Dynamic impact on the construction of the railway track and on the deformability of the basement

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Abstract. The qualitative performance of the track facility in Ukraine depends upon the technical state of the rail track structure, which is determined by correspondence of the characteristics to the current Regulations for laying and maintenance the track on railways of Ukraine. And the parameters indicating the rail track stability directly depend on the carrying capacity of the rail base and the stress-strain behavior.

The main indicators of the state of the continuous welded rail (in particular, the parameters of the track geometry), deviations from the normative position of the track rails in the profile and in the plan directly depend on the carrying capacity of the under sleeper base, that is, on its deformative properties.

In this study, the under sleeper base deformability refers to the ability of the superstructure to operate under conditions of limitation to a certain level of pace (speed) accumulation of the track failures.

Determining the level of the dynamic load on the railway track, its effect on the performance of its elements, and the under sleeper base deformability of the continuous welded rail will make it possible to quantify the dynamic effects on the railway track construction and its impact on the under sleeper base deformability.

1. Introduction

The main product of the track facilities is the technical state of the railway track construction being in use. According to Clause 3.1 [1], «all elements of the railway track ... as of ... should ensure the safe and smooth movement of trains at the speeds set on this line». At the present stage, taking into account the Program [2], this requirement is supplemented by the following: with the effective functioning of the railway track construction (on a certain line), which, in turn, implies optimal costs for the track arrangement and its operation during the «life cycle».
The product quality of the track facilities (the technical state of the railway track construction) is determined by the level of compliance of its indicators with current requirements [1].

It is known that the railway track construction operates under the power load of the railway track. The level of this load significantly affects the operation of the railway track construction and causes a change in its technical state during operation. During the development of the tonnage, there is a steady tendency to deteriorate of the technical state of the railway track construction due to the accumulation of the permanent deformation in it, which leads to a decrease in the level of a train safety.

Based on the above requirements for ensuring the reliable functioning of the continuous welded rail construction in the process of its operation, issues of assessing the performance of its elements acquire certain relevance. Moreover, the need for appropriate research in this direction is determined by the increase in the intensity of the superstructure operation, observed at the present stage [3].

2. The basic part

The studies [4-5] established that at the current stage of operation of Ukrainian railways, there are steady trends in the growth of traffic volumes and, as a result, an increase in the power load from the rolling stock to the railway track construction (Table 1):

| Operational factor | Dependence of the relative ratio of the operational factor |
|--------------------|----------------------------------------------------------|
| Gross freight turnover (total) – \( Q_{oper.} \) | \( k_1 = 1 + 0.059 \cdot t \) |
| Average freight train weight – \( Q_{train} \) | \( k_2 = 1 + 0.006 \cdot t \) |
| Average operating speed of a train – \( V_{technic.} \) | \( k_4 = 1 + 0.014 \cdot t \) |
| Frequency of the train wheel pairs – \( \tau \) | \( k_5 = 1 + 0.014 \cdot t \) |

The above material confirms the relevance of addressing issues regarding the dynamic effects of the rolling stock on the railway track construction in modern conditions of its operation.

The dynamic effects of the rolling stock on the railway track construction are divided into the following groups:
- vertical forces \( P_{vert.} \);
- horizontal lateral (side) forces \( P_{side} \);
- horizontal longitudinal forces \( P_{longit.} \).

Below are mathematical models for determining the magnitude of these dynamic forces transmitted on the track from the wheels of the most common type of the rolling stock – a 4-axle freight car.

According to the current rules [6], the calculated value of the force \( P_{vert.} \) is established by the formula:

\[
P_{vert.} = P_{static} + 0.75 \cdot G_{spring} \cdot Z_{spring} + 2.5 \cdot S,
\]

where \( P_{static} \) – static load of the wheel on the rail;
\( G_{spring} \) – rigidity of the truck spring suspension transmitted to one wheel;
\( Z_{spring} \) – maximum dynamic deflection of springs;
\( S \) – mean square deviation of the wheel dynamic load on rail on a rail.

It should be noted that in curved tracks, the dynamic vertical force \( P_{vert.R} \), which is transmitted from the rolling stock wheels to the rails of the external track rail, is set [7], according to the formula:

\[
P_{vert.R} = P_{vert} + P_{R},
\]

where \( P_{R} \) – additional vertical load on the rails of the external track rail curve from the action of the cart frame force \( Z_{frame} \), the value of which for 4-axle freight car is determined by the formula:

\[
Z_{frame} = (1 + 0.0024 \cdot V) \cdot (31.5 + 26 \cdot \alpha_{n,a})
\]
where \(a_{\text{n.a.}}\) – non-amortized sway acceleration (in these calculations, \(a_{\text{n.a.}} = 0.7 \text{ m/s}^2\)).

