateral resistance stability.

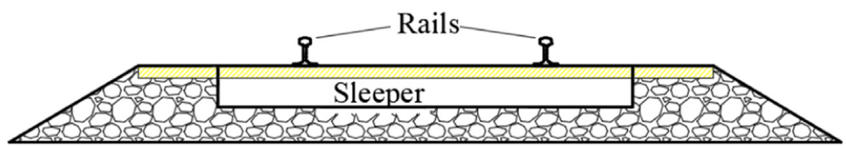
4.1.2. Ballast shape and density

Based on former research [11,15,78,79], both the wind tunnel tests and ballast flight mechanism indicate heavy ballast or high-density ballast aggregates mitigate the problem of ballast flight

Fig. 14. Polyurethane ballasted track in the Ji-Qing line [72].



(a)



(b)

Fig. 15. Full-section surface bonding [73].

on high-speed lines. The results of these studies illustrate that ballast density could be an additional parameter for HSR ballast selection, standardization, etc., eliminating the lower density but harder ballast currently employed. The optimal shape of ballast should also be investigated further and calibrated according to aerodynamic effects in addition to the common rules of CWR stability. On the other hand, new materials for HSR ballast resources are now available; for example, slag ballast: coarse aggregate sizes of air-cooled blast furnace slag and steel slag that are used on HSR tracks, which cause no problems for electrical resistance, durability, and stability, while having a higher unit density than common ballast aggregates [80,81].

4.1.3. Sleeper design

The shape and type of sleeper used may affect the ballast flight phenomenon. The risk of ballast flight may be lower with the bi-block sleeper because the connecting steel is embedded within the ballast. For example, the ADIF has developed a new type of sleeper as part of a project named Aurigidas [53]. According to early results of tests conducted at speeds up to 320 km/h, the rounded shape of the sleeper appears to mitigate the turbulent flow generated by the train. Furthermore, the ballast stones do not easily settle on the sleeper's rounded surface during tamping work, leaving less loose ballast on the sleepers.

The frame sleepers are supposed to be effective methods to reduce ballast flight for speeds above 400 km/h, with CWR stability maintained as well [82]. The frame sleeper designs were based on the addition of prominent wings around the sleeper in order to bolster some of the contributing components of lateral resistance. These frame sleepers are illustrated in Fig. 16. The frame sleeper's interaction with the ballast bed is of signal importance in shape optimization and application to super high ballasted track, and most importantly, the ballast profile, like shoulder and crib ballast, could be lowered to -50 *mm* or more.

Table 3
China HSR ballasted track standard of ballast bed profile.

Speed	Shoulder height	Required Lateral resistance
200–250 km/h	150 mm	>10 kN/sleeper
250–300 km/h	100 mm	>12 kN/sleeper

4.1.4. Polyurethane application

Innovative technical solutions have also been developed by using polymers for the same objective of improving ballast lateral stability and preventing ballast from displacement [83–85]. Reinforcement using polyurethane has several advantages, such as stabilization of the ballast bed, protection of the ballast bed from loosening to prevent ballast flight, increased resistance of the ballast bed, maintenance of the structure of the ballast bed, and stiffness variation of the ballast bed [73,86,87]. Polyurethane reinforcement and adjustment of ballast bed stiffness has successfully been used in China's HSR transition zone, mitigating ballast flight problems. However, the existing polyurethane reinforcement application to ballast beds results in maintenance problems, such as tamping and replacement, when the polyurethane was injected widely and extensively throughout the ballast bed, especially to the entire surface, becoming quasi-solid and costly. The optimal application of polyurethane to ballast beds could be an appropriate solution, since it allows tamping at the same time as a flexible increase in lateral resistance due to specific injection both in position and depth; for example, polyurethane partially sprayed on shoulder and crib, as illustrated in Fig. 17.

Another proposed method of polyurethane application against ballast flight is surface application, which is similar to the above method but relatively soft and capable of tamping. In studies, the soft polyurethane was injected into the ballast bed top surface, and lateral resistance, tamping, and wind tunnel tests were performed to observe the low-strength polyurethane effects. The results show that it is an effective ballast flight prevention method which does not affect the tamping.

