Proceedings of the 2017 Joint Rail Conference
JRC2017
April 4-7, 2017, Philadelphia, PA, USA

JRC2017-2236

Probabilistic Analysis of Flying Ballast on High-Speed Rail Lines

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ABSTRACT

Safety is a top priority for the development of worldwide high-speed rail systems. Ballast flying is a particular safety concern when a high-speed train is traveling above a certain speed on the ballasted track. Displaced ballast particles from the track may cause damages to rolling stock, as well as the track infrastructure and wayside structures close to the sides of way. The objective of this research is to develop a probabilistic modeling framework to estimate the probability of ballast flight on specific segments or routes, accounting for several principal risk factors. Based on the probabilistic assessment, we propose a methodology to quantify the probability of flying ballast under certain scenarios. The methodology can be further developed, ultimately enabling a normative risk assessment for flying ballast risk management.

INTRODUCTION

Flying ballast is one of the most common observed phenomena in rail safety, which would bring extreme damage to the railhead, train body and adjacent structures, as well as injuries to maintenance workers or standing passengers who stand near the passing trains [1]. Due to the destructive results, ballast flight always causes major maintenance costs and safety concerns for High-Speed Rail (HSR) system.

This paper aims to identify the main causes of ballast flying based on international experiences and to present a specific risk calculation methodology for ballast flying. The second section mainly summarizes the previous work that has been conducted in related fields. The third section introduces a probabilistic analysis methodology to quantify the probability of ballast flying based on the aerodynamic mechanism. A specific example of this methodology is given in the fourth section, where all the data used is collected from the literature. A short discussion is presented in the fifth section. Finally, the main conclusion is summarized.

LITERATURE REVIEW

Many studies have made great progress regarding the calculation of the probability of ballast flying. Some influential researchers are concisely described below.

The phenomenon of ballast flying is tightly associated with aerodynamics. Baker [2] presented an aerodynamic assessment of train underbody flow motivated by problems with flying ballast [3]. Khayrullina et al. [4] evaluated the effect of a passing train on the wind flow induced inside a tunnel and assessed the wind conditions at an underground railroad passenger platform.

Kwon and Park [5] developed a quantitative risk model based on the behavior of the ballast under strong wind pressure. In their study, the ballast flight probability factor (BFPF) was directly associated with the speed of the train as well as the wind. However, the model does not consider the probability distribution, which may cause an obscured explanation for the computed results.

Another semi-quantitative probability-based method was presented by Jacobini et al. [6]. In their research, the probability of ballast flying is considered as the product of three factors: P_d, the probability that a particle will move from the rest position, $P_{fb|d}$, the probability that a particle will fly due to the movement, and C, which presents the consequence from the event of flying ballast. This model assessed various factors of the ballast flying risk, including aerodynamic condition, track response and etc. The final result is a risk matrix framework.

The Stress Strength Interference Analysis (SSIA) [7], proposed by Saussine, is one of the most significant methods that takes account of reliability. The researchers generated the probability distributions of the strength to identify which part of the conditions would fail during the process and generated the probability of the ballast flying as well.

Also, many experiments [8-10] have been done in the typical operation environment of HSR lines to collect the related testing data. Some of them are used in the following analysis and calculation.

Differing from previous literature, this paper utilizes aerodynamic mechanism to simulate the process of ballast flying and figures out the probability of this phenomenon by using statistical analysis.

METHODOLOGY

Since the ballast flying is a stochastic event [11], we try to apply the concept of reliability to figure out the probability of ballast flight. Reliability, by definition, is the probability that a system will operate for a period of time under the design operating conditions without failure [12]. Now, we consider one experienced segment as a system. The reliability of the system presents the probability that no flying ballast has been observed during the experiment. In order to calculate the probability of ballast flying, a typical mechanical model is built.

According to the survey [13], Jacobini et al. presented a preliminary list of possible risk factors that may contribute to flying ballast. The chance that a ballast displacement may occur is mainly affected by train aerodynamics, track responses, ground effects, and atmospheric conditions. Referring to the most common force mechanism, as shown in figure 1, we consider the balanced system of ballast flying in the vertical direction as some variables.

