DOI: https://doi.org/10.30932/1992-3252-2020-18-54-71

Physical Mechanisms of Ballast Granules Flying during Passage of High-Speed Trains

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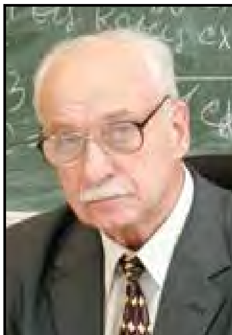

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ABSTRACT

The article analyzes the mechanisms of crushed stone flying on high-speed railways. The objective of the work was to study and identify main mechanisms entailing flight of crushed stone from the ballast bed. It is substantiated that the main mechanism consists in squeezing of crushed stone particles from the upper layer of granules and their rise above the crushed stone bed following the action of longitudinal and transverse stresses in ballast, and that the most probable places of ejection of crushed stone particles is the border of contact between sleepers and the upper layer of the crushed stone bed.

The physics of this process is presented, which consists in lifting ballast by turbulent vortices, suspension of crushed stone particles over the bed under the influence of vibration, in collision of moving particles and the process of squeezing and ejection of ballast granules. The reasons for the occurrence of horizontal and lateral stresses in crushed stone ballast are shown.

Keywords: *railway, high speed trains, lifting of granules, ejection of crushed stone, flying of crushed stone, horizontal longitudinal and transverse stresses, ballast bed, ice formation in the undercar space.*

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Article received 23.01.2020, accepted 02.07.2020.

For the original Russian text of the article please see p. 54.

Background. Once the classic track superstructure is made of crushed stone, individual crushed stones can be ejected upwards from the ballast bed due to various influences, for example, falling of large pieces of ice in winter. The crushed stone particles then collide with the equipment situated under vehicle's floor and are usually thrown forward at high speed in the direction of travel. Thereafter, the crushed stone can hit the ballast bed again and cause ejection of other stones. Thus, a vertically supported massive «crushed stone avalanche» can occur, which can severely damage the system components located in the undercar space of a rail vehicle. The problem of ejection of crushed stone granules is relevant for all high-speed trains there where the ballast track is used.

In Russia when operating Sapsan and Lastochka trains at a speed of 200 km/h and more a flying of large and small granules and dusty ballast particles can be observed in the undercar space and on the outer surface of the track near rails. Those granules and particles «bombard» the undercar equipment and electrical cables, cause damage to shock absorbers and power cables. Dusty particles damage glass windows, making their surface porous and less transparent.

The operation of high-speed trains (HST) in winter is accompanied by formation of snow-ice deposits in the undercar space of the train. Blocks of ice, when crumbling collide with rails and crushed stone, partially collapse and scatter, damaging infrastructure facilities, causing ejection of crushed stone granules and significant damage to undercar equipment.

The *objective* of this work is to study and identify the main mechanism entailing flight of crushed stone from the ballast bed using analytical *methods.*

1. Track ballast and degradation of its strength properties

In Russia in accordance with GOST [State Standard] 7392–2002, only hard rock crushed stone of grade I20 with a compressive strength in a water-saturated state of at least 20 MPa is used for the ballast layer of tracks of 1–3 classes. Crushed stone ballast, made from solid igneous rocks (granites, gabbro, diorites, syenites (deep rocks), diabase, basalts (erupted rocks)) is the best modern ballast material due to its durability, high resistance to settlement of sleepers and their displacement in the horizontal plane, good drainage, and possibility to provide crushed stone prism with elastic and electrical insulating properties.

With accumulation of ballast impurities, its drainage properties deteriorate [1]. In the crushed stone ballast prism, crushed stone is most heavily contaminated in the upper part of sleeper cribs, at the side edges and ends of sleepers, as well as under the sole, starting from the edges of sleepers and further to the middle. For crushed stone, the maximum permissible percentage of clogging (content of particles finer than 25 mm) by weight is 30 %, of which not more than 5 % can be less than 0,1 mm. The contents particles less than 20 mm in size should not exceed 5 % of the sample mass for cleaned crushed stone.

During maintenance works, laying of track or compaction of ballast, the maximum density of crushed stone of 0,33–0,34 should be reached. Usually, it is in the range of 0,36–0,40. As crushed stone becomes dirty and the total tonnage transported along the track grows, there comes a period of increasing deformations unevenly distributed along the length of the track, arising from bulging of ballast from under sleepers, accumulation of fine fractions of contaminating agents in lower and upper parts of the ballast layer, and due to splashes. The level of dynamic impact on the track and roadbed from HST grows in direct proportion to the square of their speed and, considering high-frequency vibration, causes a sharp increase in residual deformations, including intensive crushing of the ballast layer on the track and intensive wear of rolling stock.