4.2. Operational management

4.2.1. Speed reduction

The simplest mitigation strategy would be to reduce the speed of the trains [18]. This solution, however, may defeat the main

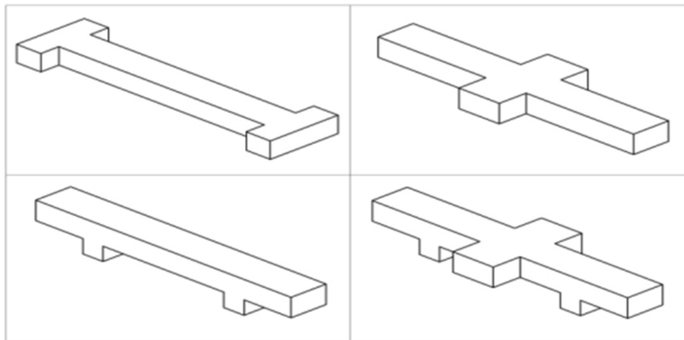


Fig. 16. The frame sleepers.

purpose behind high-speed lines. In France and other countries where snow affects the performance of the high-speed lines, there are provisions that mandate temporary speed reductions during bad weather conditions [29,89]. However, for lines that do not have extreme weather, speed reduction is usually not employed as a mitigation strategy.

4.2.2. Inspection

Inspection is an important and necessary method of reducing ballast flight during HSR operation. Ballast flight is a process of ballast relocation and displacement and could be caused by ballast profile geometry variation, hanging sleeper, and dynamic index as well [14]. The International Union of Railways (UIC) [90] recommended the verification and inspection of the ballast's profile to be taken every two weeks by senior technicians.

4.2.3. Tamping

Tamping could potentially affect the likelihood of ballast flight due to ballast stones settling on the sleeper surface. The presence of ballast particles on the top of the sleeper is believed to be an important factor in causing ballast flight. Poor and infrequent maintenance of the track increases the risk of finding ballast particles on the top of the sleeper, and SNCF believes that ballast flight is most likely to occur at the top of the sleeper, recommending that sleepers should be free of ballast stones on their surface. As a result, tamping plays a direct role in ballast flight, and sweeping should be regularly performed after stabilization or tamping. Incidences of ballast flight were reported when the first high-speed train passed on a recently maintained track [89], while subsequent passes did not result in any observed ballast flight, since the ballast particles that were present on top of the sleepers had been swept away. Thus, there is a need to carefully clean ballast particles from sleepers.

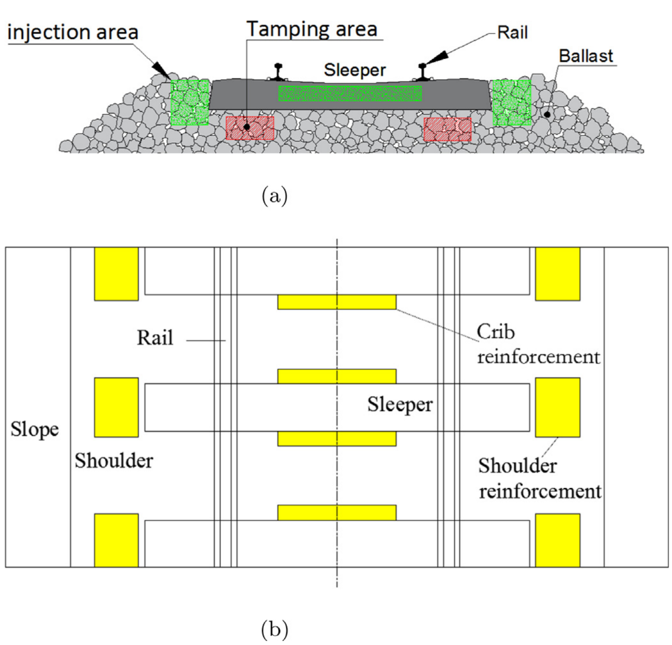


Fig. 17. Specific section bonding [88]: (a) Injection and tamping area of ballast track; (b) Specific section bonding.