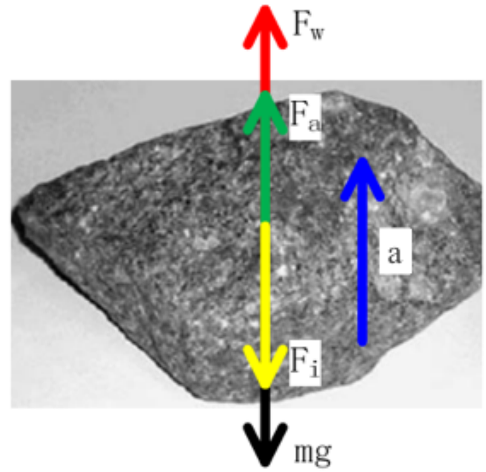

Figure 1. Ballast flying mechanic equilibrium [11]

The ballast particles will experience the gravity, interlock force, and wind pressure when the train passes by. Each variable is listed in table 1.

Table 1. The variables in the limit state function

Names	Symbols	Causes
Gravity Force	mg	Gravity
Interlock Force	F_i	Friction
Wind Force	F_w	Wind Pressure
Acceleration Force	F_a	Vibration

According to previous work, a limit state function has been established [14]. On the basis of the d'Alembert principle, the limit state of this phenomenon could be expressed as function (1):

$$F_w + F_a = mg - ma + F_i \tag{1}$$

This function can be used to indicate the state of the ballast, and transfer the order of the variables on both sides. The formula is transformed as:

$$ma = (mg + F_i) - (F_w + F_a) \tag{2}$$

Set $S = (mg + F_i)$ and $L = (F_w + F_a)$ to stand for strength variables and load variables respectively. Then, let Z replace the left part of this equation, as the acceleration of the particles generated from the dynamic mechanism. Accordingly, when the upward vertical direction force is larger than zero ($Z > 0$), the system is out of balance and the ballast flight occurs. When $Z < 0$, the mechanic model of the particle is stable and the system would stay in a condition without failure. It can be summarized as:

Table 2. The possible conditions of the system

Condition	Description	Expression
Success	Num(Flying Ballast)=0	$Z \leq 0$
Failure	Num(Flying Ballast)>0	$Z > 0$

Considering the uncertainties of these variables, we use statistical methods to estimate the probability of flying ballast.

First, it is difficult to accurately assess the weight of each particle in the field. In fact, different rail lines could have designed standards for the ballast particles. In this research, we assume that the weight of ballast approximately fits a normal distribution, for example, $mg \sim (\mu_g, \sigma_g^2)$.

As for the inter-force F_i, it is difficult to test the coefficient directly on site. Besides, the distribution pattern did not be defined yet. Based on a previous study by Jing et al., [15], we assume the probability distribution of F_i is similar to a Gaussian distribution and set $F_i \sim (\mu_i, \sigma_i^2)$. In particular, we assume $\mu_i = 0.1g = 1, \sigma_i^2 = 0$ to illustrate our methodology.

The load variables, F_w and F_a have been measured and reported in several publications and reports [16]. Based on these data resources, we also assume that they approximately follow a normal distribution, $F_w \sim (\mu_w, \sigma_w^2)$ and $F_a \sim (\mu_a, \sigma_a^2)$.

After we obtain all the parameters' distributions, we can derive the probabilistic distributions of S and L as follows:

$$\mathrm{S} \sim \left(\mu_g + \mu_i, \sigma_g^2 + \sigma_i^2\right),$$

$$\mu_s = \mu_g + \mu_i, \sigma_s^2 = \sigma_g^2 + \sigma_i^2 \tag{3}$$

$$\mathrm{L} \sim (\mu_w + \mu_a, \sigma_w^2 + \sigma_a^2),$$

$$\mu_l = \mu_w + \mu_a, \sigma_l^2 = \sigma_w^2 + \sigma_a^2 \tag{4}$$

Accordingly, the system state probability function Z, is a normal distribution as well. We can compute the mean value μ_z and variance σ_z through functions (5) and (6):

$$\mu_z = \mu_s - \mu_l \tag{5}$$

$$\sigma_z = \sqrt{{\sigma_s}^2 + {\sigma_l}^2} \tag{6}$$

So for a ballast particle, the probability of flight is:

$$P_f = P\{Z < 0\} = P\left\{\frac{Z - \mu_z}{\sigma_z} < -\frac{\mu_z}{\sigma_z}\right\} \tag{7}$$

Set $\beta = \frac{\mu_z}{\sigma_z}$, then the expression (7) can be transformed into:

$$P_f = P\left\{\frac{Z - \mu_z}{\sigma_z} < -\beta\right\} = 1 - \Phi(-\beta) = \Phi(\beta) \tag{8}$$

$\Phi(\cdot)$ is the symbol of the standard normal distribution. The smaller the probability of ballast flying, the higher reliability of the track ballast system.