The performed studies on strength properties of ballast material [2] showed that clogging of crushed stone with sands and dusty particles leads to a decrease in strength characteristics under the action of both static and vibration loads. The value of specific adhesion decreases under static load by 25 %, under vibration load by 29 %. The decrease in the angle of internal friction in the considered range of clogging of crushed stone by sands under the action of static and vibration loads is 12 and 19 %, respectively. Vibrations, as is widely known, are used in the technology of compaction and transportation of bulk materials, due to a significant decrease in structural viscosity of dispersed materials. According to the conclusion in works [3–5],

Pic. 1. Damage to the car body from impacts of crushed stone particles [6].

vibrations cause deterioration of the lower structure of the track, more intensive accumulation of residual deformations in it, and, in addition, reduce strength characteristics of crushed stone.

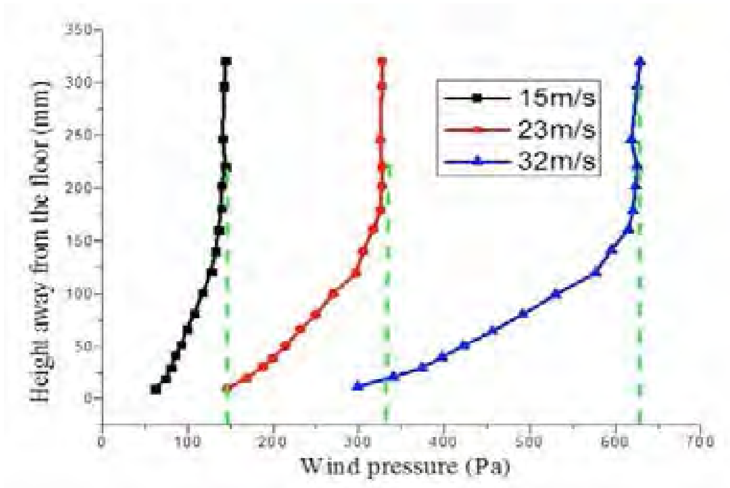
Thus, vibration contributes to the separation of crushed stone granules by size, to filling the pore space of the crushed stone layer with dust particles from the transported goods and by fine fractions of less than 1 mm when ballast, rails and wheels, brake shoes and aerosol are abraded, as well as when sand is used to improve adhesion of wheels and rails; leads to retention of precipitation and melt moisture. Biological clogging of the ballast and sandy layer by root systems of herbal vegetation, which quickly grow inward, rushing down to water (the phenomenon of geotropism), causes swelling of roots and a wedging pressure of 10–15 MPa [1]. Crushed stone granules, due to wedging pressure of growing roots, move apart, porosity increases to 60–70 %, the adhesion strength of crushed stone granules decreases. When the roots die off in spring, humus and water take their place. Due to oil pollution caused by spills on the railway bed or by grease residues from lubrication of wheels and rails, decayed plant residues begin to have a lubricating effect and can reduce structural viscosity of bulk materials by 10 ... 30 times [1].

2. Aerodynamic effect on ballast

The spectrum of aerodynamic problems arising when HST moves at speeds over 250 km/h is extremely diverse. Ballast particles or granules are believed to fly from the ballast bed under the action of turbulent vortices and damage rolling stock, track infrastructure and roadside structures in the railway right-of-way [6]. This phenomenon is a serious threat to safety of train and passenger operation (Pic. 1 [6]).

According to the date of American researchers [7], HST speed of 260 km/h can be a threshold value for rise and flight of ballast granules, and in case of snow drifts and heavy rain, the ballast granules can begin to rise at lower speeds, which is associated with a decrease in structural viscosity of crushed stone. In Russia, rise of crushed stone granules, according to the technical department of Oktyabrskaya railway, is observed starting at a speed of 210 km/h.

The problem of crushed stone granules flight from the ballast bed is usually solved by the method of theoretically calculating risks [7] followed by experimental verification and computer simulation [8; 9]. Expert assessments help to evaluate risk sequence of occurrence of the event of flight of crushed stone and of bombardment of the body or infrastructure facility followed by calculation of subsequent financial losses. The nature of the air flow pattern around the train is often not considered at all. In the report [7], five factors of the rise of crushed stone are given: operating speed, train design and structure and, accordingly, air flow and turbulence, the value of dynamic load, quality of track maintenance, and a strong side wind. The rise of ballast granules [7] can also be observed at a lower train speed in tunnels. The accumulation of snow along the track, the passage of HST in the opposite direction also contributes to lifting of ballast granules. It was noted that in tunnels where speed limit signs «no more than 140 km/h» were posted, high-speed trains also suffered significant damage from impacts of ballast granules.



