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BALLAST FLYING MECHANISM AND SENSITIVITY FACTORS ANALYSIS

G.Q Jing[1], Y.D Zhou[1], Jian Lin[1], J. Zhang[2*]

[1]Civil Engineering School Beijing, Jiao tong University, China

[*2]Department of Hydraulic Engineering, School of Civil Engineering, Shandong University, China

Emails: Jiongzhang@sdu.edu.cn

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Abstract- Ballast flying problems obsess the ballasted high speed railway, its microscopic mechanics is less of discovered. In the paper, the railway ballast particle force equilibrium is analyzed through basic mechanics and mathematic formula, and a model is set up to discover the factors and influence. The microscopic ballast flying model is used for ballast bed geometry and ballast shape optimization, and guide the ballast flying countering methods. Results show that ballast flying particle is correlated with ballast shape and mass, especially the ballast shape mass ratio corresponds to operation speed. Ballast interlock ability governs the ballast flying possibility and severity. Ballast flying possibility increases with ballast bed acceleration. The paper focus on ballast particle force equilibration, shape and mass, under the condition of vibration and wind effects, the ballast flying mechanism is analyzed and discussed with related counteracting methods presented.

Index terms: Ballast flying, high speed railway, sensitivity factors analysis.

I. INTRODUCTION

The interest in aerodynamics of high-speed trains has increased in the last decades due to the occurrence of ballast flying. Ballast flying has been considered as a problem in train aerodynamics since the 1980´s, where the train produced powerful airflows cause the ballast flying occurrence increase, results in lots of problems, for example, causing a form of railhead damage, known as "ballast pitting", as well train body damage [1]. Furthermore, due the train-track interactions are hugely altered due to ballast invasion, the high speed train safety is in danger, as well as passengers comfort. Ballast flying becoming one of the factors limiting the operating velocity of ballasted high-speed trains [2-3]. The high-speed train operators require limiting the occurrence of ballast flying, resulting in research efforts to understand its mechanism, as well as the countering measures [4].

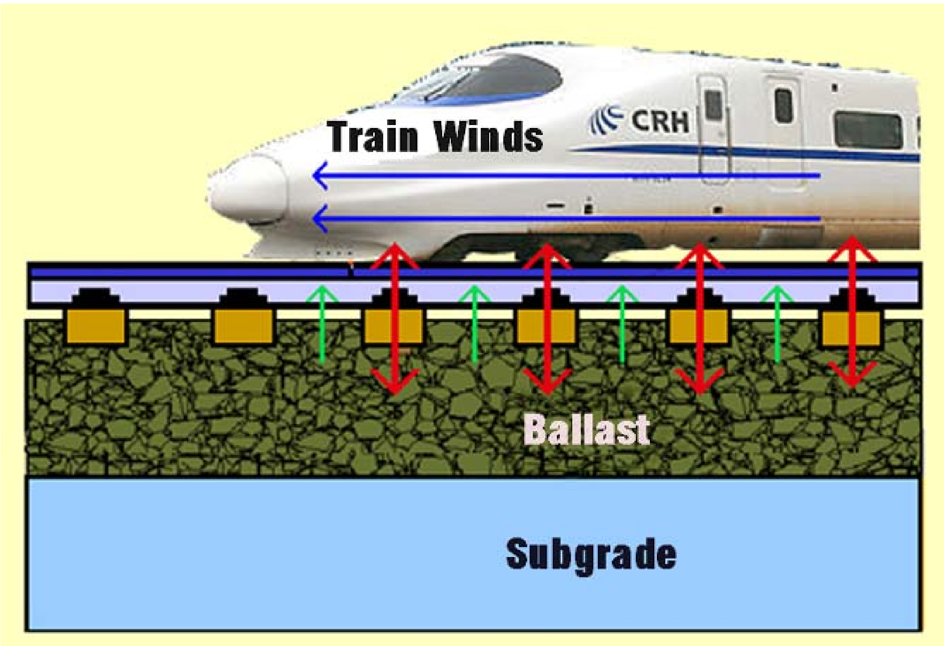

Figure 1. Ballast aerodynamic and dynamic Effects

The mechanisms involved in the phenomena are complex and complicated, which is a system problem, included train aerodynamics, track structure, and ballast material factors. In particular, the aerodynamic field caused by the train entrainment is known to play a key role [2-5]. Under proper conditions, this field is able to set in motion some ballast particles, which the aerodynamic load must counteract gravity and the reactions exerted by the ballast bed over the specific particle. This indicates that the aerodynamic and train dynamic loads induced by high-speed trains are high enough to move the ballasts on the track bed.