4.2.4. Risk assessment and management

Ballast flight risk for specific operation speeds and lines should be developed for safety and cost [15,66]. It is important to develop quantitative tools to estimate the probability of ballast flight on specific lines given certain operating conditions, accounting for risk factors such as train aerodynamics, track responses, and weather conditions. Based on a reliability assessment, HSR operators will be able to make related operation decisions according to a reliability index that quantitatively describes ballast flight risk, and this index should also account for the consequences of ballast flight as well. This methodology and tool would enable a cost-effective and safety-enhancing relative risk assessment for properly managing HSR operations [27].

5. Conclusions

The high-speed railway can exhibit the phenomenon of ballast flight, which is an important reason for restricting the development of ballasted track. This review is focused on the ballast flight mechanism, influencing factors, analytical and engineering methods, as well as risk management. Through the systematic analysis of the ballast flight problem, many technical and risk management solutions can be applied.

- Technical solutions. Sleepers are an important factor correlated with ballast flight, and innovative sleepers like frame sleepers, frictional sleepers, and aerodynamic sleepers could be developed for ballast flight risk reduction. The ballast profile should be optimized, including shoulder and crib ballast, while maintaining the balance between ballast flight risk and CWR stability. Ballast aggregates' physical characteristics like size, shape, and density should be further considered for ballast material selection; in particular, the flakiness index and density could be employed as additional standard parameters for HSR ballast. Polyurethane material could be used to reduce ballast flight risk either by partial or surface injection.
- Operational management. For lines that have extreme weather, speed reduction is usually employed as a mitigation strategy. Ballast bed inspection could be a useful prevention method to reduce ballast flight. In particular, the development of quantita-

tive tools to evaluate the probability of ballast flight on specific lines given certain operating conditions is a crucial method of enhancing HSR operators' decision-making.

Acknowledgement

Research was supported by Natural Science Foundation of China (51578051) and China Scholarship Council.

