

The influence analysis of railway track support changes on its behavior under an applied load

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ABSTRACT

The main causes of inhomogeneity in the track foundation properties are primarily the contact loss between the track and the sleeper with the ballast, the non-uniformity deformability of the granular layers and the local deformation of the railway ballast foundation. These inhomogeneities, like geometric irregularities, significantly impact the railway track operation (e.g. progressive track structure degradation or increased dynamic load). The problem of the support changes on the behavior of the rail and sleeper during the operation of a jointless railway track were analyzed in the paper. The author proposed a method for simulating a gap in the railway track (contact loss between the sleeper and ballast). The proposed method, based on the measurement in the loaded track (a static load from the locomotive wheels), allows for a description of the effect of the changing track support condition. Using the results of the author's test and the investigations described in the literature, one can propose the parameters of foundation for theoretical calculations of rail deflection during the railway track support changes. In the paper, the influence of the changing track support condition was presented in figures, which clearly show the changes in deflections and bending moments. Change of the contact loss between the track and the foundation from only along one sleeper spacing to along two sleepers spacing causes a twofold increase in rail deflection and stress for the concentrated forces analyzed in the paper. During the track operation, a lack of support along the length of the railway sleeper also occurs. The analysis showed, that lack of support in the under-rail section with an increase in the sleeper support factor (in the middle section) results in a large increase in deflection, especially for wooden sleeper. The novelty introduced by the author's analyses is generating the lack of support between the track and ballast in a known place in the track, identification of foundation parameters, their application in beam-on-elastic foundation models and the analysis of schemes of contact loss between the jointless track and foundation. The author's contribution to this problem lies in preparing a track analysis based on the numerical calculations of the analyzed models.

Keywords: jointless track, change of support, inhomogeneity of foundation, contact loss.

INTRODUCTION

The ballasted railway track is subject to settlement mainly due to permanent deformations of the ballast and granular materials (e.g. protective layer, subgrade) [1–4]. Such settlement is caused mainly by the acting load from the rolling stock and its intensity depends on the quality and behavior of the ballast, the protective layer and the subgrade. Since the granular material does not behave identically under all sleepers and the track load is non-uniform, the degree of track

settlement will vary along its length [1,5]. As a result, sleepers are not always fully supported and some may even be completely unsupported (under sleeper voids) [2]. Track irregularity occurs both during its construction and successive operation. The main reason for their formation and growth is permanent deformations of the ballast foundation. The process of irregularity formation depends on the track structure and operating conditions, as well as on the effect of loosening the structure of the sleeper foundation. The resulting track imperfections [6] are primarily:

- vertical and horizontal unevenness
- rail track height differences and twist
- unevenness/damage on the rail running surface
- formation of local unevenness of the foundation (railway track support)
- areas of contact loss between the track and the ballast (hanging sleepers) [2]
- rail corrugation, wheel flats [3]
- inhomogeneity of the foundation along the length of railway track (shown in Figure 1)

The factors described above result in progressive changes in the railway track. The unfavorable effects of such imperfections include:

- increased forces acting on the track and the running gear of rail vehicles [8]
- damage to rail fastenings and accelerated rail degradation
- rail corrugation (increasing track maintenance costs) [3]
- loosening and crushing of the ballast (resulting in rapid increase in vertical irregularities)
- frequent cracking of the rail clamps fastening the rails to the baseplates and pads.

Due to the vertical stiffness of the rails, the track grid may also lose contact with the foundation due to the loosening of the track ballast structure (track support) on short irregularities. This creates under-sleeper gaps with random gap heights on unloaded tracks. The number of these gaps and their range increase with time and track usage intensity. The acting load on the track grid restores the lost contact with the foundation, but this is accompanied by significant increases in the dynamic impact of the rolling stock, depending on factors such as the void size and the speed of the rail vehicle. This state, caused by unfavorable changes in the track grid support conditions, may

also cause a significant threat to the local stability of the jointless track in operation [1], especially at high vehicle speeds. Initial unevenness causes additional bending of the track grid (profile) and track frame (plane) due to the longitudinal forces generated in the rails due to temperature changes, rolling stock braking and horizontal ground deformations (e.g. mining areas). Therefore, the main goal of the construction technologies used, the properties of the surface structure and the maintenance of operated railways is achieving high durability of the railway track structure. Durability in railways is understood as the ability of the track to maintain its essential characteristics within permissible limits (expressed in units of time or the value of the load transferred by the track). The following factors influence the durability of the track structure (Table 1) [9]:

- overall design and material characteristics
- quality of construction and repair work
- operating conditions (velocity, axle loads, type and condition of rail vehicles, etc.)
- economic factors.

The progressive operation (including successive changes to the support) significantly changes the operating conditions of the railway track (degradation, wear of elements or changes in the track geometrical layout). Therefore, there is a need to use and further develop railway track diagnostic methods. In addition to standard diagnostic methods (e.g., track inspections, track's rounds or defectoscope tests), a new approach to railway track maintenance is being presented [10]:

- reactive maintenance
- preventive maintenance
- predictive maintenance
- perspective maintenance

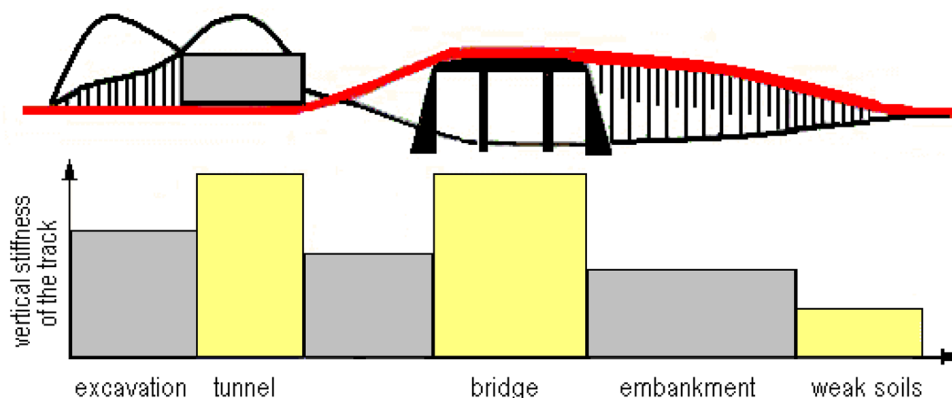


Figure 1. Variable support of the railway track along its length [7]

Table 1. The most important factors influencing the durability of railway surfaces [9]

Geometrical layout	Dynamic interactions	Quality of elements
Curve radius Downward and upward grade Calculation of cant (kinematic parameters) Shape and length of transition curves	Velocity Axle loads Sprung to unsprung masses ratio State of rolling stock maintenance	Rail steel quality Component quality Aggregate type and quality
Quality of work	Level of maintenance	Unpredictable factors
Laying of the protective layer Compaction of ballast Accuracy of installation Correct shape of the ballast pile Maintaining a neutral temperature Inter-operational inspections Work acceptance	Diagnostic level and maintenance criteria Repair terms and ranges Work acceptance Repair quality	Storms and floods Fires Other

- new diagnostic methods (automation of track's rounds (Figure 2) [11] or the InfraNoise measurement system [12]).

