Theoretical basis of quality assessment of railway technical condition

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Abstract. The qualitative performance of the track facility in Ukraine depends upon the technical state of 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 rail base consists of elements of various physical and mechanical properties, with its own deformation behavior and stressed state under force loading. Therefore, the stress-strain behavior of the rail base must be evaluated with an appropriate mathematic model showing a flow of forces from one element to another.

The rail track structure operates under the power loading from a train. This load considerably influences operation of the rail track structure and conditions the changes in the technical state in operation. In operation the technical state of the rail track structure is getting worse because the residual deformations accumulated in it, which lead to lower train traffic safety. Nowadays requirements for operational safety of the rail track structure are high, and the problem of evaluation of the stress-strain behavior of the rail base is of great importance.

1. Introduction

The main production of the track facility is technical operational condition of the rail track structure. According to [1] «all rail track elements must provide a safe and smooth running of trains at traffic speeds established for the section». At the present stage this requirement along with program [2] is supplemented with the following: an effective operation of the rail track structure (on a certain section), which, in turn, stipulates optimal charges for laying and maintenance of track during the life cycle.
Continuous welded rail track on concrete sleepers is the basic structure for the railways in Ukraine. Nowadays its length is over 70% of the whole main track length [2].

The continuous welded rail track structure consists of an assembled rails and sleepers (track panel) and rail foundation. The latter has a ballast layer and certain (working) roadbed with its upper part which directly carries the load from track and train.

The basic state characteristics of continuous welded rails (parameters of the rail track geometry) directly depend on the carrying capacity of the rail base, and on the ballast layer state, in particular.

On the basis of the above-mentioned requirement for safe operation of the continuous welded rail structure, the problem of how to evaluate its reliability is becoming urgent. Moreover, a need for appropriate studies in the field is conditioned by more intensive operation of the permanent way at present [3].

2. The basic part

It is known that the rail track structure operates under multiple cyclic loading of dynamic forces from the wheels of vehicles. Therefore, track elements are subject to various defects. And the rail track safety level in operation directly depends on the stress-strain behavior of the rail base [4 - 6].

The stress-strain behavior of the rail base is actually its operational capability under limited (to the first intensity level) accumulation of residual deformations in the track [7].

The stress-strain behavior of the rail base is determined by rigidity of its components. Let us indicate the total rigidity (in the vertical plane) of the rail base , and the rigidities of intermediate fastening unit, sleeper, ballast and road bed , respectively, and we can obtain the following equation:

\[
1/ G_b = 1 / G_{bin} + 1 / G_{sl} + 1 / G_{gr} +1 / G_{subgr}.
\] (1)

In calculations for the continuous welded rail structure on concrete sleepers \(1 / G_{sl} = 0\).

The vertical rigidity of the KB intermediate fastening unit was formed as the result of joint action of two systems. The first of them included a rail, tightly fixed by clamps, and rail absorber pad of the total rigidity , while the other included a metal pad, fixed on the support with insert bolts, and a sleeper pad of the total rigidity .

These flex systems were connected in tandem in operation, therefore, the vertical rigidity of the fastening unit \(G_{bin}\) was determined by the formula:

\[
G_{bin} = (G_i + G_2) / (G_i + G_2).
\] (2)

By estimate [8] for the KB fastening \(G_{bin} = 90\) kN / mm.

The ballast layer and working zone of a road bed (a certain zone under the track panel) created the rail base of the vertical rigidity , thus the equation had the form:

\[
1/ G_{sb} = 1 / G_{gr} + 1 / G_{subgr}.
\] (3)

The stress-strain behavior (elasticity) of the sleeper foundation were characterized by the coefficient of soil reaction, the value was determined by the formula:

\[
C_{gr} = \sigma_{gr} / y,
\] (4)

where \(y\) – the vertical rail deflection due to the train loading.

The indicated parameters were defined by the formulae:

\[
Q_{dyn} = 0,5 \cdot k \cdot l_{sl} \cdot P_{eq},
\] (5)

\[
\sigma_{gr} = 2 \cdot Q_{dyn} / a \cdot b \cdot \alpha,
\] (6)

\[
y = k \cdot P_{eq} / 2 \cdot U_{vert},
\] (7)

where \(P_{eq}\) – the equivalent loading on the track from the wheels of a vehicle (determined by the current technique [9]);
\[ k = (U_{vert} / 4 \cdot E \cdot I) \cdot 0.25, \]  

where \( E \) – the modulus of elasticity of the rail steel;  
\( I \) – the inertia moment of a rail in the vertical plane.

The rigidity of the sleeper base was calculated by the formula:

\[ G_{subgr} = 0.5 \cdot a \cdot b \cdot \alpha \cdot C_{gr}. \]

Table 1. Rigidities of the sleeper base

| Factor        | Value of a design factor |
|---------------|--------------------------|
| \( U_{vert}, \text{MPa} \) | 20  | 50  | 100 | 150 | 200 | 250 | 300 |
| \( k, \text{1/cm} \)         | 0.009 | 0.0114 | 0.0135 | 0.015 | 0.0161 | 0.017 | 0.0178 |
| \( Q_{dyn}, \text{kN} \)     | 49.8 | 62.9 | 74.2 | 81.7 | 87.7 | 93.4 | 100.7 |
| \( \sigma_{gr}, \text{MPa} \) | 0.147 | 0.186 | 0.22 | 0.242 | 0.259 | 0.276 | 0.298 |
| \( \gamma, \text{cm} \)       | 0.45 | 0.23 | 0.13 | 0.1 | 0.08 | 0.07 | 0.06 |
| \( C_{gr}, \text{kg/cm}^3 \)   | 3.27 | 8.09 | 16.92 | 24.2 | 32.38 | 39.43 | 49.67 |
| \( G_{sh}, \text{kN/mm} \)    | 110.5 | 273.5 | 572.0 | 818.0 | 1094.5 | 1333.0 | 1679.0 |
| \( G_{bs}, \text{kN/mm} \)    | 9.84 | 20.96 | 34.97 | 42.92 | 49.5 | 53.76 | 58.78 |