Integrating equations (5) and (6) into (8), we can obtain the reliability index β as:

$$\beta = \frac{\mu_s + (-\mu_l)}{\sqrt{{\sigma_s}^2 + {\sigma_l}^2}} \tag{9}$$

The calculation process can be summarized below:

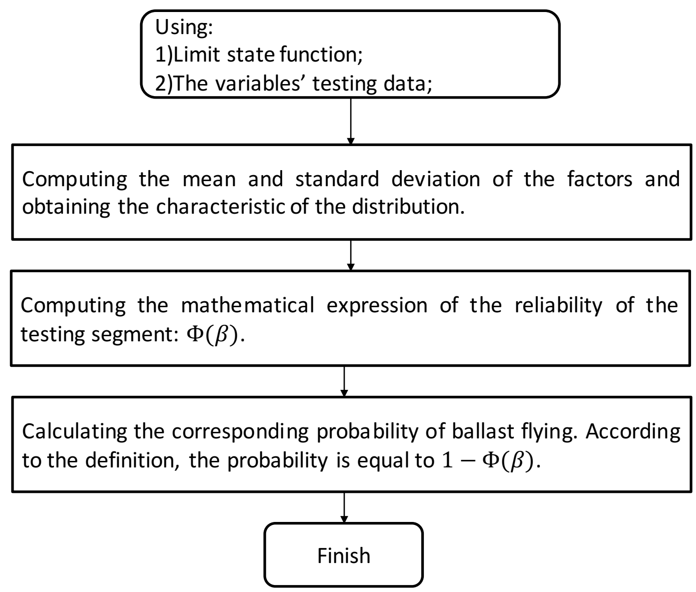

Figure 2. Flow chart for the calculation process

NUMERICAL EXAMPLE

This section uses open data resources from the literature to describe the process of estimating flying ballast probability.

Step 1: As for the strength variables (mg and F_i) which were discussed earlier, the different mass of particles can be represented by its gradation on the length. In order to achieve a better understanding, we assume that the interlocking force F_i is equal to $0.1g$. Based on [17], we generalize the probability density function of the particle length (Figure 4):

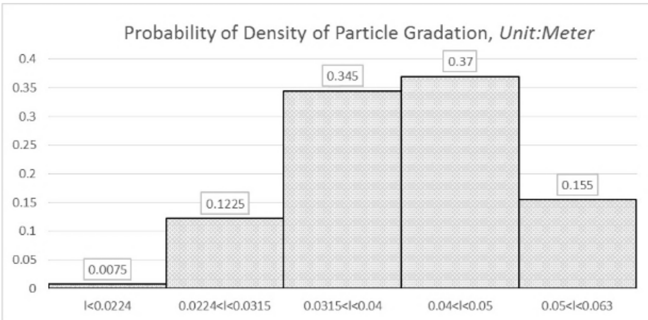

Figure 3. Probability density of the particle length

Step 2: For the load variables, F_w and F_a , the related testing values can be collected from the recorded data in [18] in which A.D Quinn assessed the mechanism coefficients of Eurostar 337 at the speed of 300km/h with 20-car. Especially, for the wind pressure F_w, which is very difficult to measure in the field, we choose the extreme values of the coefficient recorded in Figure 5 to develop a preliminary understanding of the distribution of the wind pressure.

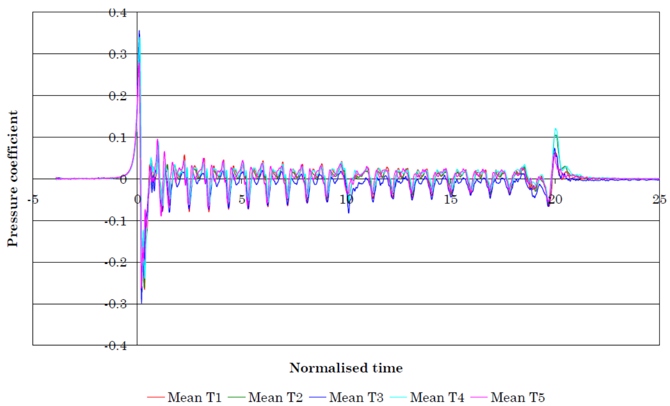

Figure 4. Mean (n=42) static pressure for 5 positions across the track [18]