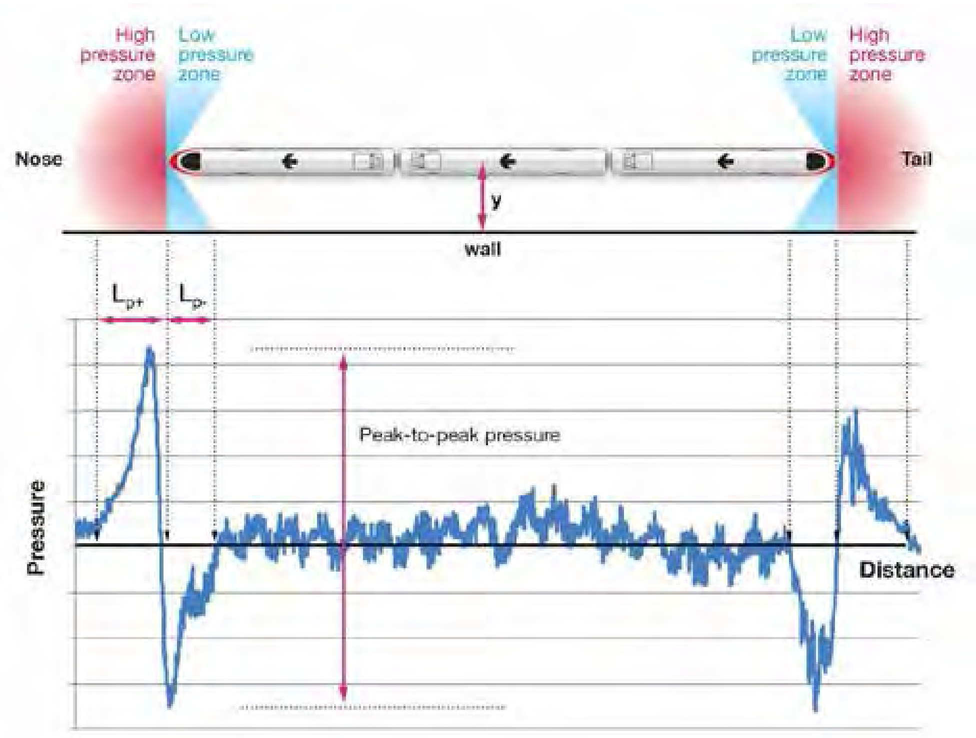
Pic. 2. Dependence of the rise of particles on their size, flow rate and its pressure [9].

In [8], optical detection of flight of crushed stone in a wind tunnel was carried out. Based on the results of laboratory studies, an aerodynamic model was developed for calculating flight of crushed stone granules. This made it possible to proceed with dynamic calculations of the inertial mass of crushed stone, of the amount of «mobile» crushed stone on the crushed stone bed for individual crushed stone granules, and to calculate probability of crushed stone getting into the train and the consequent damage. In addition, aerodynamic forces, speed of the onset of turbulent flows from bogies and other car structures were computed.

In [9], when modelling, the aerodynamic characteristics of crushed stone granules were considered: their distribution by size, surface area, mass, and shape. Using CFD software, the behavior of individual ballast particles in the air flow of a wind tunnel was simulated, and the dependences of the rise of particles on their size and flow rate and pressure, curvature of the site where the crushed stone granules were placed, were identified (Pic. 2). The paper has also suggested the minimum wind speed at which small movements of individual crushed stone granules start, that speed is of 8 m/s. At a wind speed of 25 m/s, most of the granules begin to move discretely.

In the operating mode in summer, according to the authors of works [9; 10], HST speeds $V > 340$ km/h are reasonable only under the condition of a ballastless track. For train speeds $V > 280$ km/h, a special shape and larger sizes of crushed stone granules on the bed surface are required. Operation of HST in winter, when the track is covered with ice and snow, at a speed of $V_{max} > 250$ km/h, should only be carried out on a ballastless track. SNCF recommends that the speed of HST in the range of critical temperatures and at the beginning of snowfall should be no more than 200 km/h. In France, such conditions are observed for about 20 days a year (in Russia for 90 days).

