Evaluation of the Service Life of Non-Ballast Track Based on Calculation and Test

Alexander Savin, Alexander Kogan, Alexey Loktev, Vadim Korolev

Abstract: Unique tests of non-ballast track amounting to 1.1 bln tons gross of the tonnage have been completed on the JSC VNIIZHT Test Loop near Scherbinka railway station. The calculation and experimental method for evaluation of service life of non-ballast track installed on a high-speed line is presented, based on the results of tests carried out on the Test Loop. Taking into account operation conditions on a high-speed line – 176,6 kN axle load at the speed of 300 km/h and working capacity 30 mio. tons gross, the tonnage amounts to 2270.4 mio. tons gross or 75.7 years of service.

Index Terms: Axle load,Non-ballast track, Service life, Working capacity, Speed.

I. INTRODUCTION

Under modern operation conditions comprising axle load increase, as well as the increase of trains weight and length, one of the main problems arising is track deformity. Use of a non-ballast construction is one of the alternatives for enhancing of track stability.

Conventional test scheme of various track constructions involves laboratory tests of track elements and then further tests on the JSC VNIIZHT Test Loop near Scherbinka station, followed by under-control operation on a regular line. Such scheme does not fully meet test conditions of non-ballast track for high speed traffic. The Test Loop can provide intensive resource testing within tight schedule. However, it is impossible to carry out tests at a high speed. At an action line it is impossible to perform one-time tests at high speed. High speed one-time tests are possible on a regular line; but they will not give a general idea about the constructional resource. Moreover, tests of constructions that have not been undergone a full cycle of testing are not permitted on a regular line.

During tests on the Test Loop of innovative track constructions for high speed traffic a calculation and experimental method for evaluation of service life is proposed [1].

Tests of non-ballast track constructions have been completed on the JSC VNIIZHT Test Loop near Scherbinka railway station. Tests were carried out from 2014 till 2018 [2]-[5]. The tonnage amounts to 1.1 bln. tones gross. The tonnage was achieved by a test train of 85 cars with axle load 230.3 kN and speed up to 80 km/h.

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It was experimentally proved that non-ballast track is applicable for freight traffic; as well the service life or resource for these operating conditions was estimated. The only one issue remained open, namely the service life of non-ballast track for high speed traffic. What would be the tonnage under axle load about 176.6 kN and speed up to 300 km/h? Otherwise speaking, how to forecast track structures’ behavior in some conditions using the results of tests in other ones?

To answer this question, a calculation and experimental method is proposed for conformity assessment of a non-ballast track to the required technical specifications due to having no real operational conditions available [6].

II. PROPOSED METHODOLOGY

A. Mathematic Model

Proposed method allows forecasting the number of years or the tonnage of the service life. It can be done with the use of the method which combines field testing and arithmetic modeling. Besides that, accuracy of mathematical model is verified by the field test results. In a series his works [7], [8] Prof. A. Kogan suggests considering a non-ballast track as multi-layer beam. This model worth applying to the modern non-ballast track constructions [9].

In the proposed model the track fluctuations are considered as structural fluctuations. This structure features three infinitely long beams, the lower of which lies on a modified Winkler foundation, and the upper and the middle beams rest on elastic layers, mainly having the characteristics of the Winkler foundation. For certain non-ballast track construction these are the rail, the concrete bearing plate (track concrete) and the hydraulically bound layer (common concrete) accordingly.

With the use of this model the values of stress and bending of the layers of a non-ballast track construction for the conditions observed on the JSC VNIIZHT Test Loop, as well as conditions that correspond to the perspective high speed traffic were derived.

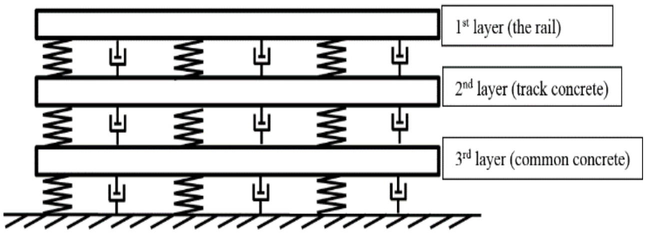

Fig 1. Calculation model

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The model of track fluctuations comprises three infinitely long beams that lay on a modified Winkler foundation (Fig. 1).

