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Experimental Investigation the Geometric Properties of Aggregates on Ballast Flight Phenomena of Railway Track

Hamidreza Heydari[1*], Mohammadreza Talaee[2], Aynaz Naseri[3]

[1]Assistant Professor, School of Railway Engineering, Iran University of Science and Technology, Iran

[2]Associate Professor, School of Railway Engineering, Iran University of Science and Technology, Iran

[3]MSc. Student, School of Railway Engineering, Iran University of Science and Technology, Iran

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A B S T R A C T

High-speed railway tracks have expanded significantly across the world in recent years. The increase in train operating speeds imposes considerable aerodynamic forces on the track, which can lead to several technical issues—one of the most important being the ballast flight phenomenon. Among the key factors contributing to ballast flight are the geometric properties of the aggregates, particularly their effective area and particle size. Since there is still limited understanding regarding how geometric properties of the aggregates (e.g. effective area and particle size) impact ballast flight, the present study aims to investigate this issue using a series of wind tunnel tests. The wind tunnel provides a controlled environment to simulate aerodynamic conditions similar to those found in high-speed railways and to evaluate the influence of various parameters on ballast flight behavior. In this study, five different standard ballast gradations defined by the Iranian Standard No. 301 were tested. The findings showed that aggregates with a larger effective area tended to initiate flight at higher airspeeds. Furthermore, an increase in particle size was associated with a higher flight velocity. Among the tested gradations, the ballast with grade No. 4 exhibited the best resistance against ballast flight, indicating its potential as an optimal choice for high-speed railway tracks

1. Introduction

The railway industry has continuously faced the challenge of increasing train speeds, pushing engineers to develop innovative solutions for addressing emerging technical demands [1]. Over the years, various challenges in both ballasted and non-ballasted track systems have been mitigated through innovative approaches [2–3]. In the past decade, with the advancement of train technologies, high-speed railway development has introduced specific issues requiring special attention. These efforts have resulted in remarkable progress, and today, high-speed railway tracks are widely used around the world, particularly in East Asian and European countries.

Ballasted tracks have reliably supported railway operations for decades by providing a safe and stable foundation for train movement. For example, nearly all high-speed lines in France are ballasted, with operational speeds exceeding 320 km/h and a maximum test speed of 574.8 km/h recorded on the eastern tracks [4].

*Corresponding author
Email address: h_heydari@iust.ac.ir

However, one of the most common problems observed in ballasted tracks at high speeds is the ballast flight phenomenon. This occurs when aerodynamic and mechanical forces acting on the ballast aggregates exceed gravitational force, causing the particles to lift and move in response to the airflow [5]. Ballast flight can lead to significant damage to the rolling stock, track infrastructure, and surrounding environment.

The main cause of this phenomenon is the airflow generated between the passing train and the ballast layer. Studies have shown that airflow is most intense in the crib ballast region (between sleepers) [6]. Premoli et al. [7] conducted full-scale tests using a wind tunnel to investigate the effect of ballast compaction, shape, weight, and the relative height of the upper ballast layer. Talaee et al. [8] selected approximately 50 kg of ballast for testing under both vibrational and non-vibrational wind tunnel conditions. Jing et al. [9] reviewed the causes and preventive strategies of ballast flight, while Ding et al. [10] examined low-speed flight events caused by frost and sudden temperature changes in the ballast layers. Jing et al. [11], in another laboratory study, evaluated factors such as aggregate shape, mass, and velocity.

While ballast consists of a mass of interlocked aggregates, its overall behavior is influenced by particle shape, gradation type, and interlocking capacity. These characteristics significantly affect the flight potential of ballast particles, but have received little attention in the literature. One important yet overlooked factor is the effective area, which refers to the visible surface of an aggregate in contact with others [12].

As showed the literature review, there is still lack of knowledge in effects of aggregate geometric properties on ballast flight. So, the present study aims to study the effects of two main geometric characteristics of ballast aggregates (e.g. effective area and particle size) using the wind tunnel tests.

The effective area is important from two aspects: the interlocking friction between aggregates and the surface exposed to airflow. An increase in the effective area can alter the aerodynamic force applied to the aggregates, thereby influencing the probability of ballast displacement. In addition, the particle size directly affects ballast gradation and its aerodynamic response.