Track settlement caused by hanging sleepers is often analyzed in publications [1, 2, 13]. In the paper [3], a vehicle's ride over a local track irregularity was analyzed (Figure 3):

The applied model [3] enables the calculation of deflections, accelerations and forces in various track elements, as well as the study of the effects of parameters such as train velocity, axle load, rail wear, wheel flats, etc., on track and vehicle elements. The effect of one or more unsupported sleepers on the train-track interaction force and on track dynamics was investigated. During operation, additional vibration waves are generated by moving trains and transferred through the railway track and foundation. The main factors contributing to their generation include [14]:

- the effect of vehicle speed (generates dynamic loads, which are transferred to the elastic half-space, causing periodic movement of track elements)
- irregularities at the wheel-rail interface (as long and short waves); long waves (with a length of $\lambda > 300$ mm) are mainly caused by rail waves and deformations over several meters (e.g. rail production or the effect of unevenness on the rail head) and short waves are caused by shock loads due to imperfections in the wheel-rail contact, such as wheel flats or rail joints
- irregularities in the track, which can be caused by several phenomena (e.g., differences in ballast settlement, sleeper spacing, stiffness changes (transition zones), foundation inhomogeneity); all of these increase the vibration amplitude and thus deteriorate the current track condition.

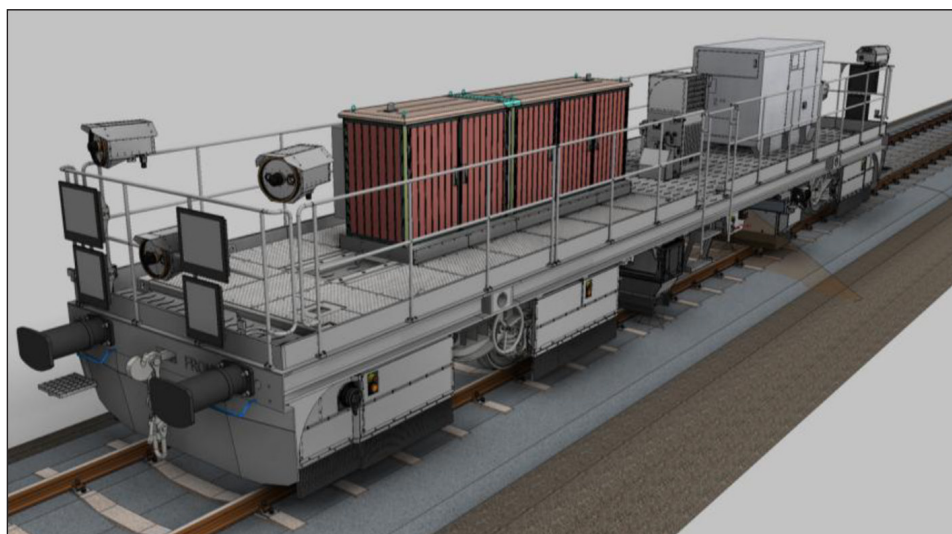


Figure 2. Automation for track's rounds (ATO) [11]

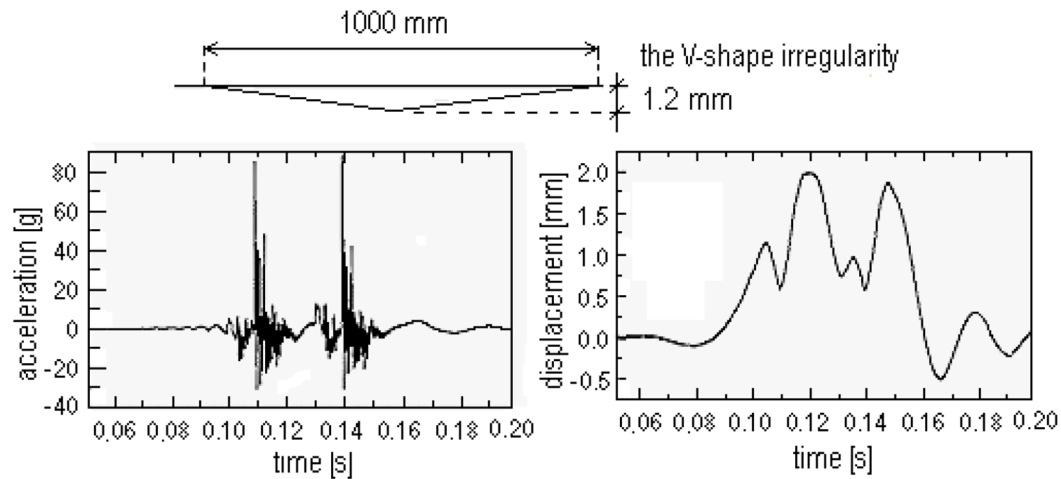


Figure 3. Time history of rail acceleration and displacement during passing a bogie [3]

THE INFLUENCE OF SUPPORT CHANGES ON THE WORK OF RAILWAY TRACK

Support changes occurring in the railway track structure are most often analyzed as follows [1, 4, 15]:

- exceeding the permissible stresses in the ballast
- locally curved an elastic foundation made of ballast
- inhomogeneous track support
- areas of contact loss between the track and the ballast foundation.

Exceeding the permissible stresses in the ballast

The force transferred from the vehicle wheel to the rail, which causes the exceeding of the permissible stresses in the ballast, is most often determined to be greater than 350 kN/wheel [16–18]. For the vertical force value over 357 kN, the stresses transferred to the ballast are 0.459 MPa and begin to exceed the permissible stresses for ballast made of hard rocks with good condition (0.45 MPa) [1].

