

METHODS TO IMPROVE THE PROCESSING CAPACITY OF THE VIBRATING SCREENING DEVICE FOR BALLAST CLEANING VEHICLE

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Abstract: With the global development of high-speed and heavy-haul railways, the demand for operational efficiency of large-scale railway maintenance machinery is increasing. As a core equipment, the processing capacity of the screening device in a ballast cleaning vehicle directly limits the overall efficiency. To address the limitations of traditional linear vibrating screens in processing railway ballast, such as screen clogging, thick material bed, and a limited effective screening area, this paper proposes an innovative solution integrating tri-axial elliptical vibration, double-layer ballast feeding, and multi-section variable-inclination screen surfaces. By innovatively utilizing the underutilized triangular space within the vehicle frame, the solution achieves simultaneous double-layer feeding and an increased screen area without enlarging the overall layout, applying the thin-layer screening theory. Additionally, the multi-section variable-inclination screen optimizes material conveyance and screening. Experimental results from a physical prototype show a processing capacity of 800 m³/h, which is over 23% higher than the traditional solution (650 m³/h), with significantly improved screening efficiency. This study provides a technically valuable pathway for overcoming the performance bottlenecks of ballast cleaning vehicles under axle load and clearance constraints.

Keywords: Ballast cleaning vehicle; Vibrating screen; Elliptical vibration; Double-layer ballast feeding; Structural optimization

1 INTRODUCTION

A ballast cleaning vehicle is a large-scale railway maintenance machine used for ballast-bed maintenance. Its core function is to excavate fouled and compacted ballast from beneath the sleepers, separate fouled soil and degraded ballast fragments from reusable ballast through a screening device, and then return the cleaned, qualified ballast to the track bed, thereby restoring the ballast bed's elasticity and drainage performance. As a core functional component of the ballast cleaning vehicle, the processing capacity of the vibrating screening device directly determines the overall operational efficiency and the cleaning quality of the machine.

With the rapid global development of railways toward high-speed, heavy-haul, and high-density operations, unprecedented demands have been placed on maintenance windows and operational efficiency. However, further improvement in the operating capacity of ballast cleaning vehicles is subject to multiple rigid constraints. Railway axle load limits, the kinematic envelope of rolling stock, and the compact overall vehicle layout collectively restrict the size and weight of the screening device. After decades of optimization, the processing capacity of the conventional single-layer linear vibrating screening device has approached its theoretical limit, making it difficult to achieve a substantial breakthrough within the existing operating principle and structural framework. Therefore, significantly enhancing the processing capacity of the screening device through innovations in screening principles and structural design under such stringent constraints has become a critical technical bottleneck in the development of a new generation of high-efficiency ballast cleaning vehicles.

2 FACTORS AFFECTING THE PROCESSING CAPACITY OF THE VIBRATING SCREENING DEVICE

The processing capacity of a vibrating screening device is a comprehensive performance indicator jointly influenced by multiple coupled variables. For ballast cleaning vehicles, the screened material is railway ballast with complex composition and highly variable moisture content. The influencing factors can generally be categorized into three aspects: material properties, screen surface structural parameters, and vibration characteristics. In recent years, with the continued development of screening theory and the emergence of new technologies, new approaches and methods for improving processing capacity have been proposed.

2.1 Material Properties: Characteristics And Challenges Of Ballast Screening

The material processed by ballast cleaning vehicles is railway ballast, whose complex and variable characteristics constitute the fundamental factors affecting screening performance.

Wide particle size distribution: The feed contains ballast particles of varying degrees of wear, broken stones, and fouled soil, resulting in particle sizes ranging from a few millimeters of sandy soil to stones exceeding one hundred millimeters.

Such a wide gradation makes screen aperture blockage highly likely.

High moisture content and adhesiveness: Especially during the rainy season or in sections with poor drainage, ballast often exhibits high moisture content. Fine soil particles are prone to forming slurry, which adheres to the surfaces of coarse particles or to the screen mesh, severely hindering the passage of undersized material. This is the main reason for the sharp decline in processing capacity.

High bulk density and hardness: Ballast stone has high density, causing significant impact and abrasive wear on the screen mesh. Its high hardness also places more stringent demands on the dynamic parameters of the screening process.