References

[1] C. Esveld, Modern railway track, 2nd editon,., Delft university of Technology, 2001.
[2] P.-E. Gautier, Slab track: Review of existing systems and optimization potentials including very high speed, Constr. Build. Mater. 92 (2015) 9–15.
[3] C. Esveld, Recent developments in slab track, Eur. Railway Rev. 9 (2) (2003) 81–85.
[4] K. Ando, S. Miura, J. Okazaki, M. Sunaga, H. Aoki, O. Maruyama, Development and practical use of concrete roadbed for slab track on earthworks, World Transport Research: Selected Proceedings of the 8th World Conference on Transport ResearchWorld Conference on Transport Research Society, vol. 2, 1999.
[5] D.N. Bilow, G.M. Randich, et al., Slab track for the next 100 years, in: 2000 Annual Conference Proceedings of American Railway Engineering and Maintenance of Way Association, 2000.
[6] K. Takagi, Development of high-speed railways in china, Japan Railway Transp. Rev. 57 (2011) 36–41.
[7] F.B. Jacobini, E. Tutumluer, M.R. Saat, Identification of high-speed rail ballast flight risk factors and risk mitigation strategies, in: 10th World Congress on Railway Research, Sydney, Australia, 2013, pp. 25–28.
[8] L. Dieleman, M. Fumey, A. Robinet, P. Ramondec, D. Martin, Experimentation of a track section without ballast on the new line of east european tgv, in: 8th World Congress on Railway Research, 2008, pp. 1–16.
[9] C. Baker, The flow around high speed trains, J. Wind Eng. Ind. Aerodyn. 98 (6–7) (2010) 277–298.
[10] C. Baker, A review of train aerodynamics part 1–fundamentals, Aeronaut. J. 118 (1201) (2014) 201–228.
[11] H. Kwon, C. Park, An experimental study on the relationship between ballast flying phenomenon and strong wind under high speed train, in: Proceedings of the World Congress on Rail Research, Montreal, QC, Canada, 2006.
[12] C. Paz, E. Suárez, C. Gil, Numerical methodology for evaluating the effect of sleepers in the underbody flow of a high-speed train, J. Wind Eng. Ind. Aerodyn. 167 (2017) 140–147.
[13] M. Jönsson, S. Loose, Experimental investigation of the flow field underneath a generic high-speed train and the effects of ground and train roughness, in: Aerodyn. Heavy Vehicles III, Springer, 2016, pp. 21–36.
[14] A. Quinn, M. Hayward, C. Baker, F. Schmid, J. Priest, W. Powrie, A full-scale experimental and modelling study of ballast flight under high-speed trains, Proc. Inst. Mech. Eng., Part F 224 (2) (2010) 61–74.
[15] G.Q. Jing, G.X. Liu, J. Lin, J. Martinez, C. Yin, Aerodynamic characteristics of individual ballast particle by wind tunnel tests, J. Eng. Sci. Technol. Rev. 7 (2) (2014).
[16] S. Giappino, A. Premoli, D. Rocchi, P. Schito, G. Tomasini, Numerical-experimental study on flying ballast caused by high speed trains, in: EACWE, 6th European and African Conference on Wind Engineering, 2013, pp. 1–8.
[17] F.P. Banko, J.H. Xue, Pioneering the Application of High Speed Rail Express Trainsets in the United States, Parsons Brinckerhoff Group Incorporated (2013).
[18] M. Saat, F. Bedini-Jacobini, E. Tutumluer, C. Barkan, et al., Identification of high-speed rail ballast flight risk factors and risk mitigation strategies-final report., Tech. rep., United States, Federal Railroad Administration (2015).
[19] J.-H. Rho, Y.-C. Ku, S.-H. Yun, H.-I. Park, H.-B. Kwon, D.-H. Lee, Ballast flying probability analysis for ballast types and underbody flow conditions, J. Korean Soc. Railway 12 (6) (2009) 829–834.