For the past decades, researchers applying experimental characterization of the flying ballast phenomena [3-5], but the sporadic phenomenon are difficult to characterize by both wind tunnel and in situ tests of high speed lines, and some statistic observations and predictions are conducted by DEM method[6], and even the CFD related simulations and tests [7-9]. All these work involved complex tests or simulations, limited by the calculation ability or couple methods. In the paper, a simplification and illustration of ballast flying mechanism is provided based on ballast particle mathematics and mechanics.

The outline of this paper is as follows: section 1 introduces the needs for research on assessing and discovering ballast flying mechanism due to high speed train dynamic and aerodynamics. Section 2 explores and characterizes ballast particle flying mechanism based on force equilibrium. Then, section 3 discusses in the proposed methodology used to counteract the ballast flying. Finally, section 4 highlights the main conclusions of the present paper and points out directions for further research.

II. BALLAST FLYING MECHANISM

The ballast flying phenomena requires at least two stages or conditions, ballast particles and particle movements, which involved with train dynamic response both from lateral wind and sleeper interactions. Based on the direct reasons, the ballast flying problems influence factors include: sleeper dynamic force induced by train load, and lateral wind by train. The following parts are to analyze and discuss influence factors based on worldwide research and reports.

High speed video recording of the ballast particles motion or ballast wind tunnel tests has clarified some of the mechanisms involved ballast flying [4]. The processes include two stages, ballast initial motion and move with wind. Firstly the ballast particle is set in motion, and then followed by a longitudinal transport stage close to the ballast bed that is propelled by aerodynamic forces, and where the particle/particle contact actions play a dominant role. When the particle has reached sufficient longitudinal momentum, or the ballast particle stability balance is expired, the contact actions can lead to the particle gathering enough vertical momentum to initiate the ballast flying.

Based on above ballast mechanics and Fig.1 illustrated. Simple mechanics models can be lay down to detect the key parameters. Here, the ballast particle vertically analyzed and characterized by the mg , F_i , F_w F_a .Where mg is gravity force by mass, F_i is ballast particle interlock force, F_w is high speed train resulted wind force acted on ballast effective surface, and F_a is ballast acceleration due to ballast bed vibration.

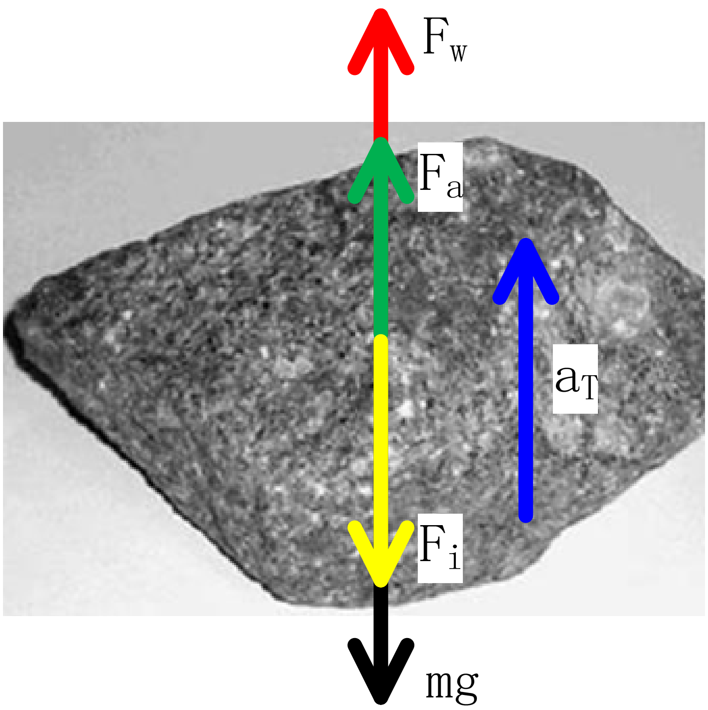

Figure 2. Ballast Flying Mechanic Equilibrium

Based on d'Alembert principle, the equation for ballast particle balance is (1),

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

For engineering safety consideration, the ballast particle interlock force F_i presumed to be 0, then the formula (1) can be simplified as：

$$\begin{aligned} ma_T &= F_w - mg + F_a \\ ma_T &= F_w - mg + ma = F_w - m(g-a) \end{aligned} \tag{2}$$