2.2 Screen Surface Structural Parameters: Determining The Probability of Passage And The Effective Flow Cross-Sectional Area

The screen surface is the direct working interface where the screening process is accomplished, and the design of its structural parameters is therefore of critical importance.

Screen aperture shape and open area ratio: Square apertures generally provide a higher throughput than circular ones, but they are more prone to particle wedging and blockage. For railway ballast, elongated apertures or combined screen decks are commonly adopted. The open area ratio directly determines the effective screening area, and increasing it is a direct means of improving processing capacity; however, such improvement is constrained by the strength and service life of the screen mesh.

Screen surface dimensions (width and length): The screen width, B , directly affects the cross-sectional area available for material flow and is a key parameter governing the maximum theoretical processing capacity. The screen length, L , influences both material residence time and screening accuracy. Insufficient length may result in incomplete screening, whereas excessive length enlarges the equipment size and may lead to unnecessary material breakage.

Screen surface inclination angle, α : The inclination angle affects both the conveying velocity of the material and the thickness of the material bed. Increasing the inclination angle can enhance conveying speed and processing capacity, but it also reduces the effective screening time and may lower screening efficiency. The conventional single-inclination design makes it difficult to achieve a globally optimal balance between efficiency and processing capacity [1].

2.3 Vibration Characteristics: Providing The Driving Force For Screening And Governing Material Flow Behavior

Vibration parameters provide the driving energy for material stratification, conveying, and passage through the screen apertures [2].

Vibration intensity, K : $K=A\omega^2/g$, where A is the amplitude, ω is the angular frequency, and g is the gravitational acceleration. The vibration intensity should be matched to the material characteristics. For heavy and coarse railway ballast, a relatively high vibration intensity (typically $K=3\sim 5$) is required to achieve effective throwing and loosening.

Vibration direction angle, β : The angle between the direction of vibration and the screen surface. It determines the ratio of the material's forward and vertical velocity components during its throwing motion, thereby affecting conveying velocity and bed thickness. In conventional linear vibrating screens, β is typically around 45° ; however, for materials that are difficult to screen, optimizing the β angle can improve screening performance.

Vibration frequency, f , and amplitude, A : These two parameters must be properly coordinated in design. High frequency with low amplitude is favorable for the passage of fine particles through the apertures, but results in relatively slow conveying. In contrast, low frequency with high amplitude facilitates the transport of large particles, but may accelerate screen wear or damage. Conventional vibrating screens used in ballast cleaning vehicles generally employ linear vibration with a single frequency, resulting in a fixed material trajectory and poor adaptability.

Vibration trajectory: Traditional ballast cleaning vehicles predominantly adopt linear vibration, in which the material undergoes directional throwing. However, this mode provides limited dispersion, leads to uneven bed thickness, and readily results in low utilization of the screen surface. By comparison, circular or elliptical vibration can generate three-dimensional throwing and rotational motion, enabling the material to roll and disperse more thoroughly over the screen surface. This not only facilitates the passage of fine particles through the apertures, but also reduces screen clogging, making it an advanced vibration mode for improving the processing capacity of difficult-to-screen materials [3-5].

3 INNOVATIVE METHODS FOR IMPROVING THE PROCESSING CAPACITY OF VIBRATING SCREENING DEVICES FOR BALLAST CLEANING VEHICLES

Based on the above analysis, in order to overcome the limitations of the traditional linear vibrating screen, this paper proposes and describes an efficient vibrating screen solution for ballast cleaning vehicles that integrates multiple innovative technologies (core patents: CN212714317U, CN111851170A). The overall structural principle of this solution is shown in Figure 1. The key methods for improving processing capacity are reflected in the following four aspects.

3.1 Application Of Tri-Axial Elliptical Vibration Principle To Optimize Material Motion State

Traditional vibrating screens used in ballast cleaning vehicles mostly adopt dual-axis linear exciters, causing the

material to undergo directional throwing motion. In this scheme, a tri-axial synchronous rotary exciter is innovatively adopted. By precisely configuring the mass and phase angles of three groups of eccentric blocks, their resultant force generates a spatially rotating excitation force on the screen body. This excitation force can be decomposed into harmonic forces in the vertical, horizontal longitudinal, and horizontal transverse directions, and the combined motion causes each point on the screen surface to produce an approximately three-dimensional elliptical trajectory.