Accordingly, this study evaluates the ballast flight behavior of five commonly used gradations, based on the specifications of Iranian Standard No. 301 [13]. The gradations were tested in a wind tunnel device that simulated real railway track conditions. Wind speed was measured continuously, and the effective area and size of flying particles were analyzed. The results are presented and discussed in this paper.

2. Methodology and Ballast Aggregate Characteristics

In this study, a wind tunnel device, composed of components such as a honeycomb, test chamber, wind duct, fan connector, anemometer, and control panel, was used (Figure 1). For the laboratory tests, ballast aggregates were first graded according to the standard gradation categories defined in Iranian Standard No. 301 [13], and then placed in the test chamber of the wind tunnel device.

It should be noted that in each test, all ballast aggregates were used in their unaltered (natural) form. An anemometer was used to measure the wind speed inside the chamber. After the uniform distribution of ballast aggregates, the wind tunnel fan speed was gradually increased at a fixed rate, allowing the ballast flight phenomenon to be carefully monitored. The gradation characteristics of the tested ballast aggregates are shown in Table 1.

Table 1. Ballast gradations and sieve sizes according to Iranian Standard No. 301

AREMA		Sieve Sizes (in) or number								
		3	$2\frac{1}{2}$	2	$2\frac{1}{2}$	1	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{3}{8}$	#4
G1	NO24	100	90-100	–	25-60	–	0-10	0-5	–	–
G2	No25	100	80-100	60-85	50-70	25-50	–	5-20	0-10	0.3
G3	No3	–	100	95-100	35-70	0-15	–	0-5	–	–
G4	No4 A	–	100	90-100	60-90	10-35	0-10	–	0-3	–
G5	No4	–	–	100	90-100	20-55	0-15	–	0-5	–

3. Method

A ballasted track model was simulated in the middle section of the wind tunnel test device. In this section, the crib ballast—identified as the most critical area for ballast flight—was recreated between two sleeper segments using ballast aggregates with defined gradation. To begin the process, the required sieves were

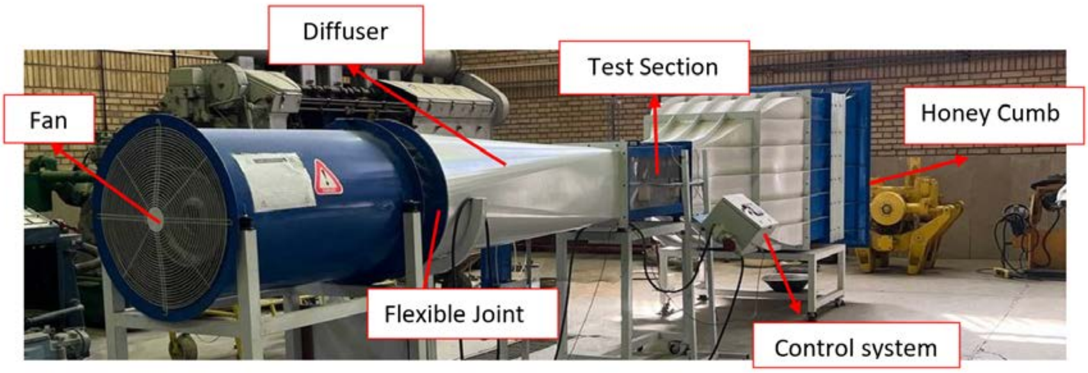

Figure 1. Components of the wind tunnel test

prepared according to the gradation shown in Table 1, arranged from the largest to the smallest sieve from top to bottom [14–15].

Based on the volume of the wind tunnel test chamber, 50 kilograms of ballast aggregates were selected for each gradation, in accordance with ASTM C136. The weight of aggregates

retained on each sieve was determined based on the gradation curves and the specified percentage for each sieve. These were uniformly mixed and placed inside the test chamber of the wind tunnel device.

After each test, displaced aggregates were identified, and parameters such as effective area and particle size were measured. For each ballast gradation, six tests were performed under uncompacted conditions. Given the evaluation of five different ballast gradation types, a total of 30 tests were conducted. It is also worth mentioning that for calculating the effective area of the aggregates, a precision grid sheet with 1 mm accuracy was used.

4. Results

In this section, the results obtained from wind tunnel tests performed on various ballast gradations are presented. To assess and compare the performance of different ballast gradation grades against the occurrence of ballast flight, the parameters of effective area and diameter of the flying aggregates were analyzed. The results of these evaluations are discussed below.