The typical loading time generated by flat wheel surfaces can range from 1 ms to 10 ms (the magnitude of the impact force can reach 600 kN per rail [16]). In the paper [17], a maximum impact force of 400–500 kN was observed. The impact generates a number of physical phenomena (elastic and plastic wave propagation, cracking and fragmentation, perforation and spalling). The dynamic behavior of materials

causes degradation of the ballast. When the dynamic load reaches 355.8 kN, a large-scale degradation follows in the track [18,19]. The data from computational models, laboratory experiments and field tests using instruments have shown that the maximum impact load on railway ballast can be as high as 500 kN.. Force values exceeding 500 kN are possible during railway track structure operation. The vertical forces exerted on the track (F_v) consist of many different components [19,20]:

$$F_v = F_{v0} + F_{vk} + F_{vds} + F_{vdh} + F_{vdb} + F_{vj} \quad (1)$$

where: F_{v0} is the static wheel force (100%), F_{vk} is the quasi-static effect of the position in curves (0–40%), F_{vds} is the dynamic effect of rail unevenness (0–300%), F_{vdh} is the dynamic effect of flat spots on the wheel (0–300%), F_{vdb} is the effect of braking (0–20%), F_{vj} is the effect of load asymmetry (0–10%).

Railway track resting on locally curved foundation

The initial track irregularities occurring in the vertical and horizontal planes are one of the main factors causing the loss of stability of ballasted tracks [21]. When compressive longitudinal forces arise, the locally deformed track is subjected to simultaneous compression and bending, which adversely affects its stability. Often, in equilibrium analyses of jointless tracks, the track is treated as a weighted beam resting on

a curved elastic foundation (with a vertical stiffness coefficient U [MPa] (Figure 4):

In the jointless track, temperature changes create a compressive longitudinal force H , which with large profile irregularities can cause the track deflection in the vertical plane and contact loss with the foundation. Describing such a local, single irregularity ACB of length l_p (Figure 4), occurring, for example, on a curve of radius R_0 , rounding a concave bend in the longitudinal profile:

$$z_p = \frac{f_p}{2} \cdot \left[1 - \cos \left(2 \cdot \pi \cdot \left(0,5 + \frac{x}{l_p} \right) \right) \right] + \frac{x^2}{2 \cdot R_0} \text{ for } |x| \leq \frac{l_p}{2} \quad (2)$$

$$z_p = \frac{x^2}{2 \cdot R_0} \text{ for } |x| \geq \frac{l_p}{2} \quad (3)$$

where: f_p – the curve of the unevenness formed on the ground, shaped according to the railway line design, according to a second-degree parabola with a radius of curvature R_0 .

Due to the symmetry of the system, only the right-hand side of the *CBE* track is considered. In the paper [21], the influence of three local unevennesses on the work of the railway track was considered (Figure 5).

$EI = 12.831 \text{ MNm}^2$ (track stiffness), $g_t = 0.0026 \text{ MN/m}$ (track weight), $U = 41 \text{ MPa}$ (coefficient of foundation), $H = 1.837 \text{ MN}$ (compressive force in rails)

As can be seen in Figure 5, the foundation irregularities assumed in [21] cause changes in

track support. In the case of three foundation irregularities, the track-foundation contact loss length is as much as 5.283 m, which has a unfavorable influence on horizontal track work during periods of high temperatures.

The influence of non-uniform track support on rail deflection under applied load

In the analyses of the effect of regular foundation non-uniformity (Figure 6) on rail deflection, a single concentrated force P [kN] and varying foundation stiffness are assumed according to the relationship [15]:

$$U(x) = U_0 - \varepsilon \cdot U_0 \cdot \cos \left(\frac{\pi \cdot x}{\lambda} \right) \text{ [MPa]} \quad (4)$$

where: U_0 – stiffness value of the foundation at point 0, [MPa]; $\lambda \in (1, 2, \dots)$, [m], $x \in (-2 \cdot \lambda; 2 \cdot \lambda)$, [m] and $\varepsilon \in (0; 1)$, [-].

Assuming the values: $U_0 = 90 \text{ MPa}$ and $\varepsilon = 0.9$, we obtain: $U(x) = 90 - 81 \cdot \cos(\pi \cdot x / \lambda)$ [MPa]. Figure 7 and Table 2 show the effect of the non-uniformity of half-wave length U on the maximum bending stresses in the rails and the vertical stresses in the ballast.

Figure 7 clearly shows that the bending stress in the rail foot [MPa] increases with the growth of half-wave length of the non-uniformity in the rail foundation stiffness. The maximum stress in the ballast is achieved at twice the sleeper spacing (i.e. for a half-wave length of approximately 1.2 m). Therefore, non-uniformity with short half-wave lengths (below 5 m) is important for ballast work.

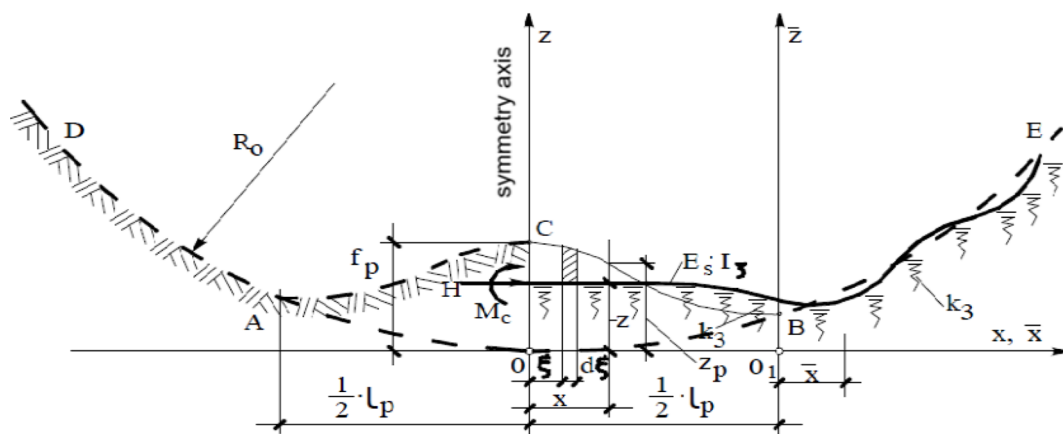


Figure 4. Schematic diagram of a railway track resting on a curved foundation

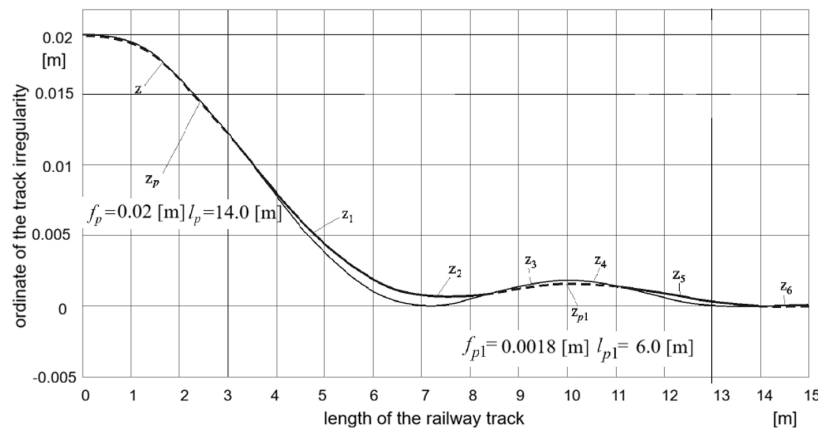


Figure 5. Track deflection line on local foundation irregularities (triple foundation irregularities: $f_p = 0.02$ m and $l_p = 14.0$ m (central irregularity) and $f_{pl} = 0.0018$ m and $l_{pl} = 6.0$ m (side irregularities) [21]