[20] J.-S. Goo, J.-S. Kim, K.-B. Shin, Evaluation of structural integrity after ballast-flying impact damage of a gfrp lightweight bogie frame for railway vehicles, J. Mech. Sci. Technol. 29 (6) (2015) 2349–2356.
[21] A. Premoli, D. Rocchi, P. Schito, C. Somaschini, G. Tomasini, Ballast flight under high-speed trains: wind tunnel full-scale experimental tests, J. Wind Eng. Ind. Aerodyn. 145 (2015) 351–361.
[22] H. Kaltenbach, P. Gautier, G. Agirre, A. Orellano, K. Schroeder-Bodenstein, M. Testa, T. Tielkes, Assessment of the aerodynamic loads on the trackbed causing ballast projection: results from the deufrako project aerodynamics in open air (aoa), in: Proceedings of the World Congress on Rail Research, Seoul, South Korea, 2008.
[23] M. Agretti, Sollevamento del ballast sulla linea av roma-napoli, F. Bedini Jacobini, Interviewer, 2012.
[24] G.Q. Jing, J. Lin, J. Zhang, et al., Ballast flying mechanism and sensitivity factors analysis, Int. J. Smart Sensing Intelligent Syst. 5 (4) (2012) 928–939.
[25] W. Powrie, J. Priest, Behaviour of Ballasted Track During High Speed Train Passage, University of Southampton, 2011.
[26] G.Q. Jing, L. Gao, X.L. Sun, Ballast flying dem microscopic analysis and counteracting measures, in: Applied Mechanics and Materials, Vol. 97, Trans Tech Publ, 2011, pp. 266–270.
[27] G. Saussine, E. Allain, N. Paradot, V. Gaillot, Ballast flying risk assessment method for high speed line, in: 9th World Congress on Railway Research-May, 2011, pp. 22–26.
[28] M. Antoni, Using lcc modelling to determine the best track choice: Minimising life-cycle costs whilst maintaining reliability, in: Cost optimisation: Track maintenance and renewals, 2012.
[29] L. Kloow, High-speed train operation in winter climate, Transrail Publication BVF5 2 (2011) 2011.
[30] P. Claus, Overview of past ballast projection incidents, Aerodyn. Open Air (2008) 77–82.
[31] M. Sima, E. Grappein, M. Weise, N. Paradot, M. Hieke, C. Baker, R. Licciardello, M. Couturier, Presentation of the eu fp7 aerotrain project and first results, in: The ninth world congress on railway research, 2011.
[32] P. Deeg, M. Jönsson, H.-J. Kaltenbach, M. Schober, M. Weise, Cross-comparison of measurement techniques for the determination of train induced aerodynamic loads on the track bed, in: Proceedings of the BBAA VI, Milano, Italy, 2008, pp. 20–24.
[33] H.-J. Kaltenbach, Wp1 underfloor aerodynamics summary report, DeuFraKo Project Aerodynamics in Open Air (AOA), 2008.
[34] N. Tahvili, Winterization of railways-issues and effects, Master's thesis, NTNU (2016).
[35] F. Michelberger, A. Wagner, M. Ostermann, T. Maly, Proposal of an intelligent wayside monitoring system for detection of critical ice accumulations on railway vehicles, IOP Conference Series: Materials Science and Engineering, vol. 236, IOP Publishing, 2017. p. 012047.
[36] J.S. Molarius, S. Toivonen, J. Keränen, J. Törnqvist, P.N. Juga, J. Rauhala, Review on extreme weather impacts on transport systems, EWENT project Deliverable, 2011.
[37] K. Kawashima, S. Iikura, T. Endo, T. Fujii, Experimental studies on ballast-flying phenomenon caused by dropping of accreted snow/ice from high-speed trains, RTRI Rep. 17 (8) (2003) 31–36.