Where a is ballast particle vertical acceleration caused by sleeper induced dynamic responses. Based on aerodynamics, the ballast particle force can be calculated by:

$$F_w = \int_0^A \int_{v_1}^{v_2} f(A) f(v) \mathrm{d}A \mathrm{d}v \tag{3}$$

Where the A is wind loads effective area of ballast particle, and v_1、 v_2 is the points where the ballast particle interaction beginning and ending wind speed. Due to wind speed calculation complexity, we usually take the wind pressure coefficient α , and then the (3) is:

$$F_w = \alpha \int_0^A f(A)\mathrm{d}A \tag{4}$$

Submit the (4) into (2), the formula (5) is:

$$ma_T = \alpha \int_0^A f(A)\mathrm{d}A - m(g - a) \tag{5}$$

And then the (6)

$$a_T = \frac{\alpha \int_0^A f(A)\mathrm{d}A}{m} - (g - a) \tag{6}$$

From the (6), the part is to evaluate the ballast shape area divided by the mass

$$\alpha \int_0^A f(A)\mathrm{d}A / m \tag{7}$$

The a_T indicator reflects the particular ballast particle state of balance. For example, under certain train speed, the dynamic response of ballast bed acceleration a induced by the sleeper, if the $a_T < 0$ for the certain surface ballast particles, then illustrate the ballast particles are stable and free of ballast flying; if $a_T = 0$ proves to belong to the critical state of stability, the corresponded train speed is the critical speed (simultaneously, the critical wind speed) ; and if the $a_T > 0$ which results in the possibility of ballast flying phenomena accordingly. Furthermore, the left side of $(g - a)$ is an constant value for ballast particles under certain train and track conditions, which are train dynamic response interactions with track structure, can be measured and analyzed, for example, by the acceleration apparatus added on the surface ballast layers. The other part $\alpha \int_0^A f(A)\mathrm{d}A$, which governs ballast stability balance state, included the wind load effective area, the ballast particle mass, all these factors influenced by ballast shape, ballast density, ballast size etc. furthermore, they have relationship with ballast compaction, ballast bed geometry and ballast gradation. Especially the part (7), under the constant value α , the value has direct influence to determine the ballast particles stability, and this value can be defined as ballast flying shape mass ratio, it clearly demonstrates that different high speed train corresponds to determined value of shape mass ratio. Further research related with the ratio effects and determination, the ratio can be measured and statically analyzed by laser or similar system, further details can be followed in part 4.

The formula (6) could be explained by the form of (8), where the volume of ballast can be calculated with the integral of surface area multiplied with the thickness of the ballast, or flatness.

$$a_T = \frac{\alpha f(A)}{\rho \int_{z_1}^{z_2} A(z) dz} - (g - a)z \tag{8}$$

It could be roughly taken that the *A(Z)*and *f(A)* are equal to some extent, could be eliminated then the (8) finally leads to (9).

$$a_T = \frac{\alpha}{\rho \int_{z_1}^{z_2} dz} - (g - a) \tag{9}$$

Where the $(g - a)$ (10) are determined and known values when the train speed and ballast bed vibration constant, depend on ballast particle position, density, shape etc.

III. SENSITIVITY ANALYSIS AND COUNTERACTING MEASURES

Ballast flying influence factors include the train dynamic effects of vibration and train winds, complicated multi-body dynamics coupled with wind fluid effects. As the ballast flying indication, it needs the ballast material factor and flying “conditions”. From the ballast flying source, it is related with single ballast particle, but also railway ballast bed structure, such as gradation and geometry shape. Train dynamic force is an important factor, both the track dynamic response and train aerodynamics effects. Based on the above ballast flying mechanics formulas, several ballast flying influence factors are analyzed, and then the corresponded engineering method or possible measures are proposed.

a. Train winds

From the formula (1) and (3), the aerodynamic forces are necessary and predominant factors to ballast flying. For example, different train streamline result in aerodynamics effects, even at the same speed. During the ballasted high speed railway system, more attention should be put to the ballast flying lateral wind reduction, not only for the train body. A case in point is reported that ICE3 train caused ballast flying while ALSTOM not at the same running conditions. With the train streamline optimization, high speed train V150 can run as up to 574.8km/h without ballast flying [3]. Simultaneously, due to the train speed non-line increase relationship with the lateral wind loads, the ballast flying possibility increases non-lineally with train speed, for example, the Korea KTX ballast flying tests showed that the ballast flying possibility at 350km/h is twice of 300km/h, it signifies that when the high speed increased, ballast flying considerations and measures should be further counted [5, 10].

It also illustrates that reduction the ballast particle wind loads can be effective method, on condition that ballast resistance force sufficient, both the height and geometry of ballast bed. For example, China high speed ballast standards require ballast surface layer reduced 5 cm, and propose the surface layer smooth and compacted [11].