The report [10] describes for the first time the effect of ulceration of HST front bogie due to «bombardment» by rushed stone particles and by the products of their crushing. As part of this study, the vibrations in ballast generated by HST were measured using strain gauges. Analysis has shown that stresses in the crushed stone bed are not related to aerodynamic factors. Therefore, the authors assumed that mechanical vibrations of the roadbed contribute to suspension of particles, and due also to vertical turbulent air flows, a «cloud» appears where the highest concentration of particles is situated in front of the first car and a reduced concentration is at the tail car. These particles, colliding with HST body, are crushed and fly away from both sides of the train. To substantiate the proposed vibration mechanism for flight of crushed stone, the authors refer to inspections of HST damage and the testimony of repairmen. For a more detailed verification of this theory, according to the authors, additional research is required. Pic. 3, taken from the report [10], schematically shows the structure of the turbulent flow arising in the nose and tail zones of HST. The intensity of color in the zones corresponds to



Pic. 3. Zones of high pressure and low pressure, arising during HST movement [10].

the higher pressure. The front area or high pressure front, called Slipstream or sliding stream, in the form of a «tongue» can lift particles of crushed stone. The pressures in the indicated areas pulsate in time and may differ markedly for different HST.

The work [11] experimentally investigates speeds and pressures in the aerodynamic field of the undercar space using Pitot tubes and strain gauges. Near the ballast bed, the average speed is only 1/3 of the train speed, while the standard deviation of fluctuations in the air flow rate is about 1/10 of the train speed. The average air flow rate changes under the influence of parts in the undercar space and their shape, including the axles of bogies, transitions between cars and auxiliary equipment. The vertical profile of speed fluctuations is approximately uniform. At a crushed stone bed, the flow rate is 0,06 of the train's velocity. High speed video recording of motion of ballast particles helped to clarify some of the mechanisms that determine their movement. The process of motion of crushed stone granules includes the stage of starting movement or starting movement of individual small granules. Then, longitudinal migration of small granules begins along the «rough» surface of the ballast bed followed by collisions with neighboring larger particles.

The driving force of the process, in our opinion, could be associated with the alternating aerodynamic forces of turbulent vortices stabilized by silty mineral particles, snow (in winter), ballast contaminants, and ice particles of 1 ... 10 mm.

The authors of [11] believe that the contact interactions of moving granules with crushed stone particles of larger sizes play a central role. When small particles reach a sufficient longitudinal momentum, contact interactions can provoke a large granule to gain sufficient horizontal momentum to make the neighbouring particle rise into the air upon the collision.

The Slipstream s in front of HST (Pic. 3 [10]) picks up the escaped granules and raises them to a great height. Vertical vibrations of the roadbed help to reduce the structural viscosity in the upper layer of crushed stone, facilitating the process of lifting large granules of crushed stone. The results of research works cited in this section and the conclusions made in these works, especially based on model experiments with a small number of granules and without considering vibration exposure, as well as numerical experiments based on laboratory experiments, may inadequately describe the process of crushed stone granules ejection.

3. Analysis of the methods for flight of crushed stone granules from the ballast bed

Based on the consideration of research publications [6–11], it is possible to systematize the possible mechanisms of ejection of ballast particles described there-in.

1. Lifting of ballast granules by turbulent vortices [6–9], which, according to the authors [6; 7], arise at a high train speed. Ejection of crushed stone is facilitated by the design flaws of the cars, which worsen the flow around, and lead to an increase in the turbulence of the air flow. The reasons, according to the authors, that increase the lifting of ballast granules are: poor condition of the upper layer of crushed stone prism and small size of granules on its surface; strong side wind; train movement in tunnels, in which air flow turbulization occurs at much lower speeds; the passage of the oncoming HST; and accumulation of snow along the tracks.

2. Suspension of crushed stone particles over the bed under the action of mechanical vibrations of the roadbed [10], which, in combination with vertical turbulent air flows and a slipstream in front of HST contributes to the flight of crushed stone particles.

3. Contact collisions of moving small particles with granules of larger sizes and accumulation of sufficient horizontal momentum happening in such a way that, upon collision with a neighboring particle, a large granule rises into the air [11].

To implement the *first mechanism* (lifting of ballast granules by turbulent vortices), a high speed of HST is required, that is about 300 km/h. Unsatisfactory aerodynamics of the undercar space of HST will lead to a decrease in speed near the ballast bed below 1/3 of the train speed [11]. Contamination of the upper layer of the prism will only improve the flow due to a decrease in roughness of the ballast bed and reduce concentration of turbulent tubes. The strong crosswind only displaces the slipstream and boundary flow around HST.

Turbulent vortices in the air, according to our research [12], are «tubes» with a diameter of 30 ... 40 mm with a low vacuum inside. To gain power of «tornado», turbulent vortices must accumulate a significant mass of mineral dust, but at the speed of HST, this process will not have time to be realized. Consequently, the first mechanism of crushed stone granules ejection is unlikely.

Let us evaluate the possibility of implementing the *second mechanism* (suspension» of crushed stone particles over the bed under the action of vertical mechanical vibrations of the roadbed). The vertical component of vibrations of the ballast layer of crushed granite has a complex character with sharp bursts of recording and significant differences in the oscillatory process during the passage of wagons [13].