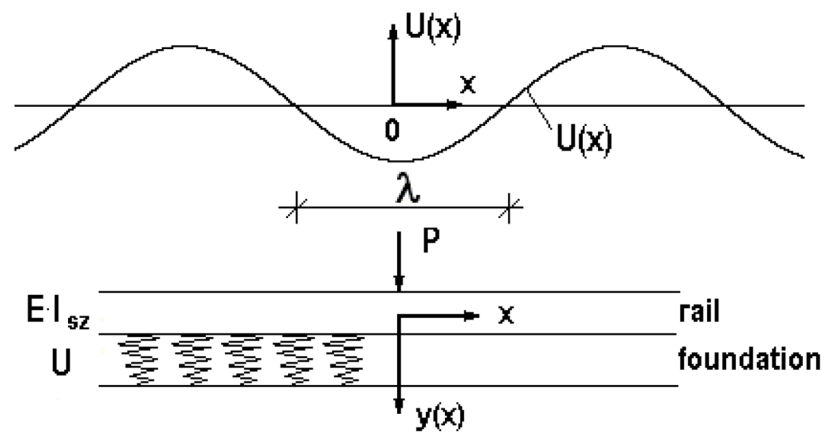


Figure 6. Variability of railway track support [15]

In the unloaded state (without the vehicle loads) the track stiffness causes that the sleepers rest on the ballast with varying degrees of contact. In the worst case, a sleeper may lose full contact with the ballast. In an unloaded track, it is difficult to determinate how such localized irregularities affect the vertical behavior of a track. The changing way of the track support can only be characterized under load, after applying the forces from a locomotive axles. Analysis of load transferring from the wheel, through the rail, to the sleeper allows visualizing the impact of such irregularities on the track.

Due to the before-mentioned factors, the author proposed an individual method of simulating the intended vertical irregularity in a railway track structure with adequate site surveys [5]. The author's research explains the way in which the simulated track irregularity changes the deflections, stresses, forces, and parameters of the railway track structure.

THE INFLUENCE OF LACK OF TRACK SUPPORT ON THE WORK OF RAIL AND SLEEPER UNDER APPLIED LOAD

During the progressive degradation of the railway track, the contact between the track and the ballast gradually disappears (shown in Figure 5). Such areas of contact (e.g. hanging sleepers) significantly affect the work of railway track elements. Analysis of such a phenomenon requires the determination of the parameters of the interacting foundation.

Method of the author's simulation a gap in the track

The paper [22] presented an individual model of a ballast box with a sleeper, supported by springs that allows for the simulation of the development of voids in the track. The paper [23] presented an approach for estimating the intensity

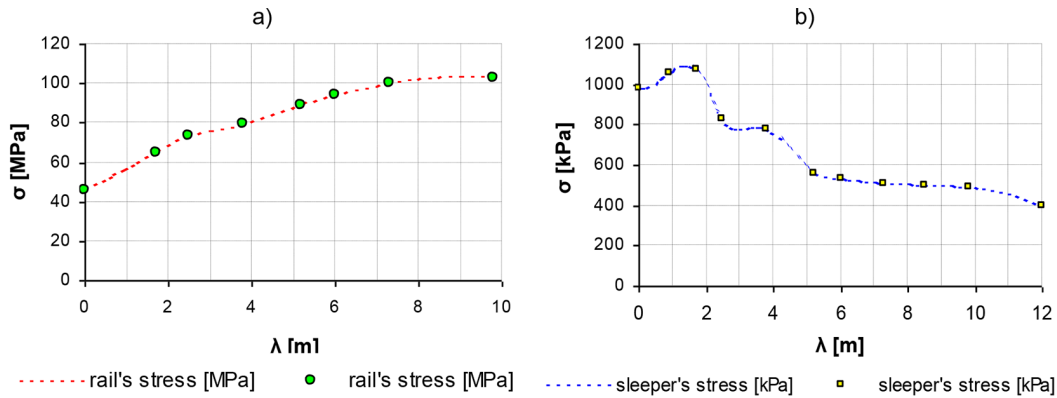


Figure 7. Effect of the half-wave length of the non-uniformity U on the maximum bending stress in the rails [MPa] and the vertical stress in the ballast [kPa]

Table 2. Effect of the unevenness half-wave length U on the maximum bending stresses in the rails and the vertical stresses in the ballast [15]

λ [m]	σ_{sz} [MPa]	σ_p [kPa]
1	2	3
0	46	980
1.7	65	1070
2.5	73	830
3.8	79	780
5.2	89	560
6	94	530
7.3	100	510
9.8	103	490

of ballast settlement in void zones. An approach that considers cyclic ballast loading, impact loading, and minimum preload using simple analytical relationships was proposed.

In the paper [24] it was stated that the impact location relative to the maximum rail deflection

depends on the sensor's position along the track. Therefore, one important issue is locating the measuring sensor as close as possible to the wheel impact point. The author proposed and carried out investigations (according the scheme from Figure 8) generating the lack of support between the track and ballast in a known location (on a length equal to double the sleeper spacing). The novelty introduced by the author's research is also measurement, the identification of foundation parameters from field investigations, their application in beam on elastic foundation models and the analysis of specific schemes of contact loss between the jointless track and foundation. An optical system Pontos, by GOM GmbH (Gesellschaft für Optische Messtechnik, Technische Universität, Braunschweig) was used for measurements. The system makes precise (with an accuracy of 0.001 mm), non-contact measurements of position at short time intervals in 3D [1,5].