In the tests, high speed video recording can be used to witness the pulse of air, which is quite turbulent, travelling in front of train, which may give rise to downward force into ballast.

b. Surface ballast interlock ability

From the formula (1), ballast flying can be reduced or eliminated with ballast particle interlock ability, especially the surface layer ballast particles. Several methods can be used to improve the ballast particle interlock force. The ballast bed compaction is a practical method; such as ballast bed well compacted, squeezed and pressed. China high speed railway ballast bed standards require ballast density no less than 1.75g/cm3 to assure ballast compaction as well as the interlock. From the ballast material characteristic part, the ballast surface roughness or texture is considered to increase the ballast particle interlock or friction. The ballast specifications stipulated crushed or fractured ballast particles, which ask have a minimum 3 crushed fresh faces. The dynamic ballast interlock force is difficult to conduct, but the static ones can be used to measure or evaluate the ballast particle interlock ability. The schematic diagram is illustrated by Fig.3.

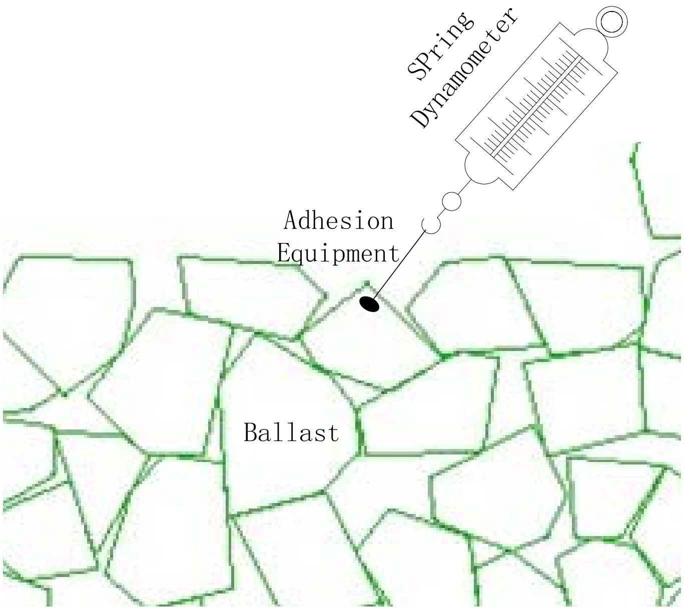

Figure 3. Interlock force survey

The 100 ballast particles interlock ability tests were conducted in site. Results showed that the ballast particle mass ranged from 34g to 185g, the interlock force ranged from 3.5N to 20.8N relied on self weights and concrete positions. The interlock forces were within 20% of self weight mostly, and 28 particles weighed bigger than 20%, while 9 particular weighed as high as 50%. It should be noted all the data are within static tests range, without train dynamic effects.

It should be noted that keep the smooth and even ballast bed geometry can reduce the wind effects, but also increase the ballast particle interlock ability, keep the ballast particle interacts with others, not independent and separated.

Other method to increase the ballast particle interlock force is using glue bonding material, which substantially increase the interlock force, but lack of long term maintenance experience. The steel or plastic web to increase the ballast particle stability method was experimentally used.

c. Ballast bed vibration

From the (5), ballast flying is influenced by the ballast bed acceleration, with the ballast bed acceleration increase, the ballast flying possibility and severity improve. Hence, the ballast bed acceleration and vibration reduction and optimization methods are used to reduce or terminate the ballast flying phenomena.

From the design or operation stages, we could alter the sleeper type, distance, fastener, rail or sleeper pad, ballast mat, ballast depth and density and so on. For example, increase the sleeper mass, increase the rail pad elasticity, ballast mat application reduce the sleeper and ballast vibration. Especially, from the above formula (2), there is a unique condition should be noted, during ballast spreading or tamping, the ballast particles are easily fell on to the sleeper surface. In the cases, sleeper vibration is 10-20 times of ballast bed, far more bigger than the gravity g, so based on the (5) and (6), even the train wind very small, the ballast flying possibility is relatively higher than normal ballast bed case. In French 574.8km/h, strictly noted that the ballast particles should be swept off sleeper, and it also reported by simulation [6]. Furthermore, the ballast vibration distribution affect the results, for example, the surface ballast particles along or adjacent to the sleeper, with fierce vibrations and less interlock restrict, which are easily flying off the surface than the normal sections. A case in point is that the ballast particles falls onto the sleeper will result in ballast vibration far more bigger than ballast along the sleeper, the latter normally bigger than ballast in the crib, it is possible to take correspond measures for counteracting.