The three-dimensional elliptical vibration trajectory can enhance material dispersion and tumbling, thereby reducing screen clogging. During the throwing process, the elliptical trajectory imparts a tangential rotational force component to the material. As a result, when particles fall back onto the screen surface, they exhibit a rolling motion. This not only gives fine particles more opportunities to contact the screen apertures, but also causes particles stuck at the edges of the apertures ("near-size particles") to be thrown out as the force direction changes, significantly reducing the probability of screen clogging. Studies have shown that, for wet ballast, elliptical vibration can effectively reduce the clogging rate compared with linear vibration [6].

In addition, the three-dimensional elliptical vibration trajectory enables a better balance between material stratification and conveyance. By adjusting the phase angles of the eccentric blocks on the three shafts, the ratio of the major axis to the minor axis of the elliptical trajectory can be varied within a certain range, thereby regulating the effect of the vibration direction angle. At the feed end, a flatter ellipse can be adopted to strengthen the vertical component and promote rapid stratification of the material; at the discharge end, a rounder ellipse can be adopted to strengthen the horizontal component and accelerate material conveyance. This inherent adjustability allows the screening process to be further optimized.

The good loosening state of the material brought about by elliptical vibration can increase the effective screening bed thickness by about 15%, thereby increasing the material throughput under the same screen width conditions.

3.2 Adoption Of A Double-Layer Ballast Feeding Mode In Accordance With The Thin-Layer Screening Theory

1 Mixed-ballast conveyor, 2 Vibrator, 3 Screen frame, 4 First-layer screen mesh, 5 Second-layer screen mesh, 6 Third-layer screen mesh, 7 Ballast discharge hopper, 8 Ballast cleaning vehicle, 9 Vehicle frame, 10 Waste soil conveyor

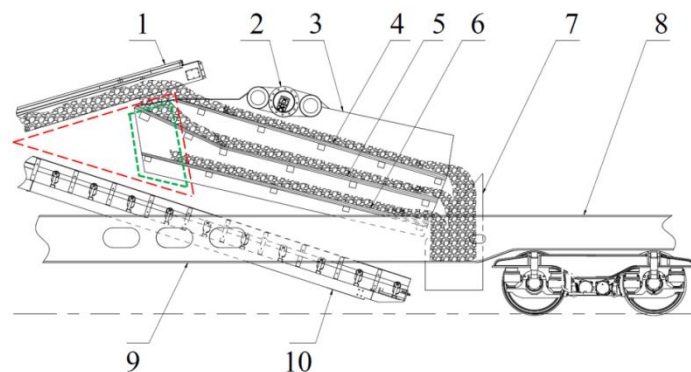


Figure 1 Schematic Structural Diagram of the In-House Developed Solution

According to the thin-layer screening theory, when the thickness of the material layer on the screen surface approaches or is less than 2–3 times the screen aperture size, fine particles in the bottom layer can rapidly pass through the screen, while the upper material continuously collapses to replenish the lower layer, allowing screening efficiency and processing capacity to reach their optimum levels. In the conventional single-point centralized feeding mode, a thick material pile tends to form at the feed end, resulting in low screening efficiency. Therefore, reducing the initial material layer thickness at the feed end is one of the fundamental approaches to increasing processing capacity.

The proposed design introduces a double-layer ballast feeding mode. As shown in Figure 1, after the mixed-ballast conveyor (1) elevates the material, a distributing mechanism divides the material flow into two streams, which are simultaneously fed to the feed end of the first-layer screen mesh (4) and to the feed end of the second-layer screen mesh (5) located beneath it.

The double-layer ballast feeding mode can substantially reduce the load per unit screening area. Assuming the total processing capacity is Q , under the traditional single-layer feeding mode, the entire load Q is concentrated at the feed end of a single screen surface. With the adoption of double-layer ballast feeding, the initial load at the feed end of each screen surface is theoretically reduced to approximately $Q/2$. This enables the material to begin the screening process in a thinner bed, closer to the ideal condition described by thin-layer screening theory, thereby fundamentally improving screening efficiency, especially for intermediate-size materials.

