Determining service life of non-ballast track based on calculation and test

A V Savin¹, V V Korolev² and I V Shishkina²

¹Deputy Director General – Head of Test Center, Railway Research Institute (JSC "VNIIZHT"), 10, 3rd Mytischinskaya str., Moscow 107996, Russia
²Department of Transport construction, Russian University of Transport (MIIT), 22/2, Chasovaya str., Moscow 125190, Russia

E-mail: shishkinaira@inbox.ru

Abstract. At the Test Loop of JSC VNIIZHT there have been finished unique testing of non-ballast track in a volume 1.1 milliard tones gross of passed tonnage. The calculation-test method for service life definition of non-ballast track at high-speed track is presented under test results on the Test Loop. Taking into account operation conditions at the high-speed track 176.6 kN on axle the speed is 300 km/h and working capacity is 30 mln. t gross, the passed tonnage will make up 2270.4 mln. t gross or 75.7 years of service. The authors developed a calculation-test method, which allows predicting for a good reason a service life of innovate track construction upon the calculation and accelerated test results on a closed polygon. The article provides a way to forecast the behaviour of various track constructions in advanced operation conditions that are not yet created according to the results of tests on the Test Loop. The reasonably calculated service life of a non-ballast track makes it possible to objectively compare it with the payback period, thus determining the expediency of its construction at the testing stage.

1. Introduction

In modern operation conditions at high axle load, increase of trains weight and length one of the main problems becomes track deformability. Application of non-ballast construction is one of the variants to increase track stability.

Ordinary scheme of various constructions testing provides laboratory tests of track elements than tests at the Test Loop of JSC VNIIZHT, station Sherbinka and after under-control operation on active line. Such scheme meets the conditions of test terms for non-ballast track at high speed. At the Test Loop it can be provided intensive resource testing’s in tight schedule. However, it is impossible to carry out tests at high speed. At action line it is possible to perform one-time tests at high speed. But this will not give useful indication about construction resources. Moreover, it is unauthorized to operate construction at the action line, which has not passed full testing.

At the track constructions, tests for high-speed traffic at the Test Loop it is pro-posed to use calculation-test method for service life determining [1].

There have been finished tests of non-ballast track constructions at the Test Loop of JSC VNIIZHT, station Sherbinka. Tests were performing from 2014 till 2018 year [2-5]. Passed tonnage made up 1.1 milliard tones gross. Tonnage run was performed by tested train from 85 cars with axle load 230.3 kN and speed 80 km/h.
It is experimentally proved possibility of non-ballast track use for freight traffic and determined service life or resource for these operation conditions. There is one issue is left opened, concerning service life of non-ballast track for high-speed traffic. What would be passed tonnage at axle load about 176.6 kN and speed 300 km/h? In other words, how according to the results of tests of track structure in some conditions, can one predict its behavior in other conditions?

To answer this question there was proposed the calculation-test method to acknowledge correspondence of a non-ballast track to specified technical requirements due to absence of real terms of exploitation [6].

2. Arithmetic model

Proposed method allows predicting of service life of a non-ballast track in number of passed tonnage. It manages to be done thank to method application which combine actual test and arithmetic modeling. Besides, according to test results, an arithmetical model is verified. Professor A. Kogan suggests examining a non-ballast track as multi-layer beam in a series his works [7, 8]. This model worth to apply for modern constructions of a non-ballast track [9].

In the proposed model the track fluctuation is examined as construction fluctuation that contains three infinitely long beams, the lower of which lies on the modified Winkler base, and the upper and middle rests on elastic layers, mainly having the characteristics of the Winkler base. For a certain construction of non-ballast track this is consequently rail, concrete structural board (track concrete) and hydraulically bound layer (common concrete).

Using this model there were obtained magnitude of voltage and layers bend of a non-ballast track construction for current terms at the Test Loop of JSC VNIIZHT at the Sherbinka station and terms that meet perspective high-speed traffic.

In the model of track fluctuation which contains three infinitely long beams that lay in modified Winkler base (Figure 1).