4-1. Evaluation of Effective Area Variations of Flying Aggregates

The effective area of ballast aggregates is one of the key and influential factors in the ballast flight phenomenon [16]. For this reason, it has been considered as a parameter for evaluating and comparing the performance of different ballast gradation grades. Based on the data obtained from wind tunnel tests, the variations of flight velocity against the effective area of aggregates for different ballast gradations under uncompacted conditions are illustrated in Figure 2. As observed in these diagrams, with an increase in the effective area of aggregates, the flight velocity of the particles also increases. These plots show a generally upward trend, indicating that as the cross-sectional area of the aggregate grows, its flight velocity also increases, meaning the particles are harder to lift off from their initial position.

Interpreting these results, it can be concluded that the effective area of aggregates influences ballast flight from two main aspects: friction and wind pressure. The friction between ballast particles depends on the contact area and the material type. Since the material of the aggregates is identical, the effective area is the primary factor in the interlocking of particles. Accordingly, the results demonstrate that the greater the contact surface between particles, the more difficult it is for them to displace from their original position.

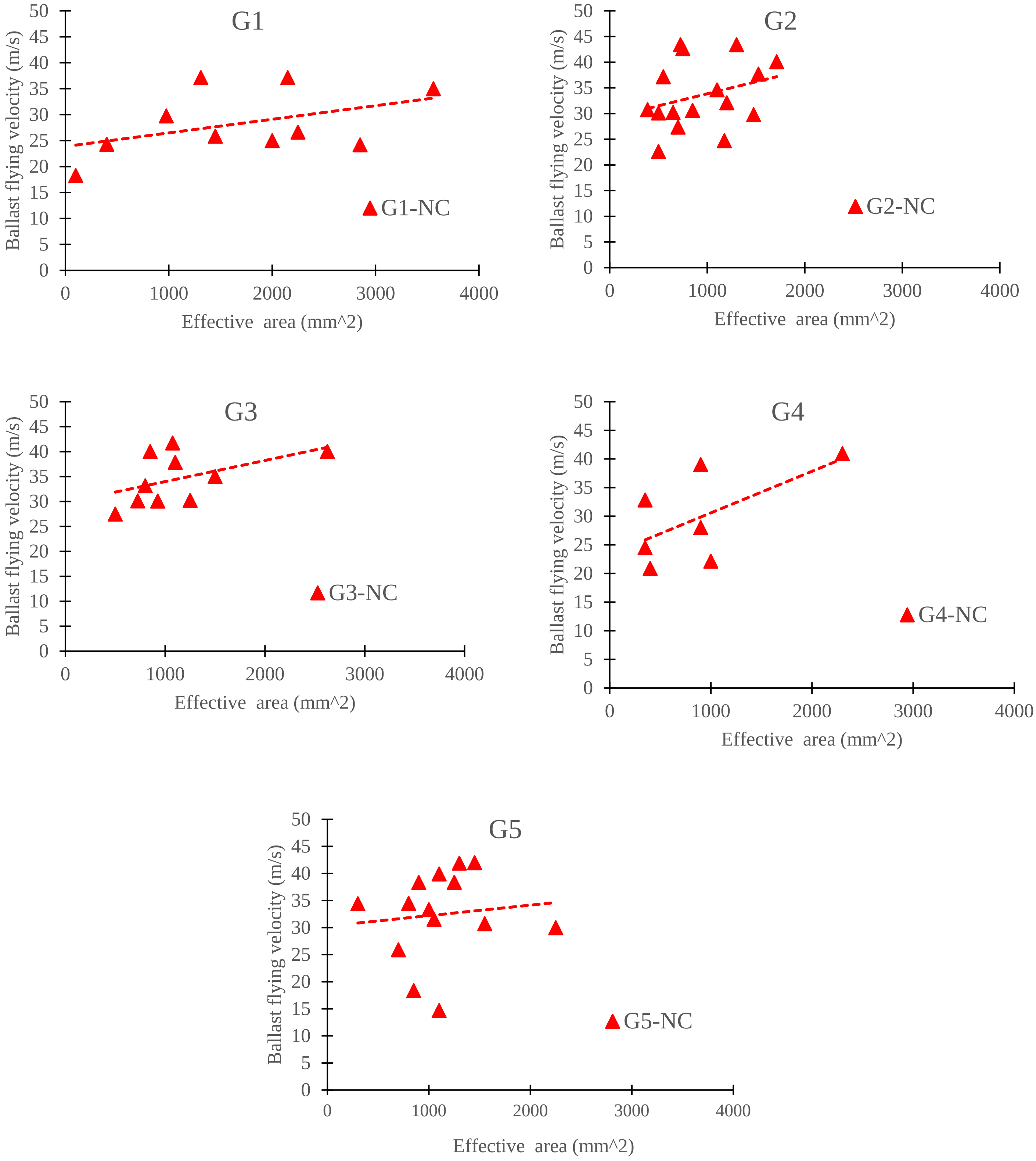

Figure 2. Variation of ballast flight velocities against effective area of flying aggregates

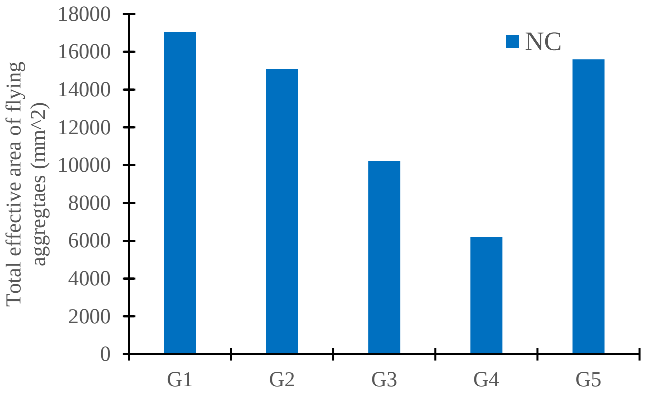

Figure 3. Total effective area of flying aggregates

In addition, the wind pressure generated by the wind tunnel airflow also depends on the effective area, as wind force acts on the particle's cross-section. Therefore, with a smaller contact area, less wind pressure is required to displace the aggregates.

Moreover, as shown in Figure 3, the total effective area of the flying aggregates was used as an indicator for evaluating resistance against ballast flight, enabling a comparison between different ballast gradations. In this comparison, if the total effective area of flying aggregates in a certain ballast gradation is higher, it reflects a more critical condition for that gradation. According to the results obtained from this perspective, it was observed that Grade 4 demonstrated the best resistance to ballast flight, whereas Grade 1 exhibited the weakest performance in this regard