Moreover, with the addition of elliptical vibration, the risk of screen clogging at the feed end is reduced, the rate of particle passage through the screen is increased, and material conveyance over the screen surface becomes smoother. As a result, the overall flow resistance is lowered, allowing the average material flow velocity to increase under the same power input, thereby directly enhancing processing capacity.

3.3 Innovative Structural Layout Through Utilization Of Unused Triangular Space

Another notable strength of this proposed solution lies in the innovation of its structural layout. In the central section of the ballast cleaning vehicle frame (9), owing to the arrangement of components such as the mixed-ballast conveyor (or the excavation chain drive mechanism) and the waste soil conveyor, there is typically an underutilized “triangular space” beneath the discharge point of the mixed-ballast conveyor and between the main frame beam and the vibrating screen (the area outlined by the red dashed line in Figure 1). In conventional designs, the vibrating screen is positioned entirely below this space, leaving the triangular region unused. In this proposed solution, the screen frame (3) of the vibrating screen is reshaped and deliberately integrated into this triangular space. Specifically, the feed end of the second-layer screen mesh (5) is extended upward and forward into this region. As a result, the total effective screening area is significantly increased without enlarging the overall external dimensions of the screen box. The additional screen area (the region outlined by the green dashed line in Figure 1) is derived entirely from the utilization of this otherwise unused space.

This newly added area naturally forms the front section of the lower screen surface in the double-layer ballast feeding arrangement, making it possible to implement the double-layer feeding scheme within the limited physical space available on the vehicle. This design reflects a high degree of integration between mechanical structural design and overall vehicle layout.

3.4 Realization of A Multi-Section Variable-Inclination Screen Surface To Intensify The Screening Process

Building upon the successful utilization of the triangular space to achieve a double-layer screen arrangement, this proposed solution further optimizes the dynamic parameters of the screen surface. Inspired by the operating principle of the “banana screen,” in which multiple screen sections with different inclinations are arranged in series, the second-layer screen mesh (5) in this design is configured as a multi-section variable-inclination screen surface.

High-inclination feed section: The feed section located within the triangular space is designed with a relatively large screen inclination angle, such as 25°–30°. This steep inclination enables the material falling from the upper screen after preliminary screening—whose particle size has already become relatively uniform—together with the material directly fed into the second layer, to spread rapidly and move forward at an accelerated rate, thereby preventing accumulation and allowing the screening process to begin promptly.

Lower-inclination main screening section: After leaving the triangular space, the main screening section transitions to a standard inclination angle. This section provides the principal screening length, ensuring sufficient screening time and accuracy.

This inclination pattern—steeper at the front and gentler toward the rear—accords with the changing particle-size distribution and screening difficulty of the material throughout the screening process. As a result, the distribution of screening intensity along the full length of the screen surface becomes more rational, enabling maximum utilization of the screen length while screening efficiency and enhancing overall throughput.

4 THEORETICAL CALCULATION OF PROCESSING CAPACITY

For the verification of processing capacity, the calculation is generally conducted using the modified average method provided in the Design Specification of Vibrating Screen [7-9].

Formula:

$$Q = Fq\gamma L_{cu} K_{xi} I_s E_o G_k H_x D_c J_x + Q_d \quad (1)$$

In the design of ballast cleaning vehicles, processing capacity is typically expressed as the hourly volumetric throughput. For the sake of computational convenience, the quantity of material in the feed exceeding the aperture size per unit time (Q_d) is converted into K_1 , the content of material larger than the screen aperture.

$$Q_v = \frac{Q_d}{K_1 \rho} \quad (2)$$

By combining Equations (1) and (2), and further incorporating the elliptical vibration influence coefficient (K_2), the following processing capacity formula is obtained.

$$Q_v = \frac{Fq\gamma L_{cu} K_{xi} I_s E_o G_k H_x D_c J_x K_2}{(1 - K_1) \rho} \quad (3)$$

Where:

Q_v —processing capacity, in m^3/h ;

F —effective screen area, in m^2 ;

q —unit area capacity, in $t/(h \cdot m^2)$;

γ —inclination influence coefficient;

G_k —influence coefficient for open-area ratio of screen surface;

D_c —influence coefficient for the number of screen decks;

H_x —influence coefficient of aperture shape;

K_1 —content of material larger than the screen aperture size; K_2 —elliptical vibration influence coefficient;

ρ —bulk density of ballast, in t/m^3 ;

L_{cu} , K_{xi} , I_s , E_o , J_x —correction coefficients.