The sleeper and ballast vibration can be measured using geophones, but the geotechnical effects (ground accelerations) alone are insufficient to cause ballast flight: the cause is probably a combination of aerodynamic and ballast acceleration effects, as illustrated by the former, new test sensors can be used to detect parameters[12-13].

China high speed railway ballast flying experience shows that, ballast flying possibly on bridges bigger than subgrade sections. Ballast bed vibration on bridges bigger than subgrade, and simultaneously, the wind get s stronger, so the train speed limit of ballast flying is governed by the bridge section passing speed, and additional measures or monitoring practices should be taken. The SNCF high speed test in the east line and China high speed test got the ballast off the sleeper above.

d. Ballast shape and mass

Ballast particle shape and ballast bed quality not only influence the resistance ability and stability, but also the ballast flying characteristics. From formula (4), for the same mass of ballast particles, the bigger efficient wind area, the higher ballast flying possibility. It signifies that the flat, shallow ballast particles are easily projection due to wind, which requires high speed ballast shape index in ballast specifications. The statistical investigations on the shape and mass of ballast particles were conducted. 200kg ballast has been picked out from the high speed lines, and then 100 ballast particles were classified by the surface area to the mass to consider the aerodynamics effects. The surface mass ratio was presented by the Figure 4.

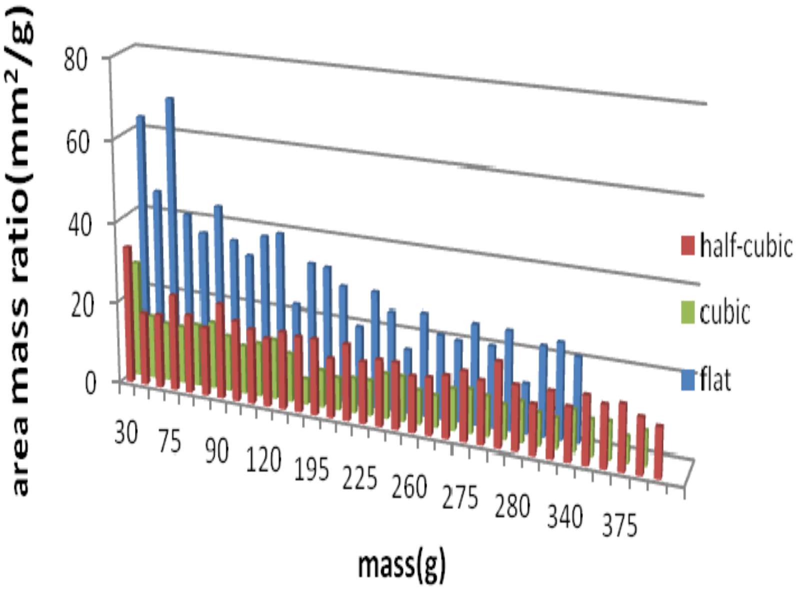

Figure 4. Ballast Surface Mass Ratios

For the surface mass ratio results, it agrees well with the ballast shape classification. The area mass ratio critical value should be further determined by the specific conditions, for example, a case calculation and tests validation, from the wind tunnel tests to the real site operation.

It should be noted that even for the same hard strength level ballast particle, the ballast density varies. With meeting the requirements of ballast specification, the higher ballast material ballast produces more stability, in our ballast experiments, the basalt density is 3.1 g/cm3, while the granite is 2.86 g/cm3.

IV. CONCLUSIONS AND PERSPECTIVE

The characteristics of ballast flying mechanism of high speed trains have been theoretically investigated. A simple method is presented without involving huge costly tests, with ballast surface area and mass classification and determination, ballast flying mechanism is illustrated. Mechanics formula and sensitivity factors have been used to discover the ballast flying phenomena. A novel ballast flying physics determination and calibration procedure has been applied to obtain the individual ballast stability balance states. Influence factors of ballast flying have been characterized: ballast particles accelerations and ballast shape mass ratio. Qualitative results as following:

Ballast flying is correlated with ballast shape and mass, especially the ballast shape mass ratio.

Ballast interlock ability governs the ballast flying possibility and severity.

Ballast flying possibility increases with ballast bed acceleration directly, additional measures and monitoring should be taken when passing the bridges or ballast bed tunnel zones where the vibration is higher.

The ballast shape, mass, gradation, and interlock ability parameters should be further measured and analyzed, correlated wind and site tests are needed for quantitative determination.

There possibly exists a critical value for the ballast surface mass ratio under certain high speed train operation, which is useful for ballast shape control.

V. ACKNOWLEDGEMENTS

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