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LONG-TERM GEOMETRY EVALUATION IN SWITCHES AND CROSSINGS AND THEIR MUTUAL COMPARISON

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Abstract

This paper focuses on the influence of switch and crossing structure types on track settlement. Track settlement is one of the most important parameters influencing track quality and its dynamic behaviour by passing trains. Measurements were taken on switches and crossings with various innovative structural elements installed into the network of the Czech Railways (Správa železnic) since 2010. Using levelling of rail head at regular intervals, the settlement of individual areas of turnouts were evaluated. Conventional turnouts, turnouts with elastic fastening systems, turnouts with under sleeper pads (USP), fixed crossings as well as crossings with movable parts and turnouts designed for high-speed lines, were measured and evaluated. Each turnout area was divided into five specific zones, which were further monitored and compared with each other. The monitored track sections were the area in front of the turnout, the switch panel, the closure panel, the crossing panel and the area behind the turnout. This paper focus on the crossing panel, considered the most dynamically loaded region. The primary goal of the research was to evaluate all measured data over time and compare the rate of settlement of the individual turnout structural type with each other while maintaining the same method and equipment for measurements. Through a long-term comparison, the benefits of individual innovative structural elements have been gained, and the degree of this benefit has been established for each turnout.

Keywords: turnout, switch, crossing, settlement, geodetic levelling

1 Introduction

With the increase in speed and the construction of high-speed lines, emphasis is placed on reducing the dynamic stresses generated by the passage of vehicles when testing new switch and crossing elements. Currently, all designed innovations in turnouts (i.e. shape of running surfaces of running rails and crossings, innovative turnout elements, fastening systems and bearers) lead to a reduction of dynamic stresses. This is reflected by an increase in the stability of the geometric parameters of the track, a reduction of maintenance interventions, an extension of the service life of the structure or component, and therefore a reduction in the life cycle costs of the turnout. In the validation of innovative turnout elements, the stability of geometric parameters in turnouts is monitored primarily over a long-time horizon.

The manufacturer DT - Výhybkárna a strojírna, a.s. (Czech manufacturer of switches and crossings) based in the Czech Republic has been monitoring and evaluating turnouts with innovative elements in the network of Správa železnic, s.o. (Czech Railway Administration) for 10 years. It carries out long-term measurements of the longitudinal height of the rail head tops using the geodetic method of levelling and evaluates geometrical track parameters.

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The Faculty of Civil Engineering of Brno University of Technology also participates in the monitoring on a long-term basis. The turnouts included in the long-term monitoring process are turnouts with different modifications. This paper presents the degree of settlement of crossing panel of the turnouts in the load passed, which can be considered as a key parameter with regard to the need for maintenance interventions. Although other parameters obtained from the levelling (i.e. cant, twist etc.) are not the focus of this paper, they are usually also evaluated during long-term monitoring of the turnout condition.

2 Description of monitored turnouts

The monitored turnouts described in this paper can be divided into the following categories: conventional turnouts, turnouts with optimised track stiffness, and turnouts with movable crossings (high speed turnouts).

Conventional turnouts with standard design without modifications: These turnouts are used as a reference for validating various innovations installed in turnouts in the same locality. The following are made use of: 60 E2 rail profiles, concrete bearers, rail fastening with the Skl 24 flexible clamps (the “K” rail fastening system), austenitic manganese steel cast monoblock crossings.

Turnouts with optimised track stiffness: These turnouts are equipped by under sleeper pads (USP) [1-4] in different variants. The stiffness arrangement of the USPs in the turnouts was determined on the basis of a mathematical model to equalize changes in track vertical stiffness and to simplify the arrangement of different types of USPs. Four types of USPs were installed (with stiffnesses ranging from 0.100 N.mm^{-3} to 0.220 N.mm^{-3}) in each turnout, including transition zones. One turnout of the 1:14-760 type had a so-called economical variant of the USPs arrangement design. The USPs are situated in a crossing panel only and the transition zones are located in the closure panel and behind the end of the turnout.

Other turnouts were equipped with elastic fastening systems [5, 6]. Specially developed elastic fastening systems are installed under the monoblock crossing and in the slide baseplates in the switch panel. These fastening systems are based on standard baseplate fastening systems used in switches and crossings with an added layer of an elastic element (usually elastic pad). The stiffness of the elastic pad was calculated by FEM model to optimize the longitudinal track stiffness along the whole turnout.