The first harmonic is a low-frequency one, and it lies in the range from 1,13 (55 km/h) to 1,48 Hz (125 km/h), and has the amplitude of 130 ... 450 microns, respectively, in the cross-section at the foot of the end of sleepers. At HST speed of 250 km/h, the first harmonic will be ~3 Hz, and the amplitude ~1 ... 1,2 mm. The oscillation period of the low-frequency harmonic practically corresponds to the time required for the carriage to travel the distance between the extreme axes of the bogie.

The second harmonic is a medium-frequency one, with a frequency of 3 ... 13,5 Hz and an amplitude of 30 ... 220 μm. It depends on speed of the train and arises under the direct force of individual axles of the cars applied to rails and ballast. At HST speed of 250 km/h, the second harmonic will be ~ 27 Hz, and the amplitude ~ 0,4 mm.

The third high-frequency harmonic with an amplitude from 0 to 21 μm at a car speed from 55 to 125 km/h is in the frequency range from 125 to 250 Hz. The high-frequency vertical component for speed will be approximately 500 Hz and, due to the inertia of the crushed stone prism, is almost completely absorbed.

The maximum speed obtained by a particle during its harmonic vibrations of the ballast is $v_{max} = A\omega$, where A is the amplitude and ω is the circular frequency of the vibration component. For a granule with a size of 60 mm, the kinetic energy will be $\sim 3 \cdot 10^{-7}$ J. In case of elastic collision of particles of the upper and lower layers, without considering friction of a particle against neighbouring granules, the potential energy of the upper particle will increase, and the maximum rise height will be ~0,5 μm. Considering the collision with three neighbouring particles in the lower layer, the ascent height will not exceed ~ 1 μm.

For medium-frequency vibrations and the same granule, the lift height will be ~ 0,23 mm, and when colliding with three underlying neighbouring particles, the lift height will be ~ 0,5 mm. Such a rise of the granule from the crushed stone bed, near which the flow speed, as shown in [11], is close to 15 km/h, is not enough. Besides, the turbulent vortices near the wall move in the opposite direction. Therefore, capture of light granules by slipstream is also unlikely.

The *third mechanism* is associated with contact interactions of moving small particles with granules of larger sizes resulting in flight above the crushed stone bed, and it is also unlikely, since the granules are densely packed even in the upper layer and cannot independently move under the action of the air flow, and, considering its low speed at the boundary section of air flow and crushed stone bed, impulses received by particles due to collisions with neighbours will be scattered in the surface layer of the crushed stone.

4. New mechanism: squeezing of granules from the ballast bed

In our opinion, the most probable mechanism of crushed stone ejection is squeezing out and flight of granules from the upper layer of the crushed stone bed when longitudinal and transverse horizontal and vertical stresses reflected from the inner layers of the crushed stone prism occur in the crushed stone ballast. Horizontal longitudinal and transverse stresses in the crushed stone ballast between the sleepers arise during the stealing of rails as a result of HSP braking from high speeds and at high temperature gradients along the track, and then they are concentrated near the lateral surfaces of the sleepers. The twisting of sleepers when wheels hit them also contributes to squeezing out of crushed stone granules. Longitudinal forces also arise during wheel slip on rails in curves and regenerative braking of trains.

For a motor powered car with two brake axles, friction rate of wheels against rails of 0,24, the load from the wheel set on rails 80 kN, fraction of the total weight used in braking of 0,5, the thrust force from braking will be equal to $F_t = 2{:}2 \cdot 0{,}24 \cdot 0{,}5 \cdot 80 = 9{,}6$ kN. Let us take the coefficient of transfer of thrust force to the sleeper, equal to 40 % [14; 15], then the force acting from the sleeper on the top layer of ballast will be 3,8 kN. The highest stresses are observed near the sleepers under the rails, therefore, for the geometric area of the lateral surface of the sleeper equal to $S_l = 0{,}154 \cdot 2{,}7 = 0{,}416$ m^2, the true contact area of granules of the surface layer of granules will be half as much, that is, 0,208 m^2. The proportion of the area of the foot of the sleeper β_g with granules under the load of 80 kN in contact with crushed stone granules is $\beta_g = 8$ % [16]. Since the actual area of elastic contact is directly proportional to the normal load [17], fraction of the lateral surface area of the sleeper under the load of thrust force of 3,8 kN with surface ballast granules will be twenty times less (0,4 %). Approximately $n \approx 50$ granules are in contact with the lateral surface of the sleeper; therefore, a stress force will act on the boundary of contact of each granule with the sleeper, the vector of which is directed normally to the lateral surface of the sleeper:

$$\tau_g = (0{,}4 \cdot F_{t)} / (\beta_g \cdot S_l \cdot n) = (0{,}4 \cdot 9{,}6 \cdot 10^3) / (0{,}004 \cdot 0{,}208 \cdot 50) \approx 91{,}3 \text{ kPa}. \quad (1)$$

