Technology of crushed stone ballast cleaning

Vadim Korolev¹, Alexey Loktev¹, Irina Shishkina¹, Evgenia Zapolnova¹, Vladislav Kuskov¹, Dmitry Basovsky², Olga Aktisova³

¹Russian University of Transport (RUT - MIIT) - Chasovaya st., 22/2, Moscow, 125190, Russia
²Emperor Alexander I St. Petersburg State Transport University - Moskovsky pr., 9, Saint Petersburg, 190031, Russia
³Academy of urban management, urban planning and printing - Rustaveli str., 33 letters A, Saint Petersburg, 195273, Russia

E-mail: korolevadim@mail.ru

Abstract. The article analyzes the influence of various factors on the application of the technology of crushed stone ballast clearing. A model of a ballast prism composed of crushed stone of various fractions in the form of an elastic isotropic flat layer of varying thickness, bounded around the perimeter by a contour of arbitrary shape, is considered. Criteria for evaluating crushed stone ballast cleaning technologies are given: performance of a ballast cleaning machine - estimated by operating speed, volume of cut out and cleaned ballast (per hour) and depends on the initial state of the path superstructure, initial contamination and ballast moisture, cutting depth and width of the ballast; technical characteristics of the screen, bar chain, conveyor system; quality of ballast cleaning - depends on the initial state of the ballast layer (moisture, debris), surface area and angle of screen inclination, amplitude and frequency of vibration of the screen; the purity of rubble that is returned on the way, also depends on the effectiveness of protection against weed spills on conveyors and bunkers with clean rubble, and protection against the spill of weeds from the machine onto the ballast prism after it has been cleaned. The choice of a variant of the production technology for ballast cleaning is also based on an analysis of the condition of the path before and after repair and reduces, as a rule, to the formation of a chain of heavy track machines. Analysis of the application of crushed stone ballast cleaning technology, taking into account a set of technical, operational features of the repair site, technical characteristics of track machines for deep cleaning of crushed stone ballast, as well as technological and production requirements for various types of the path repair, showed the need for further study of this issue to reduce operating costs for Russian Railways.

1. Introduction

Crushed stone ballast is the most common kind of ballast for the railways of Russian Railways. For the first and second classes of railway, the typical type of ballast is rubble with a layer thickness of not less than 40 cm under reinforced concrete sleepers. As it is known, the need to clean the rubble is due to its pollution, which is the cause of the loss of the filtration capacity of the macadam layer and general path disorder. Contamination of rubble occurs as a result of mechanical wear of its grains under the influence of a moving load and tamping mechanisms, as well as the ingress of external weeds.
Periodic restoration of bearing capacity and performance characteristics of crushed stone ballast prism is made by cleaning rubble or, in case of discrepancy of the ballast laid in the way to the required characteristics, due to its complete replacement with crushed rock for machines for cleaning rubble and replacing ballast.

Modern requirements for the ballast prism, the quality of cleaning of rubble, the periodicity of its cleaning largely determine the parameters of machines for cleaning of rubble and replacement of ballast, as well as methods of work taking into account the specific condition of the superstructure and the type of repair.

The Department of Transport Construction of RTH MIIT is working to consider the use of cleaning technology of crushed stone ballast for various types of railway track repair, the conclusions of which can be used when applying the technology of cleaning crushed stone ballast that takes into account the complex of technical, operational features of the repair site, technical characteristics of track machines for deep cleaning crushed stone ballast, as well as technological and production requirements for various types of track repair.

In accordance with the requirements of GOST 7392-2014 [1], rubble for the ballast layer of a railway track is divided into three categories:
- category B - grain composition 22.4-63 mm;
- category I - grain composition 30-60 mm;
- category II - grain composition 25-60 mm.

The lower 1 and upper 2 borders of its granulometric composition are reflected in Figure 1.

![Figure 1](image_url)  
*Figure 1. Graphics granulometric composition of rubble: 1 and 2 - the lower and upper boundaries of clean rubble; 3 - composition of extremely clogged rubble.*