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

$$\begin{cases} E_1 I_1 \frac{\partial^4 z_1}{\partial x^4} + m_1 \frac{\partial^2 z_1}{\partial t^2} + f_1\left(\frac{\partial z_1}{\partial t} - \frac{\partial z_2}{\partial t}\right) + U_1(z_1 - z_2) = 0; \\ E_2 I_2 \frac{\partial^4 z_2}{\partial x^4} + m_2 \frac{\partial^2 z_2}{\partial t^2} + f_1\left(\frac{\partial z_2}{\partial t} - \frac{\partial z_1}{\partial t}\right) + f_2\left(\frac{\partial z_2}{\partial t} - \frac{\partial z_3}{\partial t}\right) + \\ + U_1(z_2 - z_1) + U_2(z_2 - z_3) = 0; \\ E_3 I_3 \frac{\partial^4 z_3}{\partial x^4} + m_3 \frac{\partial^2 z_3}{\partial t^2} + f_2\left(\frac{\partial z_3}{\partial t} - \frac{\partial z_2}{\partial t}\right) + f_3 \frac{\partial z_3}{\partial t} + U_2(z_3 - z_2) + U_3 z_3 = 0. \end{cases}$$

where: z_i is a vertical bend of the i-layer;

E_i is an elasticity modulus of material of the i-layer;

I_i is an inertia moment of the i-layer at its bend towards the transverse horizontal axis;

m_i is a distributed reduced mass of the i-layer;

f_i is a distributed reduced damping of the i-layer;

U_i is an elasticitymodulus of foundation of the i-layer under vertical bending;

x is an abscissa of the given beam section, measured from a stationary zero point;

t is time;

$Q(t)$ is an oscillatory load;

v is a speed of oscillatory load.

Taking functions $z_i(u,t)$ as a system reaction to the impact$Q(t) = e^{i\omega t}$, with regard to the operator's linearity, we can write:

$$z_i(u,t) = e^{i\omega t} W_{zi}^{Q}(u, i\omega)$$

By the substitution $u = x - vt$ the system is transformed into:

$$\begin{cases} W_{z1}^{IV} + a_1 W_{z1}^{II} + a_2 W_{z1}^{I} + a_3 W_{z1} + b_1 W_{z2}^{I} + b_2 W_{z2} = 0; \\ W_{z2}^{IV} + b_3 W_{z2}^{II} + b_4 W_{z2}^{I} + b_5 W_{z2} + a_4 W_{z1}^{I} + a_5 W_{z1} + c_1 W_{z3}^{I} + c_2 W_{z3} = 0; \\ W_{z3}^{IV} + c_3 W_{z3}^{II} + c_4 W_{z3}^{I} + c_5 W_{z3} + b_6 W_{z2}^{I} + b_7 W_{z2} = 0. \end{cases}$$

Solutions of this system are presented as follows

$$W_{zi}^{Q}(u, i\omega) = \begin{cases} W_{zi+}^{Q}(u, i\omega) \text{where} \quad u \geq 0; \\ W_{zi-}^{Q}(u, i\omega) \text{where} \quad u \leq 0. \end{cases}$$

Using amplitude-frequency characteristics of beam layers bends $W_{zi}^{Q}(u, i\omega)$, the bends sizes z_i under acting load $Q(t)$ can be calculated. The formulas are as follows:

$$z_i(u,t) = Q(t) W_{zi}^{Q}(u, i\omega); \; i = \overline{1.3}.$$

Frequency characteristics of bending moments in the layers to be determined as follows:

$$W_{Mi}^{Q}(u, i\omega) = \begin{cases} W_{Mi+}^{Q}(u, i\omega) \text{at} \quad u \geq 0; \\ W_{Mi-}^{Q}(u, i\omega) \text{at} \quad u \leq 0, \end{cases}$$

where $W_{Mi}^{Q}(u, i\omega)$is a frequency characteristic that defines determining at the entrance point the bending moments in beams of three layers in a non-ballast track construction in cross sections u with the use of the dynamic force in the wheel-rail contact *Q(t).*

Using frequency characteristics $W_{Mi}^{Q}(u, i\omega)$, we can find average value of stress vectors in the targeted points of the layers $\langle \sigma_i \rangle$ under the load vector $Q(t)$ by the following formulas:

$$\langle \sigma_i \rangle = W_{Mi}^{Q}(0) \cdot \frac{\langle Q \rangle}{W_i}; \; i = \overline{1.3};$$

$\langle Q \rangle$ is a column-vector of the average values of vertical forces Q;

W_i is a moment of resistance at a given point of the *i*-layer.

III. CALCULATION AND TEST RESULTS

Initial data for mathematical model are presented in Table I.

Table II shows the results of model calculation and measurements of layer's bends of a non-ballast track as a multi-layer beam, as well as the stress in layers for speed up to 80 km/h and axle load 230.5 kN on the Test Loop.

Table III contains the results of calculation of layers bends of non-ballast construction as a multi-layer beam and stress in layers for speed up to 300 km/h and axle load at 176.6 kN.

The 50 cm thick bottom layer is a chemically stabilized soil, which is achieved by a mixture of grounds blend (70% of medium-grained sand and 30 % of clayed soil) with chemical additives.

Average value of deformation module on the second loading path is 146 MPa. Design values of deformation module for the stabilized soil should be no less than 80 MPa.