The angle of inclination of the lateral surface of the sleeper to the horizon is $\alpha \approx 72°$. The horizontal reactions of a granule touching the sleeper will be compensated by two adjacent granules in the same plane as that of the main granule (worst case). If neighbouring granules are located slightly below the main granule, for example 30° lower, then additional vertical stress will appear:

$$\tau_{vert.} \approx 2\tau_g \cdot \cos 30° \cdot \cos 30° \cdot \sin 30° = 0{,}76\tau_g. \quad (2)$$

The vertical impulse of thrust force acting on the round granule closest to the sleeper, 60 mm in size and weighing 0,07 kg, will be equal to:

$$\tau_g \cdot Sc \cdot \Delta t \cdot [\cos\alpha + 0{,}76 + 2\cos 30° \cdot \cos 30° \cdot \sin 30°] = 1{,}81\tau_g \cdot Sc \cdot \Delta t = m_g \cdot V_g, \quad (3)$$

where S_c is area of contact of a granule with the sleeper, equal to $\beta_g \cdot S_l/n = 1{,}7 \cdot 10^{-4}$;

$\alpha = 72°$ is angle of inclination of the contact area to the surface of the crushed stone bed;

time of the pulse is equal to $\Delta t = l/V_{tr}$;

l is half of the distance between sleepers (~273 mm);

V_{tr} is train speed (250 km/h).

The friction rate of dry concrete against dry concrete is 0,7, and for concrete, partially contaminated with oil products and covered with watered dust particles, the friction rate is two to three times lower (0,35). The friction force acting along the lateral surface of the sleeper and with adjacent granules is:

$F_{fr} = k_{fr} \cdot \tau_g \cdot S_c \cdot (\cos 72^\circ + 2\cos 30^\circ) = 2{,}1 k_{fr} \cdot \tau_g \cdot S_c$. (4)

We add to the left side of equation (3) a vertical negative projection of the impulse of the friction force $F_{fr}\Delta t$, and, having solved the equation with respect to the initial speed of the crushed stone particle that flew out of the bed, in the final form we obtain:

$$V_G = \frac{(1{,}81 - 0{,}73) l \cdot S_c}{m_g \cdot V_{tr}} \tau_g = \frac{1{,}08 \cdot 1{,}73 \cdot 10^{-4} \cdot 0{,}273 \cdot 91{,}3 \cdot 10^3}{0{,}07 \cdot 69{,}4} \approx 0{,}94 \text{ m/s}. \quad (5)$$

For a 25 mm granule, ejection speed is 2,2 m/s. When evaluating squeezing of crushed stone granules out of the ballast bed, we did not take into account the downward force impulse when the wheel hits the sleeper and the reverse elastic reaction of the roadbed. In section 3 of this article, when assessing the possibility of realizing the second mechanism suspension of crushed stone particles in the cross section at the foot of the end of sleepers is carried out by the second harmonic energy with a frequency of ~27 Hz and an amplitude of ~0,23 mm. The average vertical harmonic force applied to the granule near the sleepers during the half-period for the first harmonic will be:

$$\overline{F}_{harm1} = \frac{m_g \cdot A\omega^2}{\pi} \int_0^{\pi} \sin \omega t dt = \frac{2Am_g\omega}{\pi} = 3{,}9 \cdot 10^{-3} N. \quad (6)$$

For the second harmonic $F_{harm2} = 1{,}24$ k. The force impulse for a half-wave of the second harmonic is $5{,}5 \cdot 10^{-2}$ N • s, and the additional speed of a 60 mm granule will be 0,8 m/s, and for a 25 mm granule the velocity will be 0,34 m/s.

The sleeper rotation angle is not included in the standardized parameters of the railway track, we calculate it relative to the fastening for a uniform rail deflection by 3 mm in its middle part between sleepers. For the ratio of the rail shoulder (546: 2 mm) and height of the sleeper (183 mm), the angle α is 6,4°. But, since we did not consider the nonlinear deflection of the rail, we take the angle of rotation α ≈ 6°. Considering the rotation of the sleeper by 6°, equation (3) takes the form:

$\tau_g \cdot Sc \cdot \Delta t \cdot \cos(\alpha - 6^\circ) = m_g \cdot V_g$, (7)

and speed, found from equation (4), will increase by 1,1 and will be 1,03 m/s plus 0,8 m/s.