Turnouts with continuous running edge in the crossing: This category includes turnouts with movable crossings, which are mainly used for high-speed lines [7, 8]. Two high-speed turnouts of the type 1:33.5-8000/4000/14000 were chosen for monitoring, which are intended for speeds of 160 km/h in the branch line. In terms of turnout geometry, unlike the turnouts mentioned above, these turnouts use entry and exit transition curves. In terms of structural design, the main difference is in the crossing panel, where a movable crossing is installed.

All monitored turnouts are listed in the Table 1 below. All turnouts are in ballasted trackbed in the main tracks of the main lines for both of passenger and freight trains. The standard turnout is labelled S; turnouts with the USPs are labelled P; turnouts with elastic fastening systems are labelled Z; and turnouts with crossings with movable parts are labelled V. Table 1 also gives an overview of the speeds in the main and branch line and whether the investigated area of the specific turnout has (Y) or doesn’t have (N) a modification to reduce the dynamic load compared to standard turnout.

Table 1 Monitored turnouts

Turnout	Geometry	V_{main} [km/h]	V_{branch} km/h]	Modification reducing dynamic loads (in zones A to E)				
				A	B	C	D	E
S1-UNO	1:12-500	130/160	60	N	N	N	N	N
P1-PLA	1:12-500	160	60	Y	Y	Y	Y	Y
P2-UNA	1:14-760	160	80	N	N	Y	Y	Y
P3-UNB	1:12-500	160	60	Y	Y	Y	Y	Y
Z1-UNA	1:12-500	130/160	60	N	Y	N	Y	N
Z2-UNB	1:12-500	130/160	60	N	Y	N	Y	N
V1-PRA	1:33,5-4000	160	160	N	N	N	Y	N
V2-PRB	1:33,5-4000	160	160	N	N	N	Y	N

3 Measurement methodology

For measurement by the geodetic method of levelling, the turnout is longitudinally divided into cross sections of three meters m apart (on which the height of all rail head tops occurring in the specific cross section are measured). The distance of three meters is related to other frequently evaluated parameters, such as track twist. The division of these sections is chosen so that the first cross section in the turnout is placed at the beginning of the turnout. Connecting plain track sections before and after the turnout are also monitored, where in some cases the distance of the measuring cross sections is chosen to be double (6 m). The length of the connecting plain track sections is chosen taking into account the local conditions of the turnout position in the railway station. The lengths of the monitored sections outside the turnout range from about 20 m to 100 m. If there is another turnout in the vicinity of the monitored turnout, whose position interferes with the monitored section, the monitored area is terminated either at the beginning or end of this turnout. In some cases, it is therefore not possible to evaluate the sections before or after the turnouts. For turnouts labeled P2 and P3 (turnouts equipped by USPs), in addition to the transition areas, the monitoring also included connecting plain track sections without USPs. The distance of the mesured cross sections in the area with USPs outside the turnout was chosen to be three meters.

In terms of the accuracy of the measuring system, the precise levelling was carried out with levelling instruments for which the standard km deviation is $\sigma_{km} \leq 1.5$ mm; the telescope magnification is at least 24×; the sensitivity of the levelling spirit level is at least 20.6″ (per 2 mm scale part) or in coincidence adjustment 4″/2 mm or a compensator of the corresponding accuracy. If digital levelling instruments and equipment are used, they should meet the characteristics previously mentioned. The lengths of the back- and foresights are measured to an accuracy of 0.1 m. The level traverse is always closed.

4 Evaluation methodology

Each individual monitored section was divided into the area before the turnout (A), the switch panel (B), the closure panel (C), the crossing panel (D) and the area behind the turnout (E), (see Figure 1). The more loaded branch, i.e. the main (straight) branch of the turnout, was evaluated.