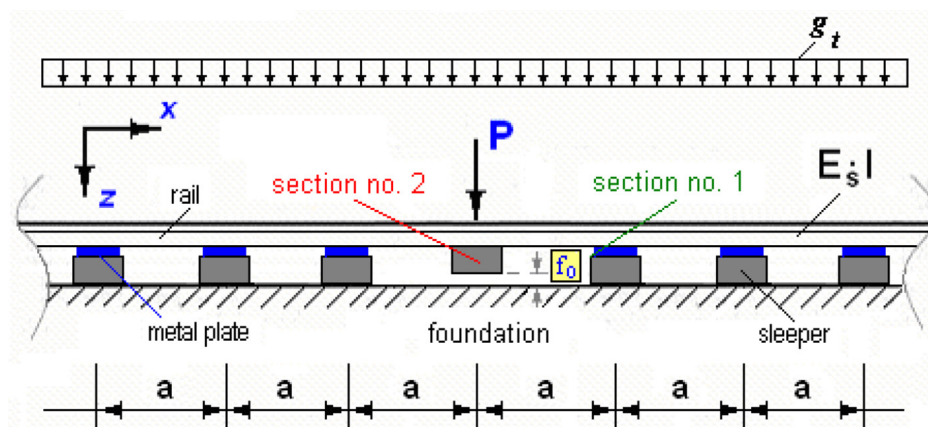


Figure 8. A scheme of simulation a gap in the railway track

The procedure of carried out investigations and validation of simulation model

In the course of the proposed author's method of simulation the gap in the railway track, the following actions are performed [1]:

- an intended local gap (lowering the track by a parameter f_0 shown in Figure 8);
- an intended gap is obtained by enabling a free move of rails and lifting the track with a screw elevator;
- next the metal plates are placed and reattaching the both rails to the co-operating sleepers;
- the value of f_0 is gradually increased from 0 mm successively to 1, 2 and 3 mm;
- the static load is $Q = 180 \text{ kN/axle}$, i.e. 90 kN/wheel ;
- the Pontos system is used during field investigations for the static analysis [1,5].

The proposed method for generating track deformations (by insertion of spacer plates into the track and the placement of measuring sensors in sole-plate) allows for the simulation of a gap in the track with known initial parameters, such as length l_0 and the amplitude f_0 of irregularity. This is a non-destructive method for inducing deformation that does not disturb the initial contact between the rail and the sleeper

with foundation. The presented method is particularly useful for investigating the changes in track support conditions and may be a proper tool for evaluating the behavior of loaded railway track elements.

Contact loss of support along the length of a railway track on rail work

For the rail work analysis, the diagrams of load and track-ballast contact interaction (Figure 9a and b) are assumed. Diagram *a* (Figure 9a) represents the track-ballast contact loss along two sleepers spacing, while diagram *b* (Figure 9b) represents the track-ballast contact loss along a single sleeper spacing:

Contact loss of support along the length of the sleeper on its work

Contact loss with the ballast can affect both the length of the track and the sleeper along its length (Figure 10).

The analysis takes into account the effect of ballast raveling in the under-rail cross-sections (assuming contact loss over a length of 12.6 cm ($x_2 + x_3 = 12.6 \text{ cm}$ and $x_7 + x_8 = 12.6 \text{ cm}$ – Figure 10) in the under-rail cross-sections).

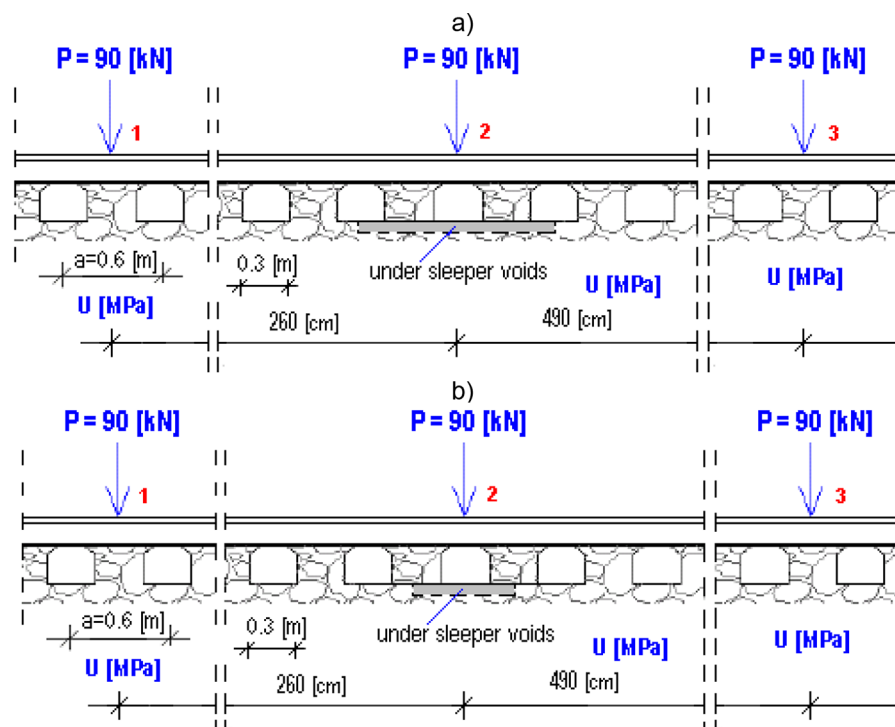


Figure 9. Contact loss along the length of the railway track with the foundation
a) diagram (contact loss along two sleepers spacing); b) diagram (contact loss along one sleeper spacing) [1, 5]

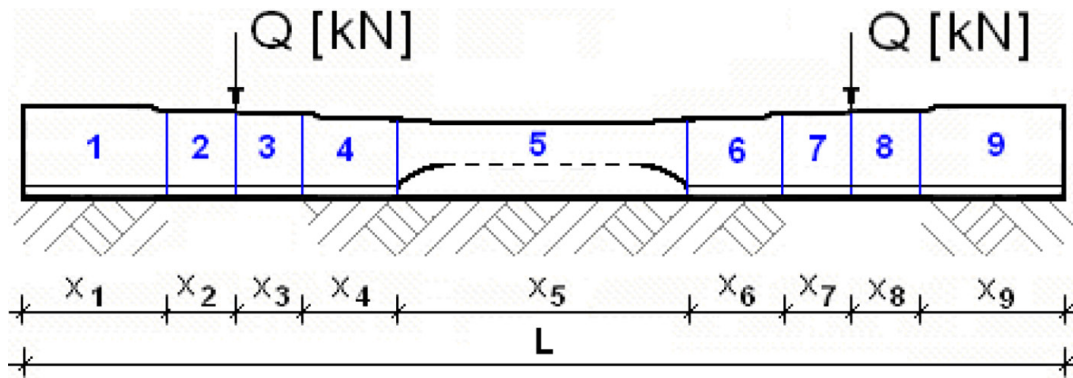


Figure 10. The analyzed railway sleeper (an assumed diagram of the considered support discontinuities; Q – force transferred from the rail to the sleeper)

For the calculations the following parameters of wooden and concrete sleepers are assumed (Table 3) [1, 21]:

- a prestressing force on the concrete sleeper: $N = -0.310$ MN,
- a force transferred from rail to the sleeper $Q = 45.094$ kN (value determined on the basis of author's research [1,5]),
- a foundation parameter $U = 27.144$ MPa (value from Table 3).