According to the theoretical calculation, the processing capacity can exceed $816 m^3/h$.

5 EXPERIMENTAL VALIDATION AND PERFORMANCE ANALYSIS

Based on the innovative scheme outlined above, a physical prototype was developed. In accordance with both industry standards and a self-designed testing protocol, systematic static inspection, no-load operation tests, and multi-condition load tests were carried out to comprehensively verify the performance improvements achieved by the new design.

5.1 Test Objectives And Experimental Framework

The purpose of this experimental program was to quantitatively verify the performance advantages of the integrated innovative scheme over the conventional linear vibrating screen in ballast cleaning operations. The experimental framework was established around two principal dimensions—processing capacity and screening quality—and specifically included the following key evaluation indicators:

1) Maximum stable processing capacity: The maximum volume of ballast that can be processed per unit time while maintaining the required screening efficiency.

2) Material property parameters: Moisture content, fouling content, particle size distribution, and bulk density of the ballast.

3) Equipment operating parameters: Vibration frequency, amplitude, and vibration direction angle.

4) Screening efficiency: The mass percentage of qualified ballast in the oversize product (backfilled ballast), or alternatively, the loss rate of qualified ballast in the undersize product (fouled soil).

The experiment followed the principle of single-factor comparison. A conventional single-layer linear vibrating screen (QS-650 benchmark model) was used as the control group, while the vibrating screen incorporating the integrated novel scheme proposed in this study served as the experimental group. Tests were conducted under identical material sources, feeding methods, and testing conditions, and the results were averaged for comparative analysis.

5.2 Test Conditions and Methods

Test prototype: A full-scale (1:1) vibrating screening device designed and manufactured in accordance with Patent CN212714317U.

Test material: Typical fouled ballast collected from railway sites, with a fouling rate of approximately 25%.

Benchmark for comparison: The conventional single-layer linear vibrating screen used in the QS-650 ballast cleaning vehicle, with a maximum rated processing capacity of $650 m^3/h$.

Test method: During the loading tests, the mixed-ballast was fed continuously and uniformly by the ballast conveying system. By combining gravimetric and volumetric measurement methods, the output of clean, qualified ballast discharged from the screening device per unit time was determined. Meanwhile, the proportion of qualified ballast contained in the spoil discharge was measured to evaluate the screening efficiency.

Photographs of the test procedure are shown in Figures 2–5.



Figure 2 No-Load Test Setup

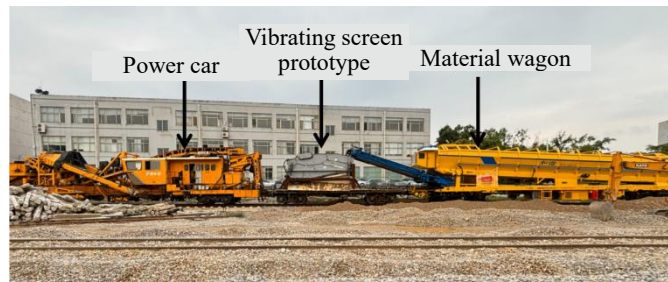


Figure 3 Loading Test Trainset: Power Car + Flatcar (Vibrating Screen) + Material Wagon



Figure 4 Double-Layer Feeding and Material Distribution Mechanism



Figure 5 Test Procedure

5.3 Test Results And Data Analysis

Processing capacity: Through continuous feed loading tests, under the premise of ensuring the screening efficiency (with coarse ballast content in the oversize not exceeding 3% and fine ballast content in the undersize not exceeding 10%), the test data are shown in Table 1.