The magnitude of the force \(P_R\) is determined by the formula:

\[
P_R = Z_{\text{frame}} \cdot r_{\text{wheel}} / 1.6,
\]

where \(r_{\text{wheel}}\) – radius of the rolling stock wheel, m;
\(1.6\) – the distance between the rail axes of the external and internal track rails in the curve, m.

During the movement of the cart along the curve, the frame force \(Z_{\text{frame}}\) causes the appearance of horizontal lateral load \(P_{\text{sideR}}\), which is transmitted from the wheel to the rail. When exposed to a 4-axle freight car, the value of this load [7] is established by the formula:

\[
P_{\text{sideR}} = (1 + 0.003 \cdot V) \cdot (54 + 25 \cdot a_{\text{n.a.}}).
\]

On tangents, when the cart is wagging from its wheels, the horizontal lateral force \(P_{\text{side}}\) is transmitted to the rails, in order to determine the probable value of which, the calculation formula is proposed in [8]:

\[
P_{\text{side}} = \mu \cdot P_{\text{vert.}} \cdot V \cdot \sin \alpha \cdot (m_{\text{equiv.}} \cdot \beta_{\text{equiv.}})^{0.5} \cdot \Pi \cdot n_i,
\]

where \(\mu\) – pseudo-slip friction coefficient in the contact zone of the wheel and rail;
\(\alpha\) – angle of a wheel flange attack on a rail;
\(m_{\text{equiv.}}\) – equivalent weight of the wheel-rail interaction in the horizontal plane;
\(\beta_{\text{equiv.}}\) – equivalent wheel-rail rigidity in the horizontal plane;
\(\Pi \cdot n_i\) – the product of the coefficients that take into account the condition of the rail track and the cart wheels, the construction of the connection between its trolley and the body.

Note that longitudinal dynamic forces \(P_{\text{longit.}}\) on the track, they arise only in the zone of rail deflection under the influence of the wheel load \(P_{\text{vert.}}\), that is, they are local. The point of their application moves (along the track in the direction of the cart movement) along with the wheel, which causes a rail deflection.

The magnitude of force \(P_{\text{longit.}}\) [9] can be established by the formula:

\[
P_{\text{longit.}} = P_{\text{vert.}} \cdot V^2 \cdot [(1 + \gamma) \cdot \psi / g \cdot h],
\]

where \(\gamma\) – coefficient taking into account the loss of the wheel kinetic energy during its translational motion (for 4-axle freight car \(\gamma = 0.03 - 0.04\));
\(\psi\) – deviation of the curved neutral axis of the rail under the wheel (in these calculations, \(\psi = 1\));
\(g\) – gravitational acceleration;
\(h\) – rail height (for rails of R65 type \(h = 0.18\) m).

In the study [5], for the railway track construction with rails of the R65 type, intermediate fastening of the KB type, concrete sleepers (contraflexure 1840 pcs./km) on the broken stone ballast (the summer period of the track operation was considered), the dependences of the change above the specified dynamic forces (through relative ratios) with increasing of the operating speed of the \(V_{\text{tex.}}\) train (Table 2):

| Dynamic load on track | Notation conventions | Dependence of the change in the relative ratio that characterizes the dynamic force |
|------------------------|----------------------|----------------------------------------------------------------------------------|
| Vertical force         | \(P_{\text{vert.}}\) | \(P_{\text{vert.}} = 1 + 0.00127 \cdot t\)                                   |
| Horizontal lateral force | \(P_{\text{side}}\) | \(P_{\text{side}} = 1 + 0.00118 \cdot t\)                                    |
| Horizontal longitudinal force | \(P_{\text{longit.}}\) | \(K_{\text{longit.}} = 1 + 0.00318 \cdot t\)                                 |

The question of assessing the under sleeper base deformability was considered, in particular, in [10-11], where mathematical models of accumulation of the rail track permanent deformation (in the profile and in the plan) during the operation of the continuous welded rail were proposed.

Research materials, which are described below, are associated with scientific development [12].
It is known that the under sleeper base deformability is characterized by the coefficient of subgrade resistance \( C_b \), the value of which is determined by the formula:

\[
C_b = \frac{\sigma_b}{y},
\]

(8)

where \( \sigma_b \) – stresses arising in ballast under the sleeper under the influence of the dynamic force \( Q_{dyn} \);

\( y \) – rail deflection under the rolling stock wheel.