![Figure 1. Calculation model.](image)

On the upper beam is subject to a variable in time dynamic load $Q(t)$, that moves with coefficient speed $V$. Fluctuations of this multi-layer construction are described by following system of differential equations:

$$
\begin{align}
E_1I_1 \frac{\partial^4 z_1}{\partial x^4} + m_1 \frac{\partial^2 z_1}{\partial t^2} + f_1 \left( \frac{\partial z_1}{\partial t} - \frac{\partial z_2}{\partial t} \right) + U_1 (z_1 - z_2) &= 0; \\
E_2I_2 \frac{\partial^4 z_2}{\partial x^4} + m_2 \frac{\partial^2 z_2}{\partial t^2} + f_2 \left( \frac{\partial z_2}{\partial t} - \frac{\partial z_3}{\partial t} \right) + U_1 (z_2 - z_1) + U_2 (z_2 - z_3) &= 0; \\
E_3I_3 \frac{\partial^4 z_3}{\partial x^4} + m_3 \frac{\partial^2 z_3}{\partial t^2} + f_3 \frac{\partial z_3}{\partial t} + U_2 (z_3 - z_2) + U_3 z_3 &= 0,
\end{align}
$$

where: $z_i$ – vertical bend of $i$-layer;
$E_i$ – elasticity modulus of material at $i$-layer;
$I_i$ – inertia couple of $i$-layer at its bend toward to across long axis;
\( m_i \) – distributed rotating mass of \( i \)-layer;  
\( f_i \) – distributed reduced damping of \( i \)-layer;  
\( U_i \) – modulus of foundation of \( i \)-layer at vertical bend;  
\( x \) – abscissa of the current section of the beam, measured from a fixed point of origin;  
\( t \) – time;  
\( Q(t) \) – oscillatory load;  
\( v \) – traverse speed of oscillatory load.

Taking functions \( z_i(u, t) \) as system reaction on impact \( Q(t) = e^{j\omega t} \), with allowance for operator’s linearity, note:

\[
(2)
\]

Exchange \( u = x-vt \) system is transformed into:

\[
(3)
\]

Solutions of this system are presented as follows

\[
W_{i\sigma}^Q(u, i\omega) = \begin{cases} 
W_{i\sigma}^Q(u, i\omega) & \text{at } u \geq 0; \\
W_{i\sigma}^Q(u, i\omega) & \text{at } u \leq 0.
\end{cases}
\]

From frequency-response characteristics of beam layers bends \( W_{i\sigma}^Q(u, i\omega) \), there were found bends sizes \( z_i \) under acting load \( Q(t) \) by formulas:

\[
(5)
\]

Frequency-response characteristics of bending moments in layers are defined by following method:

\[
W_{iM}^Q(u, i\omega) = \begin{cases} 
W_{iM}^Q(u, i\omega) & \text{at } u \geq 0; \\
W_{iM}^Q(u, i\omega) & \text{at } u \leq 0,
\end{cases}
\]

where \( W_{iM}^Q(u, i\omega) \) – frequency-response characteristic that defines, determining at the entrance of the dynamic force in the contact wheel and rail \( Q(t) \) bending moments in beams of three layers in a non-ballast track construction in cross sections \( u \).

Using frequency-response characteristics \( W_{iM}^Q(u, i\omega) \), we can find average mean of voltage vectors in stated points of layers \( \sigma_i \) caused by force vector \( Q(t) \) by formulas:

\[
(7)
\]

\( \langle Q \rangle \) - column-vector of average means of vertical forces \( Q \);  
\( W_i \) - moment of resistance at a given point \( i \)-layer.

### 3. Calculation and test results

Initial data for arithmetical model is represented in table 1. In the table 2 there are represented the results of calculation on the model and measurements at the Test Loop of layer’s bends of a non-ballast track in multi-layer beam and strains in layers for speed 80 km/h and axle load 230.5 kN.
In the table 3 there are results of calculation layers’ bends BVSP (БВСП) as multi-layers beam and strains in layers for speed 300 km/h and axle load at 176.6 kN.

The bottom layer with depth 50 sm is a chemical reinforced ground, which is obtained by mixture of grounds blend (70 % sand of medium grain and 30 % of clayed soil) with chemical additives.

Average meaning of deformation module on the second loading path is 146 MPa. Design point of deformation module for reinforced ground should be at least 80 MPa.

The next layer is crushed stone sand gravel (ЩПГС) by the Technical specifications 5711-284-01124323-2012 depth 70 sm. Average meaning of deformation module on the second loading path is 181.7 MPa at the design point at least 120 MPa [9, 10].

Design data and experimental values fairly good correspond between each other. After adequate checkup of arithmetical model by the test results at the Test Loop it is possible to make a prognoses about deflection and strain values in high-speed motion conditions, substituting the known motion parameters and track design parameters into the model [11,12].

Represented method allows forecasting service life of a non-ballast track in regard to passed tonnage. It is possible to do by through combination of natural experiment and mathematical modeling [13,14].