4-2. Evaluation of Aggregate Size Variations of Flying Aggregates

The diameter of ballast aggregates is considered one of the primary factors in defining their gradation. In this section, the influence of particle size on ballast flight is examined. Figure 4 presents the scatter plots of ballast flying velocity versus the diameter of flying aggregates for different ballast gradations under uncompacted conditions.

The trend observed in the recorded data reveals that as the diameter of aggregates increases, the velocity required for them to be displaced also increases. In other words, aggregates with larger diameters tend to fly at higher speeds. Therefore, the total diameter of flying aggregates for different gradation grades can be calculated and considered as a potential indicator of the likelihood of ballast flight.

Accordingly, as shown in Figure 5, the lowest total diameter of flying aggregates under uncompacted ballast conditions was observed in ballast grade 4. This suggests that this gradation demonstrates the highest resistance to ballast flight in terms of particle size.

Given the study’s focus on ballast gradation, identifying the sieve sizes associated with the highest rates of aggregate flight is particularly valuable. To this end, the distribution frequency of flying aggregates retained on each sieve was determined based on their diameters, and the results are illustrated in the relevant chart.

As seen in Figure 6, Sieve No. 1, with an opening size of 1 inch (25 mm), corresponds to the largest number of flying aggregates across all tests. Conversely, Sieve No. 2 showed no recorded flights, and Sieve No. 3 retained no flying aggregates in any of the examined gradations

5. Discussion

The results of this study emphasize the critical role of aggregate gradation—particularly the effective area and particle size—in the occurrence of ballast flight in high-speed railway tracks. The analysis showed a clear trend: larger effective areas and particle sizes are associated with higher flight velocities, suggesting a direct relationship between aggregate geometry and aerodynamic response.