Parameters \( Q_{dyn} \), \( \sigma_b \) are determined according to the existing methodology [6] according to the formulas:

\[
Q_{dyn} = 0.5 \cdot k \cdot l_{sleep} \cdot P_{equiv},
\]

(9)

\[
\sigma_b = 2 \cdot \frac{Q_{dyn}}{a \cdot b \cdot \alpha},
\]

(10)

\[
y = 0.5 \cdot k \cdot \frac{P_{equiv}}{U_{vert}},
\]

(11)

where \( P_{equiv} \) – equivalent load transmitted to the rails from the rolling stock wheels;

\( k \) – relative rigidity ratio of the base and rail;

\( l_{sleep} \) – distance between axles of sleepers;

\( a, b \) – the length of the sleepers and the width of its lower surface;

\( \alpha \) – coefficient taking into account the bending of sleepers under the force \( Q_{dyn} \);

\( U_{vert} \) – vertical elastic modulus of the under sleeper base.

According to the established rules [6], the under sleeper base rigidity is calculated by the formula:

\[
G_{basem} = 0.5 \cdot a \cdot b \cdot \alpha \cdot C_b.
\]

(12)

In this study, the value of the \( G_{basem} \) parameter is set for the continuous welded rail construction with the following characteristics: rails of the R65 type; concrete sleepers with contraflexure 1840 pcs./km; an intermediate fastening of the KB type; a broken stone ballast.

The action of the 4-axe freight car moving at a speed of 60 km per hour is considered as the dynamic load on the rails.

The results of the calculations are shown in Table 3:

| Design parameter | Design parameter value |
|------------------|------------------------|
| \( U_{vert} \), MPa | 20  50  70  100  150  200  250  300 |
| \( C_b \), kg/cm³ | 3.27  8.09  11.28  16.92  24.20  32.38  39.43  49.67 |
| \( G_{basem} \), kN/mm | 110.5  273.5  381.5  572.0  818.0  1094.5  1333.0  1679.0 |

Appropriate processing of the data provided allowed us to establish (for \( U_{vert} \geq 50 \) MPa) the following dependencies:

\[
C_b = 0.162 \cdot U_{vert},
\]

(13)

\[
G_{basem} = 5.5 \cdot U_{vert} - 5,
\]

(14)

\[
G_{basem} = 33.95 \cdot G_{basem} - 5.
\]

(15)

It is obvious that as the \( U_{vert} \) parameter increases linearly, the vertical rigidity of the under sleeper base and its coefficient of subgrade resistance increase.

The deflected mode of the superstructure elements is to some extent determined by the level of rigidity of the under sleeper base. Thus, the higher the \( G_{basem} \) parameter value, the lower the stresses arising in the rail foot, and the less their (rails) deflection under the rolling stock wheels. Conversely, with a decrease in the under sleeper base rigidity, a rail deflection under the wheel load and the stress that appears in the rails increase, but the pressure on the sleeper and, as a result, the stress on the surface of the ballast bed (under the sleeper) also increase.
The dynamic action of the rolling stock wheels on rails during operation of the continuous welded rail gradually leads to uneven under sleeper base rigidity (through certain properties of the components of this base). Typically, the uneven under sleeper base rigidity is accompanied by the appearance of plays (gaps) between the sleeper lower surface and the ballast bed.

According to the current methodology [6], when assessing the deflected mode of the superstructure, the rail «is considered to be as a beam of infinite length ... which freely lies on a continuous equal elastic base ...», that is, without taking into account the possible presence of plays between sleepers and ballast.

It was noted in [13] that even with uneven under sleeper base rigidity (with sufficient accuracy for practical calculations), one can use the indicated superstructure model, but with the conditional modulus of elasticity of the under sleeper base, the value of which differs (to a smaller side) from the \( U_{\text{vert.}} \) parameter value, which is set by the standard method without taking into account the gap between sleepers and ballast.

At the same time, it is proposed (according to the under sleeper base rigidity) the corresponding graduation of the track (Table 4), which is based on the dependence \( y = f (P_{\text{equiv.}}) \) with a certain limitation of the parameter \( y \).

| Variant of the superstructure by rigidity of the under sleeper base | Function \( y = f (P_{\text{equiv.}}) \), mm/kN | Boundary value of rail deflection \( [y] \), mm |
|---|---|---|
| «rigid» track | \( y = 0.0167 \cdot P_{\text{equiv.}} \) | up to 2 |
| «soft» track | \( y = 0.0706 \cdot P_{\text{equiv.}} \) | up to 8 |
| «rigid» track with a play | \( y = 0.1176 \cdot P_{\text{equiv.}} \) | up to 14 |

The rules [6] from the condition for limiting the accumulation rate of the permanent deformation in the rail track established the permissible stresses \([\sigma_b]\), which can occur in the ballast bed under the sleeper from train load. For a broken stone ballast (the action of wagon wheels is considered), these stresses are in the range \([\sigma_b] = 0.24 \div 0.4 \text{ MPa} \) depending on the traffic density of the track section.