2. Methods of analysis
In the present study, it is proposed to consider a model of a ballast prism composed of various fractions rubble in the form of an elastic isotropic flat layer of variable thickness $h(x,y)$, bounded around the perimeter by a contour of arbitrary shape [2, 3]. Displacements of an arbitrary point of the ballast layer $(x,y,z)$, provided that $z$ is the distance from the neutral surface can be represented as:

$$
u = -z \frac{\partial w}{\partial y}, \quad w = w(x, y).$$

The deformations included in the general tensor under the condition of small deformations can be written as
The components of the stress tensor are determined by the generalized Hooke law

\[ \sigma_{xx} = \frac{E}{1-\sigma^2} \left( \varepsilon_{xx} + \sigma \varepsilon_{yy} \right) = -\frac{Ez}{1-\sigma^2} \left( \frac{\partial^2 w}{\partial x^2} + \sigma \frac{\partial^2 w}{\partial y^2} \right), \]

\[ \sigma_{yy} = \frac{E}{1-\sigma^2} \left( \varepsilon_{yy} + \sigma \varepsilon_{xx} \right) = -\frac{Ez}{1-\sigma^2} \left( \frac{\partial^2 w}{\partial y^2} + \sigma \frac{\partial^2 w}{\partial x^2} \right), \]

\[ \sigma_{xy} = \sigma_{yx} = \frac{E}{1+\sigma} \varepsilon_{xy} = -\frac{Ez}{1+\sigma} \frac{\partial^2 w}{\partial x \partial y}, \]

\[ \sigma_{xz} = \sigma_{zx} = \sigma_{yz} = \sigma_{zy} = 0. \]

here, E and \( \sigma \) are the modulus of elasticity and the Poisson’s ratio of the embankment material.

To obtain the governing relations for the layer of computational material under the free edge conditions, it is proposed to use the displacement functional \( \Phi(x,y) = \Phi(u(r,\theta),v(r,\theta) \), the equality to zero of this functional reflects the fulfillment of the boundary conditions. This assumes that the Cauchy – Riemann conditions are satisfied:

\[ \frac{\partial u}{\partial r} = \frac{1}{r} \frac{\partial v}{\partial \theta}, \quad \frac{\partial v}{\partial r} = -\frac{1}{r} \frac{\partial u}{\partial \theta}. \]

In this case, you can write the defining equations in the form:

\[
\begin{pmatrix}
\frac{\partial^2 \Phi}{\partial x^2} \\
\frac{\partial^2 \Phi}{\partial x \partial y} \\
\frac{\partial^2 \Phi}{\partial y^2}
\end{pmatrix} = A^{-1} \begin{pmatrix}
\frac{\partial^2 \Phi}{\partial r^2} \\
\frac{\partial^2 \Phi}{\partial r \partial \theta} \\
\frac{\partial^2 \Phi}{\partial \theta^2}
\end{pmatrix} + \frac{1}{r^3} \left| \psi'(\xi) \right|^4 \begin{pmatrix}
\zeta_1 \\
\zeta_2 \\
\zeta_3
\end{pmatrix},
\]

where

\[ A^{-1} = \frac{1}{r^2 \left| \psi'(\xi) \right|^4} \begin{pmatrix}
v_0' \frac{2u_0' v_0' \psi'}{r} - u_0' \frac{u_0^2 \psi'}{r^2} \\
u_0' \frac{2u_0' v_0' \psi'}{r} - u_0' \frac{u_0^2 \psi'}{r^2} \\
u_0^2 - u_0' \frac{2u_0' v_0' \psi'}{r} - u_0' \frac{u_0^2 \psi'}{r^2}
\end{pmatrix}.\]
The solution of the presented differential equations can be found numerically using a computer. For this period of oscillation or time of passage of the characteristic thickness of the ballast prism by an elastic wave is divided into \( k \) parts. The duration of the elementary time interval \( \tau \) depends on the natural frequency of the prism and the speed of propagation of wave fronts in it [4].

For a sufficiently small integration step, it can be assumed that at each interval \( (n-1)\tau \leq t \leq n\tau \) unknown functions of the contact force, deflection, bending moment, etc. behave linearly, i.e. the derivative of an unknown function can be calculated as a ratio:

\[
\dot{f}(n\tau) = \frac{f_n - f_{n-1}}{\tau},
\]

where \( f \) is an unknown function of time to be determined.

Substituting this relation into the governing equations, we obtain recurrent expressions that will allow us to determine the value of the unknown functions at each time instant [5, 6].

In this paper, for the final solution of the problem, assumptions are made that any unknown quantity behaves linearly in time if a small time interval is specified \( \tau_i = \pi i \). The above numerical procedure can be automated using the existing mathematical packages MathCAD, MATLAB, Maple, Mathematica, and using the standard features of the C++ programming languages, Delphi, etc.