Table 1 Comparative Test Results of Processing Capacity

Scheme	Number of Tests	Stable Processing Capacity (m ³ /h)	Average Processing Capacity (m ³ /h)	Capacity Increase Rate	Coarse Ballast Content in Undersize (%)	Fine Ballast Content in Oversize (%)
Conventional linear screen	5 times	646	652.8	/	9.2	2.8
		655				
		640				
		665				
		658				
New elliptical	5 times	811	805.4	23.40%	8.5	2.5

screen design	821
	802
	809
	784

The results indicated that the maximum stable processing capacity of the newly developed vibrating screen exceeded 800 m³/h. Compared with the 650 m³/h achieved by the conventional design, this represents an absolute increase of 150 m³/h and a relative improvement of 23.4%. In addition, the screening efficiency was superior to, or at least on par with, the benchmark values. The experimental data exhibited good repeatability, thereby confirming the stability and reliability of the performance enhancement achieved by the new design.

Analysis of the factors contributing to the increase in processing capacity: The significant improvement of more than 23% in processing capacity is the result of the synergistic effect of multiple factors.

Thin-layer screening effect: The double-layer ballast feeding arrangement reduced the initial material bed thickness by 42%, bringing it close to the ideal thin-layer screening condition, defined as less than three times the maximum particle size (approximately 90 mm). This greatly reduced the resistance to the passage of fine particles through the screen apertures, transforming the screening process from one governed by “material-bed hindrance” to one characterized by “interfacial screening,” thereby fundamentally increasing the screening rate per unit area.

Optimization of three-dimensional elliptical motion: Elliptical vibration caused the material to undergo rolling and dispersive motion across the screen surface, thereby eliminating the “dead zones” typically associated with linear vibration. Measurements showed that, under the same conveying capacity, the standard deviation of material bed uniformity in the new design decreased by 35%. Moreover, owing to the periodic variation in the direction of force acting on the particles, the aperture blockage rate was reduced by more than 40%, while a high effective open-area ratio of the screen surface was maintained.

Enhanced conveying through variable inclination: The steep inclination angle in the feed section of the second screen layer enabled the material to spread rapidly and accelerate, thereby preventing feed accumulation. The relatively lower inclination angles adopted in the subsequent segmented sections ensured sufficient residence time for screening, thus maintaining a high screening efficiency even under high-speed conveying conditions.

Increase in effective screening area: By directly utilizing the otherwise unused triangular space, the effective screening area was expanded, thereby providing the physical capacity necessary to accommodate high processing capacity.

6 CONCLUSIONS AND PROSPECTS

To address the urgent need to improve the processing capacity of the vibrating screening device used in ballast cleaning vehicles under severe spatial constraints, this study proposed and verified an integrated innovative solution. The main conclusions are as follows:

- 1) Tri-axial elliptical vibration was adopted to replace conventional linear vibration. By generating a three-dimensional elliptical motion trajectory, it effectively promoted the dispersion and tumbling of materials, thereby creating favorable dynamic conditions for high-throughput screening.
- 2) The introduction of the double-layer ballast feeding mode essentially represents the engineering application of thin-layer screening theory. By diverting the material flow and reducing the thickness of the material bed, it significantly improved the initial screening rate and the overall screening efficiency, and proved to be the key to overcoming the bottleneck in processing capacity.
- 3) Through an innovative structural layout, the inherent unused triangular space within the ballast cleaning vehicle frame was fully utilized. Without increasing the external dimensions or the overall weight of the equipment, the effective screening area was enlarged and the physical realization of double-layer ballast feeding was achieved, demonstrating the value of innovative mechanical design.
- 4) The multi-section variable-inclination screen surface design drew on the advantages of the banana screen, making the screening process more targeted in different sections and achieving a better balance between screening efficiency and processing capacity.

The vibrating screening device integrating the above technologies was verified through physical prototype testing. The processing capacity exceeded 800 m³/h, representing an increase of more than 23% compared with the conventional solution, and the expected objectives were achieved. This study lays a solid technical foundation for the development of a new generation of high-efficiency and intelligent ballast cleaning vehicles.

Looking ahead, the development of screening technology for ballast cleaning vehicles can be further advanced through systematic optimization and upgrading. Future research may focus on the coordinated control of the screening process with excavation and backfilling operations, as well as on the adaptive adjustment of operating parameters based on real-time material characteristics, so as to promote ballast cleaning operations toward greater intelligence and system integration.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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