Applying formulas (8) and (12) and taking into account the value of \([\sigma_b]\) and \([y]\), it is possible to establish the corresponding characteristics of the continuous welded rail (the above structure) taking into account the conditions of its operation (Table 5):

| Variant of the superstructure by rigidity of the under sleeper base (boundary value \([y]\)) | Parameter | The parameter value mln.tkm gross/km per year |
|---|---|---|
| | \([\sigma_b]\), MPa | \( > 80 \) | \( 41 - 80 \) | \( 40 - 26 \) | \( 25 - 10 \) | \( < 10 \) |
| «rigid» track (\([y] = 2 \text{ mm} \)) | \( C_b \), \( \text{kg/cm}^3 \) | 12.0 | 13.0 | 15.0 | 17.5 | 20.0 |
| | \( G_{\text{basem.}} \), \( \text{kN/mm} \) | 405.6 | 439.4 | 507.0 | 591.5 | 676.0 |
| «soft» track (\([y] = 8 \text{ mm} \)) | \( C_b \), \( \text{kg/cm}^3 \) | 3.0 | 3.25 | 3.75 | 4.38 | 5.0 |
| | \( G_{\text{basem.}} \), \( \text{kN/mm} \) | 101.4 | 109.9 | 126.8 | 148.0 | 169.0 |
| «rigid» track with a play (\([y] = 14 \text{ mm} \)) | \( C_b \), \( \text{kg/cm}^3 \) | 1.70 | 1.86 | 2.14 | 2.50 | 2.86 |
| | \( G_{\text{basem.}} \), \( \text{kN/mm} \) | 57.5 | 62.9 | 72.3 | 84.5 | 96.7 |

3. Conclusions

Based on the results of the research, the level of the dynamic load on the track and its influence on the performance of the railway track elements have been determined.

It was determined that, based on the above requirements for ensuring the durability (as an indicator of reliability) of the operation of the continuous welded rail construction during its operation, more attention should be paid to the assessment of the track under sleeper base deformability. The
application of the results in the design and operation of the railway track will significantly increase the life of all its basic elements.

4. References

[1] [1] Instructions for the arrangement and maintenance of the railway track of Ukraine (Kyiv: Polygraphservice, 2006) p. 336

[2] Report of Ukrzaliznytsia Director General Mykhailo Kostyuk to the Ukrainian Railways Forum on December 16, 2009 (Kyiv: Highway, 2009) 97-98

[3] A M Shtompel 2011 Rail Freight Operational Turnover in Ukraine in 2008-2011 and its Impact on Railway Track Construction (Odessa, Chernomore) 4 (3), p. 67-70

[4] A M Shtompel 2010 The power load of the main tracks of the railways in modern conditions (Kharkiv UkrDAZT) 113, p. 153-157

[5] A M Shtompel 2011 Dynamic load on the track and its effect on the performance of the elements of the rack and trellis (Kharkiv UkrDAZT) 123, p. 179-184

[6] E I Danilenko, V V Rybkin 2006 Rules for calculating the railway track for strength and durability (Kyiv, Transport of Ukraine) p. 168

[7] A F Zolotarskyi 1980 Reinforced concrete sleepers for rail track (Moscow, Transport) p. 270

[8] Ye G Andreev 1979 Determination of the greatest lateral forces in straight sections of the track during high-speed movement (Dnipropetrovsk, DIIT) 204 (21), p. 14-28

[9] V M Lyashchenko 1966 On dynamic longitudinal horizontal forces along the path (Kharkiv, HIIT) p. 56-64

[10] A M Shtompel, V P Shramenko 2010 A mathematical model of the accumulation of vertical deformations of a railway track during operation (Kyiv, Railway transport of Ukraine) 4 p. 58-59

[11] A M Shtompel, O O Skoryk, V P Shramenko 2011 Mathematical model of accumulation of residual deformations of a track in plan during tonnage development (Kharkiv UkrDAZT,) 122, p. 261-265

[12] A M Shtompel, O I Chernysh, S I Baidai 2012 Deformity of the bearing base of the non-stick track (Kharkiv UkrDAZT) 128, p. 100-104

[13] A D Koniukhov 2000 From standardization and control of rigidity of the rail foundation to the elimination and kinks of rails for defect 69 (VNIIZT) 2, p. 5-11