**Table 1. Initial data.**

| Layer number | Material | Depth, mm | Width, mm | Volume in 1 running meter, m³ | Density, kg/m³ | Modulator of elasticity, E, H/m² | Inertia couple (vert.) I, m⁴ | Modulus of inelastic buckling U, Pa | Distributed rotatimg mass m, kg/m | Distributed reduced damping f, Нс/m² |
|--------------|----------|-----------|-----------|-------------------------------|----------------|---------------------------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1            | Rail     | 180       | 240       | 2500                          | 0.2110⁷        | 34.510⁷                        | 0.35510⁴                      | 0.10410⁸                       | 65                             | 0.17310²                      |
| 2            | Concrete layer | 240 | 3500 | 0.6 | 2300 | 0.35510⁴ | 0.10410⁸ | 65 | 0.17310² | 0.2910² |
| 3            | Common concrete | 300 | 4500 | 3.15 | 1800 | 0.3110⁹ | 0.31862 | 0.6910⁵ | 1420 | 0.6910⁵ |
| 4            | Crushed stone sand gravel | 700 | 6000 | 3.0 | 1350 | 0.12862 | 0.10410⁸ | 65 | 0.17310² | 0.2910² |
| 5            | Chemically reinforced ground | 50 | 6000 | 3.0 | 1350 | 0.12862 | 0.10410⁸ | 65 | 0.17310² | 0.2910² |

**Table 2. Bends and strains for 80 km/h and 230.5 kN on axle.**

| Layer number | 1 layer - rail | 2 layer concrete | 3 layer common concrete | Chemically reinforced ground |
|--------------|----------------|-------------------|-------------------------|----------------------------|
| Bend meaning under strain, mm | Measured | 3.7 | 2.5 | 1.5 | 1 |
| Calculated | 3.5 | 2.9 | 0.7 | 0.5 |
| Strain meaning under strain, kgf /sm² | Measured | 950 | 7.5 | 1.3 | 0.8 |
| Calculated | 820 | 6.3 | 1.12 | 0.92 |

**Table 3. Bends and strains for 300 km/h and 176.6 kN on axle.**

| Layer number | 1 layer - rail | 2 layer concrete | 3 layer - crushed stone sand gravel | Chemically reinforced ground |
|--------------|----------------|------------------|------------------------------------|----------------------------|
| Bend meaning under strain, mm | 1.2 | 0.9 | 0.3 | 0.01 |
| Strain meaning under strain, kgf /sm² | 670 | 4.9 | 1.23 | 0.95 |
Passed tonnage for a non-ballast track at high-speed network under known meanings and at the Test Loop are defined as follows [15, 16]:

\[ T_1 = T_0 \cdot \frac{D_0}{D_1} \cdot \left( \frac{P_1}{P_0} \right)^k \cdot K_t \]  

(8)

where \( D_1 \) – damage indicator (on the first or second limit state) in planned terms of operation, is presented by calculation;

\( D_0 \) - damage indicator (sediment or strains) at the test section of the Test Loop;

\( T_1 \) – gross tonnage, passed on the section of active line up to resource starvation;

\( T_0 \) - gross tonnage, passed on the section of active line up to resource starvation (up to achieving critical values of deflection, strains, precipitation);

\( P_1 \) – average axle load at the section of active line;

\( P_0 \) - average axle load at the test section;

\( k \) - empirically determined coefficient from 1 till 3,

\( \gamma_1 \) - number of defrost / freeze transitions (Spring, Autumn) at 100 mln. t gross on the active line;

\( \gamma_0 \) - number of defrost / freeze transitions (Spring, Autumn) at 100 mln. t gross on the test section;

\( K_t \) – climate influence coefficient, which characterizes increase track deterioration intensity in period of defrost and freezing in Autumn \( K_t = 0.13 \cdot \frac{\gamma_1}{\gamma_0} \)

Taking into account work capacity at the Test Loop at 300 mln. t gross per year and at the high-speed network there is about 30 mln. t gross per year, the estimated tonnage in real operation terms was obtained [17-20]. Depending on meanings of the second (concrete) layer bends in tables 2 and 3 we obtain forecasted passed tonnage on high-speed network after passing at the Test Loop1100 mln. t gross:

\[ T_1 = 1100 \cdot \frac{2.5}{0.9} \cdot \left( \frac{176.6}{230.5} \right)^{0.13} \cdot \frac{0.6}{0.06} \]

\[ T_1 = 2270.4 \text{ mln. t gross} \]

Due to the tonnage at \( \Pi \) 30 mln. t gross the service life will be 75.7 years.