The regression analysis of links between the indicated parameters \((k, Q_{dyn}, C_{gr}, \gamma, G_s)\) and the modulus of elasticity of the rail base \(U_{vert}\) made it possible to determine corresponding mathematical models (Table 2), the adequacy of which was confirmed by the established coefficients of correlation \(r\) and determination \(r^2\).

Table 2. Mathematical models of design factors

| Design factor | Mathematical model | Coefficient |
|---------------|--------------------|-------------|
| \( k, \text{1/cm} \) | \( k = 10 - 4 \cdot (108.65 + 0.25 \cdot U_{vert}) \) | (10) 0.985 | 0.970 |
| \( Q_{dyn}, \text{kN} \) | \( Q_{dyn} = 58.68 + 0.144 \cdot U_{vert} \) | (11) 0.992 | 0.985 |
| \( \gamma, \text{mm} \) | \( \gamma = U_{vert} / (1.87 \cdot U_{vert} - 106.39) \) | (12) 0.894 | 0.8 |
| \( C_{gr}, \text{kg/cm}^3 \) | \( C_{gr} = 0.162 \cdot U_{vert} \) | (13) 0.999 | 0.998 |
| \( G_s, \text{kN/mm} \) | \( G_s = U_{vert} / (0.011 \cdot U_{vert} + 1.815) \) | (14) 0.974 | 0.949 |

By the existing technique of regression analysis [10], a link between factors of the function \( y = f(x) \) was considered tight at \( r > 0.9 \), good – at \( r = 0.8 \div 0.85 \) and satisfactory – at \( r \geq 0.5 \), and the determination coefficient \( r^2 \) characterized the function change level \( y \) depending on the argument \( x \).

The results of the calculations made testify that when the parameter \( U_{vert} \) increases the vertical rigidity of the rail base and stresses in the track elements under the train loading increases, and the vertical deflection under the wheel decreases.
The functions \( y = f \cdot (U_{vert}) \) and \( G_b = f \cdot (U_{vert}) \) were described by reverse curves. Obviously, there exist the certain area \( \Delta U_{vert} \), where the parameters \( y \) and \( G_b \) are in an optimal ratio.

In a first approximation (for accepted design conditions) the authors established the intensities of changes of indicated factors in the corresponding range \( U_{vert} \) (Table 3):

| Range \( \Delta U_{vert} \), MPa | Intensity of the factor change |
|-------------------------------|-----------------------------|
|                               | \( \Delta y \), mm / MPa    | \( \Delta G_b \), (kN/mm) / MPa |
| 20-50                         | 0.073                       | 0.543                      |
| 50-100                        | 0.020                       | 0.280                      |
| 100-200                       | 0.005                       | 0.145                      |
| 200-300                       | 0.002                       | 0.093                      |

The multiple cyclic loading with dynamic forces of the rail track structure was not accompanied only by elastic deformations in the track elements. In operation there appear and develop residual (transient) deformations resulting in various structural damages in the rail track, including geometry deflections in the profile. The intensity of residual settlement accumulation \( \Delta y_{resid} \) (in the vertical plane) of the rail track structure, considered at higher values of the factor \( U_{vert} \), was characterized by the following experimental data (Table 4):

| Modulus of elasticity of the rail base \( U_{vert} \), MPa | Intensity of the residual track settlement accumulation \( U_{vert} \), mm/mln ton for rails |
|--------------------------------------------------------|-----------------------------------------------|
|                                                        | without irregularities                        | with irregularities 0.004                      |
| 40                                                     | 0.12                                          | 0.12                                          |
| 90                                                     | 0.25                                          | 0.28                                          |
| 175                                                    | 0.38                                          | 0.48                                          |
| 245                                                    | 0.48                                          | 0.57                                          |

The statistical analysis of the given data made it possible to determine for the function \( \Delta y_{resid} = f \cdot (U_{vert}) \) the following mathematical model:

\[
\Delta y_{resid} = 10 - 2 \cdot (8.51 + 0.17 \cdot U_{vert}).
\]  

Results of the research testify that factors of the track stress-strain behavior are operatively connected with the operational conditions (particularly, the vehicle’s axle loading and traffic speed). The fact shows that there must be an appropriate equilibrium between the usage rate of the rail track structure and the deformation strength under the wheel loading. Therefore, optimization problems (standardization) of deformation factors of the rail base (for various operational conditions) require further development.

### 3. Conclusions

On the basis of requirements for durability (as a reliability factor) for the contiguous welded rail structure in operation, the problem of evaluation of the track sleeper base deformation is of practical value and requires a more deep study through the system approach.

It has been established that between the use rate of the rail track structure and its deformation strength capacity under the wheel loading there must be certain equilibrium. Therefore, optimization problems (standardization) of deformation factors of the track rail base (for various operational conditions) require further development.

The research established some qualitative factors of the technical state of the continuous welded rail track. The use of the values obtained in the calculations and further development of research in the
field will encourage gaining a better technical state of the rail track, and, as a result, the whole rail infrastructure.

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