Since F_w is the product of the wind pressure and the contact surface, we make estimation of values of wind force based on the pressure coefficient in figure 4. During the same time, Quinn also tested the acceleration of the ballast and presented as below:

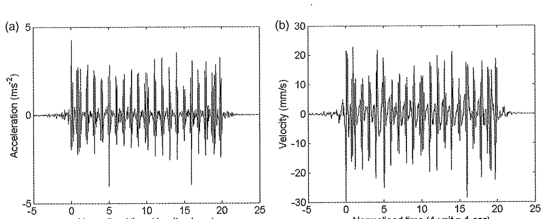

Figure 5. Measured acceleration of ballast and the related computed velocity [18]

Similarly, we simulated the probability density function of the acceleration of ballast particles in the same testing base on the given data:

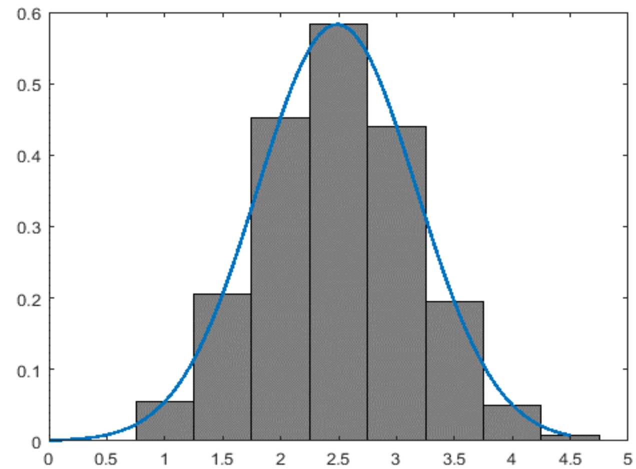

Figure 6. Histogram Distribution of Ballast acceleration (m/s^2)

Step 3: In summary, we obtained a table sheet including the characteristics of the variables in the limit state function:

Table 3. Statistic characteristic of the variables

Variable	Explanation	Distribution	Statistical Parameter[15-18]
mg	Weight	Normal	$\mu_g = 0.0411$, $\sigma_g = 0.0095$
F_i	Inter Force	Constant	$\mu_i = 1, \sigma_i = 0$
F_w	Wind Force	Normal	$\mu_w = 15.9068$, $\sigma_w = 8.697$
F_a	Acceleration Force	Normal	$\mu_a = 2.4868$, $\sigma_a = 0.6841$

Applying these statistic parameters in the function (8), we calculate the reliability of the experienced segment and present it as below:

$$P_f = P\{Y < -\beta\} = \Phi(\beta) = 0.98252$$

So the corresponding probability of flying ballast on this segment should be:

$$P = 1 - P_f = 0.01748$$

DISCUSSION AND MEASURES

The results in the last section present the probability of ballast flying that occurred under the testing situation in [18]. It means when these kinds of train models traveling at a speed of 300km/h for 42 vehicles passes with 20-car, it would have 1.748% chance of experiencing ballast flight.

In order to verify our methodology, we compare our calculated probability with the observed number of potential flying particles. This shows that under a similar scenario, within the testing length of 100km, the number of flying ballast is around 37. This result is pretty close to the observed number 42 in [19]. Our method can be further developed and ultimately can enable a mathematical assessment of ballast flight risk.

CONCLUSION

Ballast flying is one of the important rail safety issues for HSR development. In this paper, an understanding methodology to simulate the dynamic process of flying ballast on HSR is proposed. Moreover, some analysis in ballast management can be generated according to the calculation process in section three.

In addition, from the result of the numerical example, this paper develops a probabilistic approach to estimate ballast flight probability and compares the calculation result with the observation record in section four, in order to prove the correctness of this methodology. In other words, this kind of probabilistic methodology can predict the number of flying particles on the ballasted track properly.

The next step of this research is to develop a more detailed risk assessment of ballast flight under a broader set of conditions, for instance, the definition of flying ballast needs to be explained with certain measurement in the movement. Furthermore, the research is underway to identify, evaluate, and prioritize specific risk management strategies under budget constraints.

ACKNOWLEDGEMENT

The first author was partially funded by the Department of Civil and Environmental Engineering (CEE) at Rutgers University through a Graduate Student Fellowship. The second author was funded by a research grant from the Natural Science Foundation of China (51578051). However, the authors are solely responsible for all the views and analyses herein.

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