[38] G.Q. Jing, D. Ding, Snow flight characteristic and prevention research of high speed railway in cold region, J. Railway Eng. Soc. 17 (9) (2017) 29–34.
[39] F. Navarro Medina, A.P. Sanz Andres, M.I. Pérez Grande, A. Martínez Muelas, E. Vega Ramiro, M. Rodriguez Plaza, I.J. Iglesias Dia, A. Andres Alguacil, D. Alonso Gimeno, The ballast pick-up problem. a theoretical approach and two experimental campaigns, 2011.
[40] G. Saussine, C. Voivret, N. Paradot, E. Allain, A risk assessment method for ballast flight; managing the rolling stock infrastructure interaction, Proc. Inst. Mech. Eng., Part F 229 (6) (2015) 581–593.
[41] B.J. Lazaro, E. Gonzalez, M. Rodriguez, S. Osma, J. Iglesias, Characterization and modeling of flying ballast phenomena in high-speed train lines, The ninth world congress on railway research, Lille, France, Vol. 2226, 2011.
[42] R.S. Raghunathan, H.-D. Kim, T. Setoguchi, Aerodynamics of high-speed railway train, Progress Aerospace Sci. 38 (6–7) (2002) 469–514.
[43] G. Diana, D. Rocchi, G. Tomasini, P. Schito, A. Premoli, Full scale experimental analysis of train induced aerodynamic forces on the ballast of italian high speed line, in: International Workshop on Train Aerodynamics, 2013.
[44] Q. Luchao, X. Yongxian, Theoretical calculation and experimental study on ballast flight of high speed railway, Railway Eng. (3) (2014) 88–91.
[45] J. García, A. Crespo, A. Berasarte, J. Goikoetxea, Study of the flow between the train underbody and the ballast track, J. Wind Eng. Ind. Aerodyn. 99 (10) (2011) 1089–1098.
[46] F. Cheli, D. Rocchi, G. Tomasini, Study of the reynolds effects on aerodynamic coefficients of a railway vehicle through wind tunnel tests, in: 13th ICWE International Conference on Wind Engineering, Amsterdam, The Netherlands, 2011, pp. 10–15.
[47] J. Pombo, J. Ambrósio, M. Silva, A new wheel–rail contact model for railway dynamics, Vehicle System Dyn. 45 (2) (2007) 165–189.
[48] E. Kassa, C. Andersson, J.C. Nielsen, Simulation of dynamic interaction between train and railway turnout, Vehicle System Dyn. 44 (3) (2006) 247–258.
[49] D. Ding, High Speed Railway Ballasted Track Aerodynamics Research Based on Wind Tunnel Test and CFD Simulation, 2017.
[50] L. Le Pen, W. Powrie, Contribution of base, crib, and shoulder ballast to the lateral sliding resistance of railway track: a geotechnical perspective, Proc. Inst. Mech. Eng., Part F 225 (2) (2011) 113–128.
[51] F. Navarro-Medina, A. Sanz-Andres, I. Perez-Grande, Gust wind tunnel study on ballast pick-up by high-speed trains, Exp. Fluids 52 (1) (2012) 105–121.
[52] Comsa, Adif, HD Ballast, a research project on ballast flight on high-speed lines, http://www.spanishrailwaysnews.com/noticias.asp?not=460, [Online; accessed 27-January-2014] (2014).
[53] F. Alfonso, Una traviesa inteligente protege al ave del rebote de las piedras de la via, El Economista (2013) 22.
[54] H.-B. Kwon, Y.-W. Park, D.-H. Lee, M.-S. Kim, Wind tunnel experiments on korean high-speed trains using various ground simulation techniques, J. Wind Eng. Ind. Aerodyn. 89 (13) (2001) 1179–1195.
[55] G. Saussine, N. Paradot, Full-scale tests on ballast track in wind tunnel, Aerodyn. Open Air (2008) 93–98.
[56] H.-J. Kaltenbach, I.A. Portillo, M. Schober, A generic train-underfloor experiment for cfd validation, in: BBAA VI International Colloquium on: Bluff bodies aerodynamics and applications, Citeseer, 2008, pp. 20–24.