These findings are consistent with earlier research indicating that ballast flight is strongly influenced by aerodynamic forces acting on the exposed surface of the ballast particles. However, this study goes further by quantifying these relationships and linking them to gradation types. The use of AREMA Grade 4 (No. 4A) ballast proved most effective in resisting flight, likely due to its more stable interlocking behavior and balanced size distribution. This supports previous field observations that certain gradations provide greater structural integrity under high-speed airflow conditions.

In contrast, the poor performance of Grade 1 suggests that excessively coarse aggregates, with larger exposed surfaces, are more vulnerable to aerodynamic uplift—particularly in uncompacted conditions. This aligns with studies such as Quinn et al. [1] and Premoli et al. [5], which have shown that ballast flight tends to initiate in the

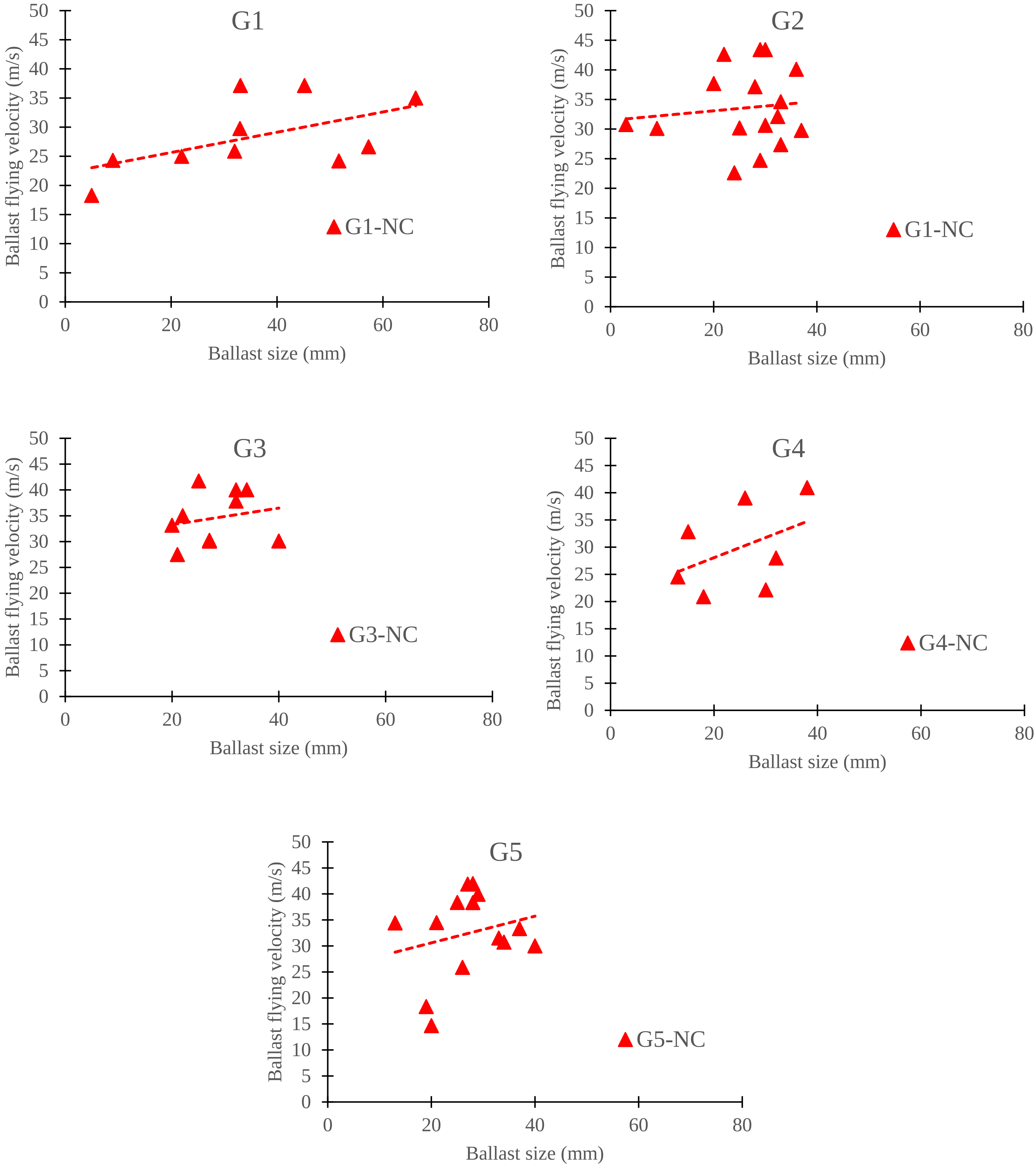

Figure 4. Variation of ballast flight velocity regard to aggregate size for different ballast gradations in non-compacted (NC) States