Rubble should have a fairly uniform granulometric distribution: when sifting it through a sieve with a cell diameter of 40 mm, the total residue on the sieve should be 35 - 70% of the total sample mass. The content of lamellar and needle-shaped particles is allowed to be no more than 15% for rubble of categories B and I and not more than 18% for rubble of category II. Particles of fractions less than 22 mm are weeds. Due to weeds, the percentage ratio of fractions changes. If the degree of contamination exceeds 35%, it is necessary to clean the ballast prism. The degree of rubble clogging after the passage of a crushed stone cleaning machine depends on the quality of the machine operation,
the initial state of the ballast (pollution, humidity) and, according to the technical requirements for crushed stone cleaning machines, should not exceed 5% [7, 8].

There are several types of track machines in each travel direction of track machines to ensure the performance of work on cleaning ballast on spans, turnouts, station paths with high and low platforms. Machines have significant differences in design (single and two-section, self-propelled and non-self-propelled, with one or two bar chains, roller and electromagnetic lifting and leveling devices), performance (from 400 to 1600 m³/h), the presence of additional working bodies and functions (ballast punch, layer-by-layer compaction device, possibility of laying geotextiles) and other differences.

For various types of track repairs using crushed stone machines, multivariate standard technological processes are being developed. On the basis of typical processes, road technical services develop working technological processes that take into account local conditions for carrying out track repairs. The main parameters of the process are the duration of the "window" and the scope of work performed during the "window". As a rule, if one of these parameters is present, calculations, taking into account the technological sequence of work and the available means used to carry them out, determine the second parameter of the technological process [9, 10].

When planning the seasonal volume of repairs, Lrep takes into account, first of all, the possible number of basic “windows” nw provided by the condition of train movement. If their number is known, the required scope of work in the “window” is determined by the expression Ssc = Lrep/nw, and the duration of the window is calculated from it [11].

The calculation of the regulatory output of computerized complexes and the main types of track machines must be carried out taking into account regional operating conditions. During the operation of various types of track machines for repairs and path maintenance, their annual output is influenced by factors common to all machines: the duration of the machine operating season and the duration of machine idle for various reasons, the number, duration and periodicity of “windows” appears, the service life of the machine and other reasons that change the output of a particular machine [12, 13].

When operating mechanized complexes for track repairing with deep cleaning of ballast, the regulatory output must be calculated on the basis of the stone cleaning machine performance, which will limit the performance of the entire technological complex.

The output of track machines is influenced by the state of the superstructure, especially the state of the ballast prism. Operating experience of crushed stone cleaning machines shows that with heavily clogged wet ballast, the technical performance of these machines is reduced to 50% due to a decrease in the efficiency of rubble cleaning on screens.

Work technology also has an impact on machine output. With deep cleaning of the ballast with the laying of an insulating layer (geotextiles, polystyrene foam plates), the output of crushed stone cleaning machines is also reduced.

3. The results of the study
The main criteria for evaluating of crushed stone ballast technology include:
- ballast cleaning machine productivity - it is estimated by the working speed, the volume of the cut and cleaned ballast (per hour) and depends on the initial state of the track superstructure, the initial contamination and ballast humidity, the depth and width of the ballast notch; technical characteristics of the screen, bar circuit, conveyor system;
- quality of ballast cleaning - depends on the initial state of the ballast layer (humidity, debris), surface area and angle of screen inclination, amplitude and frequency of vibration of the screen; the purity of rubble that is returned on the path also depends on the effectiveness of protection against weed spills on conveyors and bunkers with clean rubble, and protection against the ingress of weeds from the machine onto the ballast prism after it has been cleaned.

The choice of the production technology variant for ballast cleaning is based on the analysis of the track condition before and after the repair and is reduced, as a rule, to the formation of a chain of heavy track machines. First of all, attention is paid to the design of the track to track repair and after,
on the look and contamination of the ballast layer, the scope of work, the duration of the “windows”, the ability to work on a closed span, the possibility of shuttle operation of the trains for weeds and hopper batchers.

The following work operation variants are possible: cutting out the ballast without cleaning for its complete replacement; cleaning old ballast; cleaning of old ballast with a device in the ballast prism of a separating layer made of polystyrene foam or geotextile; cleaning of the old ballast layer with lowering the rail head marks due to ballast cutting. When forming the technological chain of machines, it is necessary to take into account a number of their design features, since this can fundamentally change the entire technological process.

The analysis of the crushed stone ballast cleaning technology use, taking into account the complex of technical, operational features of the repair site, technical characteristics of track machines for deep cleaning of crushed stone ballast, as well as technological and production requirements for various types of path repair, showed the need to summarize and further study this issue to reduce operating costs for Russian Railways.

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