[57] A. Quinn, M. Hayward, Full-scale aerodynamic measurements underneath a high speed train, Proceedings of the BBAA VI, Milano, Italy, 2008, pp. 1–9.
[58] A. Ido, S. Saitou, K. Nakade, S. Iikura, Study on under-floor flow to reduce ballast flying phenomena, in: Proceedings of the World Congress on Rail Research, Seoul, South Korea, 2008.
[59] S. Sanquer, C. Barre, M.D. de Virel, L.-M. Cleon, Effect of cross winds on high-speed trains: development of a new experimental methodology, J. Wind Eng. Ind. Aerodyn. 92 (7–8) (2004) 535–545.
[60] K. Liu, E. Reynders, G. De Roeck, G. Lombaert, Experimental and numerical analysis of a composite bridge for high-speed trains, J. Sound Vib. 320 (1–2) (2009) 201–220.
[61] C. Baker, A review of train aerodynamics part 2–applications, Aeronaut. J. 118 (1202) (2014) 345–382.
[62] H.-B. Kwon, C.-S. Park, A study on the ballast-flying phenomena by strong wind induced by high-speed train, J. Korean Soc. Railway 8 (1) (2005) 6–14.
[63] E.A.L. Pita, Ballast vibration makes new designs for high speed lines advisable, in: Proceedings of the 5th World Congress on Railways Research, Cologne, Germany, 2001.
[64] A. López-Pita, P.F. Teixeira, C. Casas, L. Ubalde, F. Robusté, Evolution of track geometric quality in high-speed lines: ten years experience of the madrid-seville line, Proc. Inst. Mech. Eng., Part F 221 (2) (2007) 147–155.
[65] A. López-Pita, F. Robusté, Effect of very high-speed traffic on the deterioration of track geometry, Transp. Res. Record 2003 (1825) 22–27.
[66] J.Y. Deng, X. Liu, G.Q. Jing, Z.Y. Bian, Probabilistic risk analysis of flying ballast hazard on high-speed rail lines, Transp. Res. Part C 93 (2018) 396–409.
[67] S. Shao, G. Jing, H. Yin, Ballast flight risk assessment based on reliability theory, Int. J. Simul.-Syst., Sci. Technol. 17 (36) (2016).
[68] A. Rüter, K. Schroeder-Bodenstein, Probabilistic assessment of the formation of ballast projection, Aerodyn. Open Air (2008) 105–112.
[69] J. GuoQing, D. Dong, S. Shuai, Reliability assessment on high speed railway ballast flight based on monte carlo, J. Railway Sci. Eng. 13 (7) (2016) 1234–1240.
[70] G. Saussine, E. Masson, T. Jaques, N. Paradot, E. Allain, F. Josse, Railway ballast flying phenomena–from numerical simulation towards risk assessment, EUROMECH Colloquim 509, 2009.
[71] M. Yhshida, M. Uchida, N. Yaguchi, N. Mifune, Countermeasures for ballast-flying phenomena caused by high-speed trains, RTRI Rep. 6 (6) (1992) 6.
[72] RailWorld, The speed of 350 km/h high-speed rail has a successful track verification, https://t.cj.sina.com.cn/articles/view/1002429827/3bbfdd8301900fczr, [Online; accessed 24-December-2018] (2018).
[73] G.Q. Jing, W.L. Jia, H. Fu, L.H. Ying, Numerical study on the aerodynamic performance and safe running of high-speed trains in sandstorms, J. Railway Eng. Soc.
[74] T. Fujii, K. Kawashima, S. Iikura, T. Endo, R. Izunami, Preventive measures against snow for high-speed train operation in japan, in: Cold Regions Engineering: Cold Regions Impacts on Transportation and Infrastructure, 2002, pp. 448–459.
[75] M. Hughes, 574.8 km/h v150 eclipses the 1990 world record, Railway Gazette International, 2007, 163 (5).
[76] H. Wetzel, European railway deregulation: the influence of regulatory and environmental conditions on efficiency, Tech. rep., University of Lüneburg Working Paper Series in Economics (2008).
[77] J.N. Song, J.G. Qing, High-speed railway ballast flight problems and prevention, China Railway 9 (2015) 62–64.
[78] L. Le Pen, W. Powrie, A. Zervos, S. Ahmed, S. Aingaran, Dependence of shape on particle size for a crushed rock railway ballast, Granular Matter 15 (6) (2013) 849–861.
[79] H. Boler, Y. Qian, E. Tutumluer, Influence of size and shape properties of railroad ballast on aggregate packing: statistical analysis, Transp. Res. Rec. 2448 (1) (2014) 94–104.
[80] A. Abateneh Yitayew, Survey of railway ballast section and aspect of modelling techniques, KTH Architecture and the Buit Environment, 2011.
[81] Y. Qian, H. Boler, M. Moaveni, E. Tutumluer, Y. Hashash, J. Ghaboussi, Characterizing ballast degradation through los angeles abrasion test and image analysis, Transp. Res. Record 2448 (2014) 142–151.
[82] K. Riessberger, Ballast tracks for high speeds, Proceedings of tracks for high-speed railways, Porto, Portugal, 2006.
[83] M.S. Dersch, E. Tutumluer, C.T. Peeler, D.K. Bower, Polyurethane coating of railroad ballast aggregate for improved performance, in Joint Rail Conference, Am. Soc. Mech. Eng. 2010 (2010) 337–342.
[84] S.H. Lee, S.J. Lee, J.G. Park, Y.-T. Choi, An experimental study on the characteristics of polyurethane-mixed coarse aggregates by large-scale triaxial test, Constr. Build. Mater. 145 (2017) 117–125.
[85] P.K. Woodward, A. El Kacimi, O. Laghrouche, G. Medero, M. Banimahd, Application of polyurethane geocomposites to help maintain track geometry for high-speed ballasted railway tracks, J. Zhejiang University SCIENCE A 13 (11) (2012) 836–849.
[86] S. Thomas, P. Woodward, O. Laghrouche, Influence of stiffening ballasted track bed overlying a masonry arch bridge using a polyurethane polymer material, Constr. Build. Mater. 92 (2015) 111–117.
[87] G. Jing, L. Qie, V. Markine, W. Jia, Polyurethane reinforced ballasted track: Review, innovation and challenge, Constr. Build. Mater. 208 (2019) 734–748.
[88] G.Q. Jing, W.L. Jia, H. Fu, High speed ballasted railway track lateral resistance characteristics and reinforcement, J. Southwest Jiaotong University, 2017.
[89] G. Saussine, E. Allain, A. Vaillant, M. Ribourg, O. Neel, High speed in extreme conditions: ballast projection phenomenon, in: International Workshop on Train Aerodynamics, 2013, p. 4.
[90] H. Goossens, Maintenance of high speed lines, Tech. rep., International Union of Railways (2010).