The next 70 cm thick layer consists of the crushed stone, sand and gravel. The composition is regulated by the Technical Specifications 5711-284-01124323-2012. 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 and experimental values fairly good correspond between each other. After verification of mathematical model using the test results obtained on the Test Loop it is possible to forecast bends and stress values under high speed traffic conditions, by substituting to the model of the known motion parameters and track design parameters.

The presented method allows forecasting service life of a non-ballast track with regard to the tonnage. It can be achieved by a combination of natural experiment and mathematical modeling.

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Table I. Initial data

Layer	Material	Thickness, mm	Width, mm	Volume in 1 running meter, m^3	Density, kg/m^3	Modulus of elasticity, *E*, H/m^2	Inertia moment (vert.) *I*, m^4	Reduced elasticity modulus *U*,Pa	Distributed reduced mass *m*, kg/m	Distributed reduced damping *f*, $H{\cdot}c/m^2$
1	Rail	180				$0.21{\cdot}10^{12}$	$0.355{\cdot}10^{-4}$	$0.104{\cdot}10^{9}$	65	$0.173{\cdot}10^{5}$
2	Concrete layer	240	2500	0.6	2300	$34.5{\cdot}10^{9}$	0.00288	$0.25{\cdot}10^{9}$	690	$0.29{\cdot}10^{5}$
3	Common concrete	300	3500	1.05	1800	$23.4{\cdot}10^{9}$	0.007875	$0.31{\cdot}10^{9}$	945	$0.65{\cdot}10^{5}$
4	Crushed stone sand gravel	700	4500	3.15	1500	$18.1{\cdot}10^{7}$	0.128625	$0.39{\cdot}10^{8}$	1420	$0.69{\cdot}10^{5}$
5	Chemically stabilized soil	500	6000	3.0	1350	$14.6{\cdot}10^{7}$	0.0625	$0.42{\cdot}10^{8}$	750	$0.73{\cdot}10^{5}$

Table II. Bends and stresses for 80 km/h and 230.5 kN per axle

	Layer number	1 layer -rail	2 layer -concrete	3 layer –common concrete	Chemically stabilized soil
Bend value under load, mm	Measured	3.7	2.5	1.5	1
	Calculated	3.5	2.9	0.7	0.5
Stress value under load, kgf /sm^2	Measured	950	7.5	1.3	0.8
	Calculated	820	6.3	1.12	0.92
	Crippling	2000	16	4.2	1

Table III. Bends and stresses for 300 km/h and 176.6 kN per axle

Layer number	1 layer -rail	2 layer -concrete	3 layer - crushed stone sand gravel	Chemically reinforced ground
Bend value under load, mm	1.2	0.9	0.3	0.01
Stress value under load, kgf /sm^2	670	4.9	1.23	0.95

Tonnage for a non-ballast track of a high-speed line under the known values on the Test Loop are defined as follows:

$$T_1 = T_0 \cdot \frac{D_0}{D_1} \cdot \left(\frac{\langle P_1 \rangle}{\langle P_0 \rangle}\right)^k \cdot K_t$$

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

D_0 is a damage indicator (settlement or strain) on the test section of the Test Loop;

T_1 is a gross tonnage on a section of a regular line up to resource run-out;

T_0 is a gross tonnage on a section of a regular line up to resource run-out (up to achieving of critical values of bending, strains, settlement);

P_1 is average axle load on the section of a regular line;

P_0 is an average axle load at the test section;

k is an empirically determined coefficient from 1 till 3,

γ_1 is a number of defrost / freeze transitions (spring, autumn) for 100 mio. tons gross on a regular line;

γ_0 is a number of defrost / freeze transitions (spring, autumn) at 100 mio. tons gross on the test section;

K_t is a climate influence coefficient, which characterizes increase of track deterioration intensity during the period of defrost and freezing in autumn $K_t = 0{,}13\frac{\gamma_1}{\gamma_0}$;

Taking into account the work capacity on the Test Loop amounting to 300 mio. tons gross per year, and about 30 mio. tons gross per year on the high-speed line, the estimated tonnage in real operational terms was obtained. On the basis of on values of the second (concrete) layer bends from tables 2 and 3 we obtain the forecast for the tonnage on a high-speed line after running of at the 1100 mio. tons gross on the Test Loop:

T_1 = 1100*(2.5/0.9)*((176.6/230.5)^2.1)*0.13(0.6/0.06)

T_1= 2270.4 mio. tons gross

Due to the tonnage of 30 mio. tons gross the service life will be 75.7 years.

IV. CONCLUSION

A calculation and experimental method are developed, which allows reasonably predicting the service life of the innovative track construction upon the calculation and accelerated tests on a closed polygon.

A method for forecasting the behavior of various track constructions under future operation conditions that are not yet created based on the results of tests on the Test Loop is found.

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

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