RESULTS

Results from field investigations

Figure 11 shows the measured deflection of the rail caused by a locomotive load (SM-42-448) for scheme from Figure 8. On the basis of performed investigations and validation, the following parameters are obtained:

P – an applied static force [MN] ($P = 90$ kN/wheel);

$E \cdot I$ – a track stiffness in vertical plane [MNm²] ($E \cdot I = 3.82$ MNm²);

g_t – the track weight [MN/m] ($g_t = 0.0022$ MN/m),

a – a spacing of the sleepers [m] ($a = 0.60$ m);

foundation parameters: $k = 45,095$ kN/mm and $U = 27,144$ MPa.

Identification of one-parameter foundation coefficients for theoretical calculations

The response of a railway track to varying deflection of sleepers caused by vertical axle loads is often defined by a single parameter – the vertical track stiffness k [kN/mm] or the U parameter [MPa]. Paper [25] presented an original method for determining vertical track stiffness based on measured vertical deflections of the track in operation during static ride of a railway vehicle on the track under consideration (at various axle loads). Deflection measurements [25] were performed on an operational section of railway track with specified static wagon axle loads (100 kN/axle, 150 kN/axle and 200 kN/axle). Based on the obtained deflections, changes in the vertical stiffness of the track were determined (on average value: 34.98 kN/mm for 100 kN/axle, 43.03 kN/mm for 150 kN/axle and 49.96 kN/mm for 200 kN/axle). Using these values, the $k(Q)$ relationship was described. The relationship between the applied force and the obtained track deflections was used in the $U(Q)$ formula (based on the deflections of the beam

Table 3. The characteristics of the railway sleepers

Wooden sleeper I/B	Concrete sleeper INBK-7
- sleeper's weight: 100 kg	- sleeper's weight: 260 kg
- sleeper's length: $l = 2.6$ m (2.5 m is assumed for calculations to compare with a concrete sleeper)	- sleeper's length: $l = 2.5$ m
- sleeper's width: $b = 0.26$ m	- sleeper's width: $b = 0.3$ m
- stiffness: $EI = 0.6983$ MNm ²	- stiffness: $EI = 3.8286$ MNm ²
- sleeper's spacing: $a = 0.6$ m	- sleeper's spacing: $a = 0.6$ m

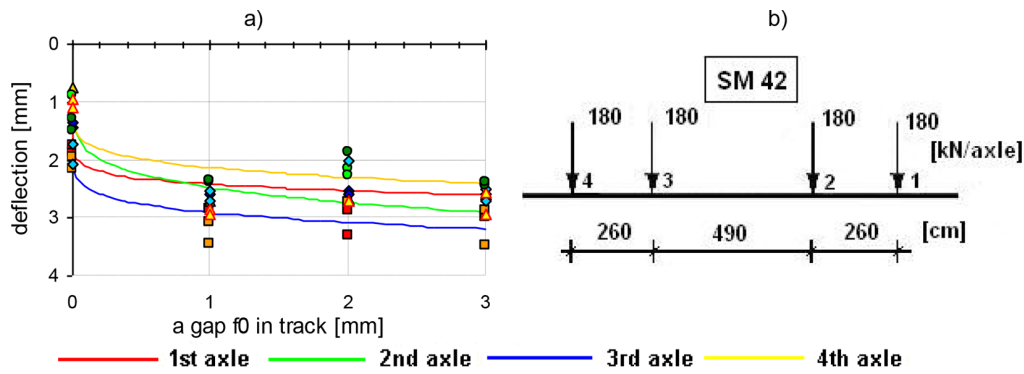


Figure 11. The obtained rail deflection in cross-section no. 2 – acting force in cross-section no. 2 (the succeeding axes of locomotive) and the scheme of acting force from the locomotive SM-42 (1st axle: $R^2=0.842$, 2nd axle $R^2=0.896$, 3rd axle: $R^2=0.926$, 4th axle: $R^2=0.905$)

(track) resting on a one-parameter foundation [25]). The obtained relationships of the k [kN/mm] and U [MPa] parameters were described by the following formulas:

$$k(Q) = 1.6312 \cdot Q^{0.6174} + 6.9785 \text{ [kN/mm]} \quad (5)$$

$$U(Q) = 0.3126 \cdot Q^{0.8216} + 6.5805 \text{ [MPa]} \quad (6)$$

Based on the track obtained deflection measurements (shown in Figure 11) described in [1,5]) and using the results of the tests [25], the following formulas can be given for a one-parameter foundation:

$$k(Q) = 1.632 \cdot Q^{0.6173} + 4.8318 \text{ [kN/mm]} \quad (7)$$

$$U(Q) = 0.3129 \cdot Q^{0.8214} + 4.8601 \text{ [MPa]} \quad (8)$$

where: Q – the force acting on the axle [kN/axle].

Figure 12 presents graphs of the dependence of the parameters k and U under acting force Q . Based on the carried out research (for 180 kN/axle – Figure 11) [1, 5] and using the obtained graphs (Figure 12), the following foundation parameters were obtained (given in Table 4).

For the scheme from Figure 9 the finite element method [26] is used for the calculations. Making use of Table 4 and Figure 12, the following graphs of changes in deflections, bending moments and stresses in the rail were obtained (Figure 13).

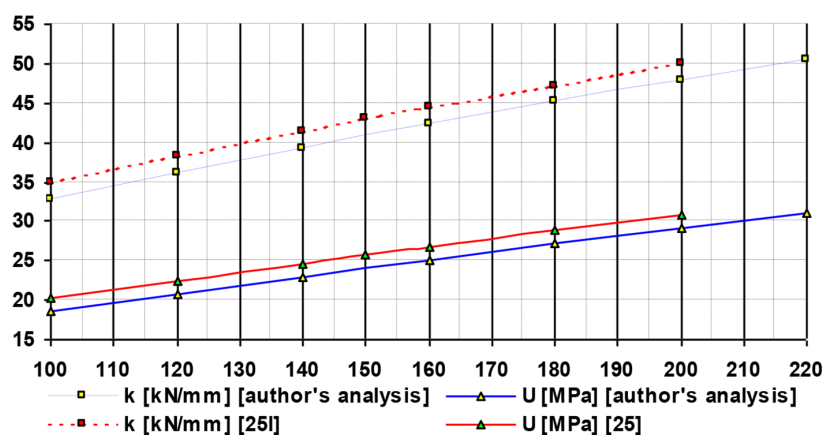


Figure 12. One-parameter foundation – obtained k and U parameters (based on [25] and the author's research)