4. Conclusions

There is developed calculation-test method, which allows to predict for a good reason a service life of innovate track construction upon the calculation and accelerated test results on a closed polygon.

Found a way to forecast behavior various track constructions in advanced operation conditions that are not yet created according to the results of tests on the Test Loop.

The reasonably calculated service life of a non-ballast track makes it possible to objectively compare it with the payback period, thus determining the expediency of its construction at the testing stage.

References

[1] Savin A V, Tretiyakov V V, Kaplin V N, Petrov A V, Tretiyakov K I 2017 Test data of a non-ballast track at the Test Loop JSC VNIIZHT Vestnik Railway-Research Institute 4 195–201
[2] Savin A V 2017 Results of a non-ballast track tests Vestnik Institute of Natural Monopolies Research: RAILWAY TECHNOLOGY 1 26–31
[3] Savin A V, Petrov A V, Tretiyakov K I 2016 Non-ballast track construction test Vestnik Institute of Natural Monopolies Research: RAILWAY TECHNOLOGY 2 28–38
[4] Savin A V, Brzhevosky A M, Tretiyakov V V, Smelyansky I V, Tolmachev S V 2015 Research of a ballast-less construction of superstructure Vestnik Railway-Research Institute 6 23–32
[5] Savin A V 2014 Combined method of railway track study *Vestnik of Volga region transport. Edition: Samara State Transport University* 4 63–68

[6] Savin A V 2017 The Service Life of Ballastless Track *Procedia Engineering* 189 379–385 http://www.scencedirect.com/science/article/pii/S1877705817321847

[7] Kogan A Ya, Nikitin D A, Poleshuk I V 2007 Track fluctuations at high traffic speeds of carriage and impact interaction of wheel and rail *Labour of VNIIZHT* (Moscow: Intext) p 166

[8] Savin A V, Kogan A Ya 2017 Method of of determining the estimated life of the non-ballast track *Vestnik Railway-Research Institute* 1 3–9

[9] Savin A V 2017 *Non-ballast track* (Moscow: PAC) p 192

[10] Savin A V, Dydyshko P I 2015 Non-ballast track and its ground *Railway transport* 12 39–41

[11] Loktev Alexey A, Korolev Vadim V, Shishkina Irina V, Basovsky Dmitry A 2017 Modeling the dynamic behavior of the upper structure of the railway track *Transportation Geotechnics and Geocology, Procedia Engineering* (Saint Petersburg) 189 133–137

[12] Glusberg B, Korolev V, Shishkina I, Loktev A, Shukurov J, Geluh P 2018 Calculation of track component failure caused by the most dangerous defects on change of their design and operational conditions *MATEC Web of Conferences* 239 01054 DOI: 10.1051/matecconf/201823901054

[13] Loktev A A, Korolev V V, Shishkina I V 2018 High frequency vibrations in the elements of the rolling stock on the railway bridges *IOP Conf. Series: Materials Science and Engineering* 463 032019 DOI: 10.1088/1757-899X/463/3/032019

[14] Loktev A A, Korolev V V, Poddaeva O I, Chernikov I YU 2018 Mathematical modeling of antenna-mast Structures with aerodynamic effects *IOP Conf. Series: Materials Science and Engineering* 463 032018 DOI: 10.1088/1757-899X/463/3/032018

[15] Loktev A A, Gridasova E A, Sycheva A V and Stepanov R N 2015 Simulation of the Railway under Dynamic Loading. Part 2. Splicing Method of the Wave and Contact Solutions *Contemporary Engineering Sciences* 8(21) 955–962

[16] Gridasova E A, Nikiforov P A, Loktev A A et al 2017 *Science and technology of transport* 2 82–91

[17] Gridasova E A, Nikiforov P A, Nisaev I P et al 2017 Changing the structure of low-carbon steel at high-frequency cyclic loadin *Introduction of modern structures and advanced technologies in track economy* 11(11) 30–36

[18] Loktev A A 2007 Impact of a viscoelastic body on an elastic isotropic plate *Mehanika kompozitsionnih materialov i konstruktii* 13(3) 417–425

[19] Loktev A A 2007 Elastoplastic model of the relationship of cylindrical impact and plate *Pis’ma v zhurnal tehnicheskoi fiziki* 33(16) 72–77

[20] Loktev A A, Zaletdinov A V 2010 Determination of the interaction points of direct and reflected waves in a plate *Vestnik MGSU* 4-3 303–308