From the equality of the kinetic and potential energy of a crushed stone particle with a size of 60 mm, we find the lifting height of the largest crushed stone granule ~ 0,17 m.

The speed of propagation of a wave of compressive stresses in steel during thrust of rails is ~ 10 km/s; therefore, a slipstream is able to lift outgoing granules to a great height, which is dangerous for HST and infrastructure. Longitudinal forces in rails due to temperature changes and during emergency braking have much greater values. For example, for new rails of R65 type, thrust force acting on the sleeper when the temperature rises by 1°C is, respectively, 20,7 kN, and the rise of particles will increase by 2,2 times.

As the crushed stone layer abrades, there will be more and more rounded particles, porosity of the surface layer will be higher and, therefore, there will be less friction, and more crushed stone granules will eject. The most probable places of ejection of crushed stone granules are hauls near settlements, where there are changes in the modes of movement (acceleration of movement and braking), as well as icing of the surface of crushed stone particles. Raised light granules, hitting the undercar equipment and flying off at high speed, can cause an avalanche process of lifting of crushed stone particles.

Conclusions.

1. Based on estimates, it is shown that the main mechanism of crushed stone ejection during high-speed movement is squeezing of particles from the upper layer of granules and their rise above the crushed stone bed as a result of action of longitudinal and transverse stresses in the ballast. The most probable place of ejection of crushed stone particles is the boundary of contact between sleepers and the upper layers of the crushed stone bed.

2. Physical mechanisms (lifting of ballast by turbulent vortices, suspension of crushed stone particles over the bed under the action of mechanical vibrations of the roadbed, contact collisions of moving small particles with larger granules) contribute to an increase in porosity of the crushed stone layer, a decrease in structural viscosity, a change in orientation of

particles and, consequently, facilitate squeezing and flight of ballast granules.

3. The blocks of ice formed in the undercar space of HST under certain weather conditions crumble, colliding with rails and crushed stone and collapsing; they are also part of the mechanism of the ejection of crushed stone particles.

4. The paper formulates a new mechanism for lifting granules over the crushed stone bed as a result of action of longitudinal and transverse stresses in the surface layer of ballast. To exclude ejection of crushed stone granules and prevent damage to HST and infrastructure, complex methods should be developed to dramatically reduce longitudinal and lateral stresses in the surface layer of ballast and ice formation in the undercar space.

REFERENCES

1. Belkov, V. M., Antipov, B. V. Physical and chemical foundations of track stability [*Fiziko-khimicheskie osnovy ustoichivosti puti*]. *Put' i putevoe khozyaistvo*, 2013, Iss. 12, pp. 21–24.

2. Kolos, A. F., Tursunov, Kh. I., Nikolaytist, D. S. Investigation of strength properties of ballast material clogged with sand dunes [Issledovanie prochnostnykh svoistv ballastnogo material zasorennogo barkhatnymi peskami]. Electronic scientific journal «Engineering Bulletin of the Don», 2007–2012. [Electronic resource]: https://cyberleninka.ru/article/n/issledovanie-prochnostnyh-svoystv-ballastnogo-materiala-zasorennymi-barhannymi-peskami/pdf. Last accessed 14.05.2020.

3. Kamenskiy, V. B. Improvement of the track management system in modern conditions of railways operation [*Sovershenstvovanie sistemy vedeniya putevogo khozyaistva v sovremennykh usloviyakh raboty zheleznykh dorog*]. Abstract of Ph.D. (Eng) thesis. Moscow, 2011, 23 p.

4. Peich, Yu. L. Interaction of track elements in conditions of clogging and humidification [*Vzaimodeistvie elementov puti v usloviyakh zasoreniya I uvlazhneniya*]. Abstract of Ph.D. (Eng) thesis. Moscow, 2011, 23 p.

5. Ogibalov, P. M., Mirzadzhanzade, A. Kh. Nonstationary movements of viscoplastic media [*Nestatsionarnie dvizheniya vyazkoplastichnykh sred*]. Moscow, Publishing house of MSU, 1977, 372 p.

6. Derkowski, P., Clark, S., Sturt, R., Keylin, A., Baker, C., Vardy, A., Wilson, N. High-Speed Rail Aerodynamic Assessment and Mitigation Report. U.S. Department of Transportation. Federal Railroad Administration, Office of Research, Development, and Technology, Washington, DC20590. Report Number: DOT/FRA/ORD-15/40. December 2015, 258 p. [Electronic resource]: https://railroads.dot.gov/elibrary/high-speed-rail-aerodynamic-assessment-and-mitigation-report. Last accessed 14.05.2020.