Table 4. The obtained parameters for one-parameter foundation

180 [kN/axle]	200 [kN/axle]	220 [kN/axle]
$k = 45.095$ [kN/mm] $U = 27.144$ [MPa]	$k = 47.809$ [kN/mm] $U = 29.158$ [MPa]	$k = 50.416$ [kN/mm] $U = 31.137$ [MPa]

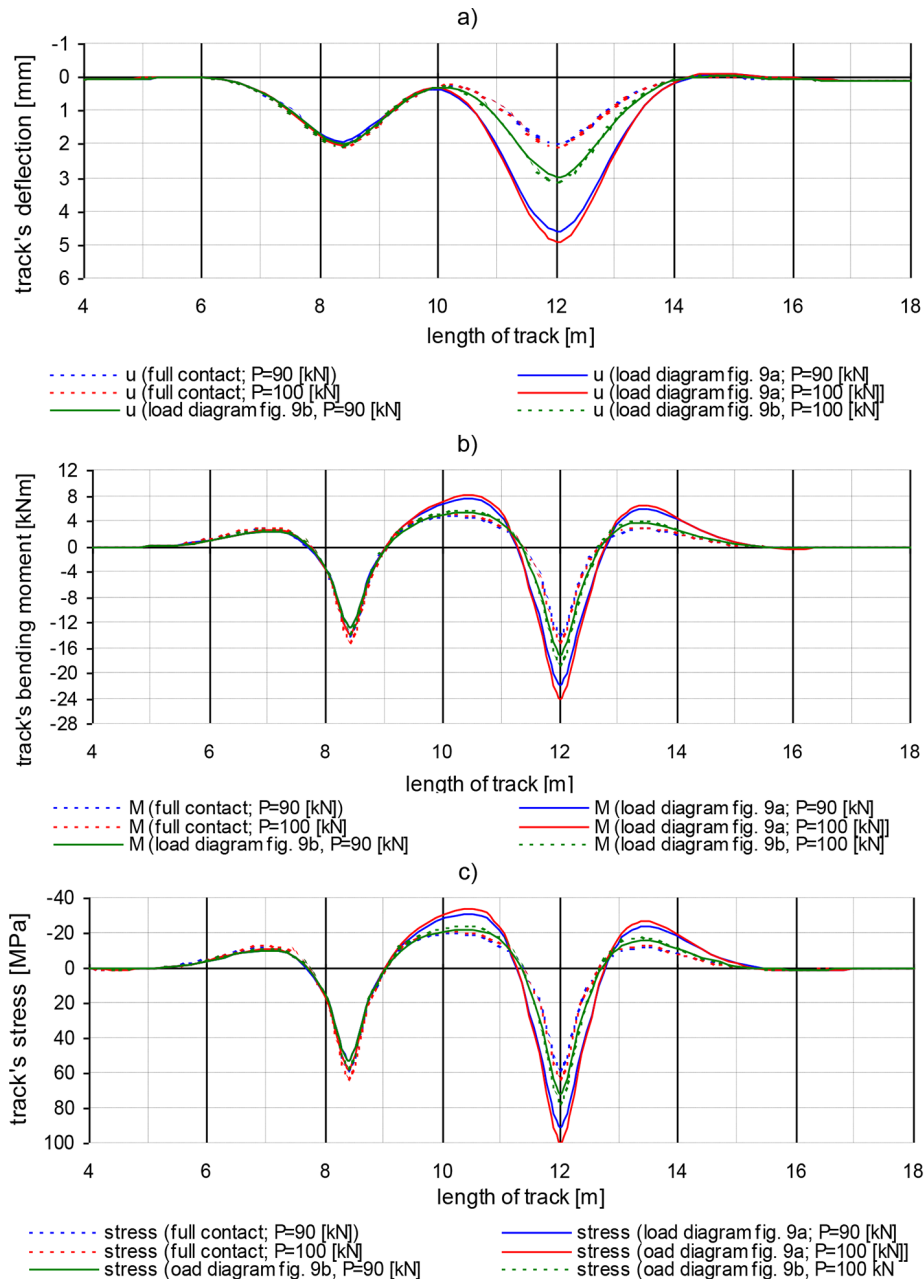


Figure 13. The influence of change of the acting force and support length on rail deflections and stresses (49E1 rail; track weight 0.0022 MN/m; sleeper spacing $a = 0.6$ m)

Figure 14 shows the obtained graphs of deflections and bending moments for different types of railway sleepers.

COMMENTS

The identification of one-parameter foundation coefficients allowed for analysis of works both the rail and sleeper in their contact loss with foundation. The obtained foundation parameters (Table 4) were used for the calculations (finite

element method for a B-E beam resting on one-parameter elastic foundation).

As can be seen from the analysis carried out in the paper, change of the support (especially the areas of contact loss of track and sleeper with the foundation) significantly changes the value of deflection and bending moment (Figures 13 and 14). The contact loss along just one sleeper spacing for a force of $P = 90$ kN and foundation parameter $U = 27.144$ MPa (Figure 9b) changes:

- deflection from 1.981 mm to 2.952 mm

- bending moment from 14.136 kNm to 17.239 kNm
- stress from 58.631 MPa to 71.50 MPa.

With increasing the length of contact loss to two sleepers spacing for a force of $P = 90$ kN and foundation parameter $U = 27.144$ MPa (Figure 9a), the following results were obtained:

- value of maximum deflection is 4.596 mm
- value of maximum bending moment is 21.894 kNm
- value of maximum stress is 90.808 MPa.

Increasing the force from 90 kN to 100 kN with foundation parameters: $U = 27.144$ MPa and $U = 29.158$ MPa (Figure 13) resulted in:

- value of maximum deflection is 3.122 mm (for scheme 9b)
- value of maximum deflection is 4.91 mm (for scheme 9a)
- value of stress is 78.316 MPa (for scheme 9b)
- value of stress is 99.717 MPa (for scheme 9a).

The obtained results can be described by a parameter illustrating the track stiffness [kN/mm]. Figure 9a shows that the track stiffness on the tested section is only 45.226 kN/mm. The following values are assumed to be optimal track stiffness [27]:

- 80–130 kN/mm
- 70–80 kN/mm on high-speed lines
- 70–80 kN/mm on freight-traffic lines.