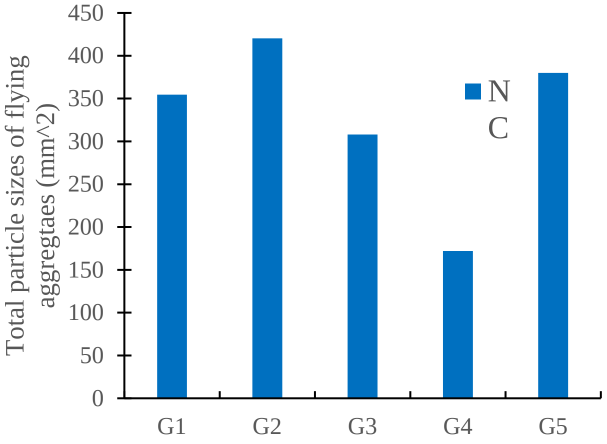

Figure 5. Total particle sizes of flying aggregates

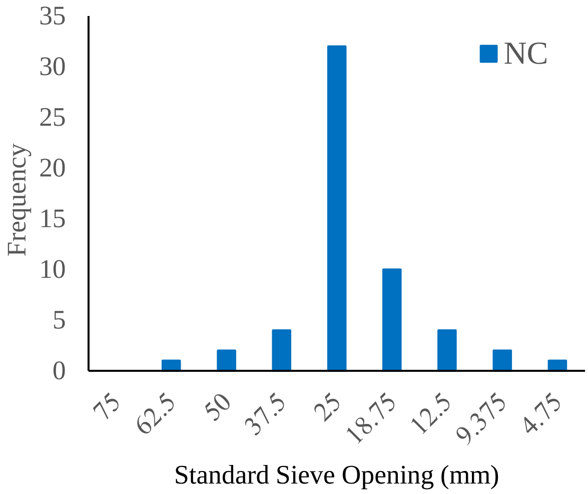

Figure 6. Frequency of Flying Aggregates per Sieve

upper, less-constrained layers of the trackbed where larger particles are more exposed.

Furthermore, the methodology of using wind tunnel testing with controlled variables allowed for a more precise simulation of real-world conditions, enhancing the reliability of the findings. The novel inclusion of total effective area and aggregate size as performance indicators offers a new framework for evaluating ballast stability, which can be integrated into design practices for high-speed rail infrastructure.

Overall, this discussion highlights that choosing the appropriate ballast gradation is not merely a structural concern but a vital aerodynamic consideration in the design of modern railway systems.

6. Conclusions

Despite the significance of the ballast flight phenomenon and the various challenges it poses, its effects have rarely been addressed in technical literature, and the lack of sufficient data in this field is evident. This issue has gained even more importance in recent years, especially with the increase in operational train speeds and the expansion of high-speed railway lines. Moreover, previous studies have seldom examined the impact of effective area and particle size on the probability of ballast flight.

In this study, two influential geometric parameters on ballast flight velocity—effective area and aggregate diameter—were considered as key indicators for evaluating ballast flight. To this end, ballast flight for five different ballast gradations was assessed under uncompacted conditions using a wind tunnel simulation, aiming to identify the optimal gradation based on these two factors. The summary of the present study's findings is as follows:

- As the effective area of ballast aggregates increased, the ballast flying velocity also increased. The results showed that with the rise in cross-sectional area of the particles, their flying velocity also increased, and the particles became more resistant to being dislodged from their original positions.
- The trend in the recorded data showed that with an increase in aggregate diameter, the required velocity for ballast flight also increased. In other words, the larger the aggregate size, the higher its flying velocity would be.
- Based on the conducted evaluations, it was found that ballast gradation Grade 4 demonstrated the best performance in resisting ballast flight. Therefore, the use of this gradation, particularly in high-speed railway tracks, is recommended.
- In contrast, gradation Grade 1 exhibited the poorest performance, with the highest number of flying aggregates observed in this gradation. Hence, the use of this gradation on high-speed tracks may result in several problems due to ballast flight.
- The remaining gradations showed moderate performance in terms of resistance against the ballast flight phenomenon.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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