7. Saat, M. R., Bedini-Jacobini, F., Tutumluer, E., Barkan, C. P. L. Identification of High-Speed Rail Ballast Flight Risk Factors and Risk Mitigation Strategies, Final Report. Federal Railroad Administration, Washington, DC, Report Number: DOT/FRA/ORD-15/03. 2015, 76 p. [Electronic resource]: https://railtec.illinois.edu/wp/wp-content/uploads/pdf-archive/TR_Identification-of-Ballast-Flight-Risk_final.pdf. Last accessed 14.05.2020.

8. Baker, C. J. A review of train aerodynamics. Part 1 – Fundamentals; Part 2 – Applications. *The Aeronautical Journal*, 2014, Vol. 118, No. 1201, 1202. [Electronic resource]: https://core.ac.uk/download/pdf/185479708.pdf; https://core.ac.uk/download/pdf/185479709.pdf. Last accessed 14.05.2020.

9. Jing, G., Liu, G. X., Lin, J., Martinez, J., Yin, C. T. Aerodynamic Characteristics of Individual Ballast Particle by Wind Tunnel Tests. *Journal of Engineering Science and Technology Review*, 2014, Vol. 7, Iss. 2, pp. 137–142. [Electronic resource]: http://www.jestr.org/downloads/Volume7Issue2/fulltext217214.pdf. Last accessed 14.05.2020. DOI: 10.25103/jestr.072.21.

10. Quinn, A., Hayward, M. Full-scale aerodynamic measurements underneath a high speed train. BBAA 6th International Colloquium on: Bluff Bodies Aerodynamics & Applications. Milano, Italy, July, 20–24, 2008. [Electronic resource]: https://www.researchgate.net/publication/237112260_full-scale_aerodynamic_measurements_underneath_a_high_speed_train/link/554898b80cf2b0cf7aced5ff/download. Last accessed 14.05.2020.

11. Lazaro, B. J., Gonzalez, E., Rodriguez, Manuel, Rodriguez, Miguel, Osma, S., Iglesias, J. Characterization and Modeling of Flying Ballast Phenomena in High-speed Train Lines. 9th World Congress Railway Research, May 22–24, 2011. [Electronic resource]: Challenge E: Bringing the territories closer together at higher speeds. http://www.railway-research.org/IMG/pdf/e4_lazaro_benigno.pdf. Last accessed 14.05.2020.

12. Belkov, V. M., Zhuravleva, M. A. Modelling of contamination of railway tracks and technical strip with dust particles [*Modelirovanie zagryazneniya zheleznodorozhnogo polotna tekhnicheskoi polosy pylevatymi chastitsami*]. *Vestnik VNIIZhT,* 2015, Iss. 2, pp. 9–14. [Electronic resource]: https://www.journal-vniizht.ru/jour/article/viewFile/22/23. Last accessed 14.05.2020.

13. Tursunov, Kh. I. Investigation on the oscillatory process in the ballast prism of a railway track, clogged with sand dunes [*Issledovanie kolebatelnogo protsessa v ballastnoi prizme kheleznodorozhnogo puti, zasorennoi barkhatnymi peskami*]. *Engineering Bulletin of the Don*, 2012, Iss. 3. [Electronic resource]: https://cyberleninka.ru/article/n/issledovanie-kolebatelnogo-protsessa-v-ballastnoy-prizme-zheleznodorozhnogo-puti-zasorennoy-barhannymi-peskami/pdf. Last accessed 14.05.2020.

14. GOST R [State Standard] 55050-2012 Railway rolling stock. Norms of permissible impact on the railway track and test methods (with Amendment No. 1) [*GOST R55050-2012 Zheleznodorozhniy podvizhnoi sostav. Normy dopustimogo vozdeistviya na zheleznodorozhniy puti' i metody ispytanii (s Izmeneniem No.1)*]. [Electronic resource]: http://docs.cntd.ru/document/1200096113. Last accessed 14.05.2020.

15. Effective underrail and rail pads made of SYLOMER and SYLODYN materials [*Effektivnie podrelsovie i nashpalnie prokladki iz materialov SYLOMER i SYLODYN*]. LLC Acoustic Materials and Technologies, Kiev [Electronic resource]: http://www.acoustic.ua/articles/113. Last accessed 14.05.2020.

16. Experimental assessment of interaction of the vehicle and track at speed and high-speed traffic: Monograph [*Eksperimentalnaya otsenka vzaimodeistviya ekipazha i puti pri skorostnom i vysokoskorostnom dvizhenii: Monografiya*]. Ed. by A. M. Brzhezovsky. Moscow, RAS, 2019, 152 p.

17. Popov, V. L. Mechanics of contact interaction and physics of friction [*Mekhanika kontaktnogo vzaimodeistviya i fizika treniya*]. Moscow, Fizmatlit, 2012, 348 p. ●