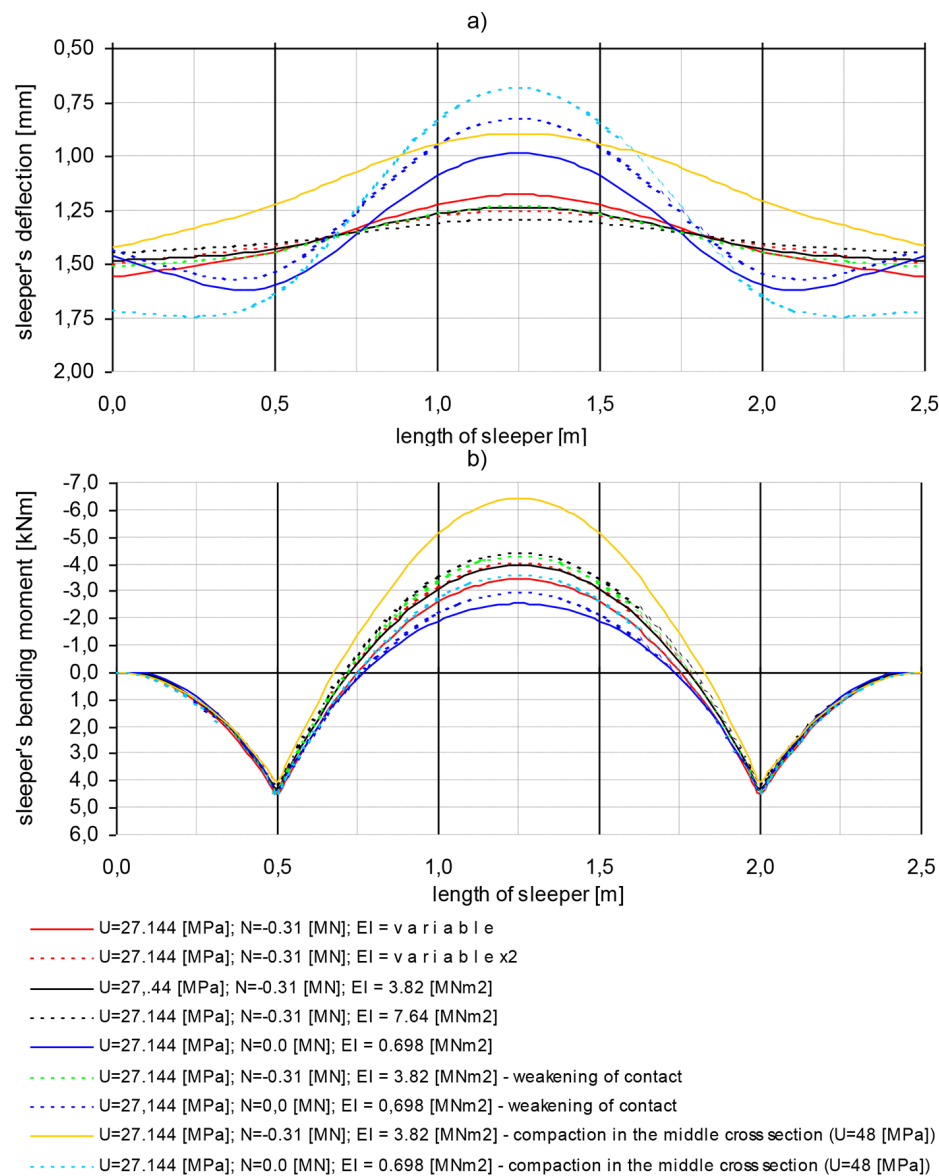


Figure 14. The deflections and bending moments along the length of the analyzed railway sleepers for the force transferred from rail to sleeper: $Q = 45.094$ kN

Therefore, the obtained value (45.226 kN/mm) is much smaller from recommended values [27]. Figure 14 shows changes in the deflection values and bending moments along the length of the sleeper. The contact loss in the under-rail section (dashed light blue and blue) in particular causes changes in deflections (at the beginning/end of the sleeper and in its middle). The highest values of deflections and bending moments for the sleepers are obtained for the scheme with foundation compaction in the middle of the sleeper. For the considered wooden sleeper (Figure 14a) with foundation compaction in the middle, the following deflections and bending moments are obtained:

- value of deflection at the beginning of sleeper is 1.716 mm
- value of deflection in under-rail cross section is 1.643 mm and bending moment: 4.472 kNm
- value of deflection in the middle of sleeper is 0.681 mm and bending moment: 3.597 kNm.

For the considered concrete sleeper (Figure 14a) with foundation compaction in the middle, the following deflections were obtained:

- value of deflection at the beginning of sleeper is 1.423 mm
- value of deflection in under-rail cross section is 1.224 mm and bending moment: 4.013 kNm
- value of deflection in the middle of sleeper is 0.893 mm and bending moment: 6.432 kNm.

An increase in the sleeper support factor ($U = 48$ MPa) in the middle section results in a significant increase in bending moments (shown in Figure 14b in yellow). Such support is particularly unfavorable to the operation of the concrete sleeper. On the basis of the obtained deflection values of the sleeper for one-parameter foundations, it can be concluded that the model (B-E beam resting on elastic foundation) is suitable for static theoretical–experimental analysis of the work of the sleeper under the conditions of small track imperfections.

Ensuring proper work of the railway track structure requires the realization of important conditions and factors:

- structural homogeneity and homogeneity of support along the length of the railway track (Figure 1)
- track geometry stability during operation
- quality of construction, construction/laying of the track (durability of the track)

- quality of used the materials and elements
- recording and measuring changes in time with their analysis (Figure 2)
- detection of weak spots in the track
- condition of the rolling stock (flat spots on the wheel).

CONCLUSIONS

On the basis of the analysis presented in paper, the following conclusions can be drawn:

- deforming railway track foundation cause areas of contact loss track with support;
- inhomogeneities in the stiffness of the foundation – in addition to the geometric irregularities of the rails and the unevenness of the rail running surface – are significant factors in additional interactions in the vehicle-track system;
- the wavelength of the inhomogeneity (λ) is significant – from the perspective of ballast loading, inhomogeneities with short half-wavelengths below 5 m are important;
- the carried out the investigations and analyses allowed for identify in the foundation parameter: 27.144 MPa for 180 kN/axle, 29.158 MPa for 200 kN/axle and 31.137 MPa for 200 kN/axle;
- the obtained parameters were used for the calculations (finite element method for a B-E beam resting on one-parameter elastic foundation);
- identification of foundation parameters allows for the analysis of changes in the support conditions of both the rail and the sleeper;
- even small contact gaps (along one or two sleepers spacing cause significant changes in the behavior of the rail and the sleeper;
- a change in the contact loss along the length of just one sleeper causes an increase in deflections by 49% and stresses by 22%; for two sleepers spacing, a respectively increase by 132% and 55% (for force $P = 90$ kN);
- with an increase in the acting force to 100 kN, the maximum deflection amounts up 4.91 mm and the stress is almost 100 MPa;
- the contact loss in the under-rail section for sleeper work causes a significant change in deflections (at the beginning/end of the sleeper and in its middle);
- an increase in the sleeper support factor ($U = 48$ MPa) in the middle section results in a large increase in bending moments.

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