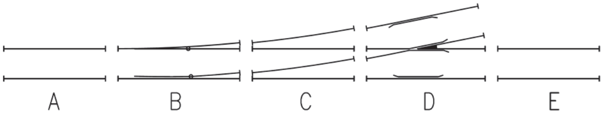

Figure 1 Evaluated zones in the turnouts

The amount of settlement in each zone (A to E, see Fig. 1) was determined from the measured rail head heights. For each zone evaluated, the average of the rail heights in the main (straight) direction of the turnout was calculated. From each measurement, one value was calculated for each zone, i.e. five values for the whole turnout area, which was usually divided into five parts. These values were used as a basis for the determination of the settlement during the period under consideration. The first measurement is taken as a reference. For the course of the rail height from the first, i.e. the reference measurement, the optimum rail height position was determined by regression. The settlement (height difference between the two measurements) was calculated to this reference height position. The analysis of the development of settlement was carried out in all the mentioned turnout zones. The regression function expressing the turnout settlement was considered in the form:

$$S(l) = s_0 + L \cdot \left(1 - e^{-\frac{k}{L} l}\right) \tag{1}$$

in which symbols denote:
s_0 – initial settlement, for l = 0 settlement $s_0 = 0$;
S(l) – function of settlement [mm];
l – operational load [MGT - million gross tons];
L – limit of settlement [mm];
k – slope of tangent at l = 0 [mm/MGT].

The settlement s_0 is introduced into Eq. (1) because of a different initial settlement after tamping of the track. The regression functions were determined by least square method to find the minimum of the function:

$$min\left\{f(\boldsymbol{x}) : \boldsymbol{x} \in X \subset E^2\right\} \tag{2}$$

in which:
x – vector of parameters of the regression function $[k\ L]^T$;
X – subset defined by constraints k › 0 and L › 0 of Euclidean space E^2.

The function was defined:

$$f(\boldsymbol{x}) = \sum_{i=0}^{n} \left[s_i - S(l_i)\right]^2 = \sum_{i=0}^{n} \left[s_i - \left(s_0 + L \cdot \left(1 - e^{-\frac{k}{L} l_i}\right)\right)\right]^2 \tag{3}$$

in which:
I – index of track levelling epoch;
N – number of last epoch;
s_i – measured track settlement [mm];
l_i – service load till levelling epoch number i [MGT].

The min occurs at the point x*:

$$\nabla f\left(\boldsymbol{x}^*\right)^T = 0 \tag{4}$$

in which ∇f(x) is gradient vector:

$$\nabla f(\boldsymbol{x})=\left[\frac{\partial f}{\partial k}\ \frac{\partial f}{\partial L}\right] \tag{5}$$

The system of nonlinear algebraic equations was evaluated from the Eq. (4):

$$\sum_{i=0}^{n}\left[\left[s_i-\left(s_0+L\cdot\left(1-e^{-\frac{k}{L}\cdot l_i}\right)\right)\right]\cdot l_i\cdot e^{-\frac{k}{L}\cdot l_i}\right]=0 \tag{6}$$

$$\sum_{i=0}^{n}\left[\left[s_i-\left(s_0+L\cdot\left(1-e^{-\frac{k}{L}\cdot l_i}\right)\right)\right]\cdot\left(1+\frac{k}{L^2}\cdot l_i\cdot e^{-\frac{k}{L}\cdot l_i}\right)\right]=0 \tag{7}$$

The system of nonlinear equations was solved by Newton’s method:

$$x^{k+1}=x^{k}-\left(\nabla^2 f\left(x^{k}\right)\right)^{-1}\cdot\nabla f\left(x^{k}\right) \tag{8}$$

in which Ñ^{2}f(x) is the symmetric Hessian matrix:

$$\nabla^2 f(\boldsymbol{x})=\begin{bmatrix}\frac{\partial^2 f}{\partial k^2} & \frac{\partial^2 f}{\partial k\partial L}\\ \frac{\partial^2 f}{\partial L\partial k} & \frac{\partial^2 f}{\partial L^2}\end{bmatrix} \tag{9}$$

Upper index k means a step number of the numerical iteration. If convergence error was less than tolerance e, e.g.:

$$\left\|\nabla f\left(x^{k}\right)\right\|\le\varepsilon \tag{10}$$

the calculation was stopped and the parameters k, L were determined.

The applicability of using exponential regression for turnout settlement can be demonstrated by the evolution of the P1-PLA turnout (see Fig. 2). This turnout has not been tamped during the whole observation period; therefore, the way of development of settlement without interruption can be compared. The example is shown for clarity only for zones A and B. The other zones showed a similar pattern of settlement.

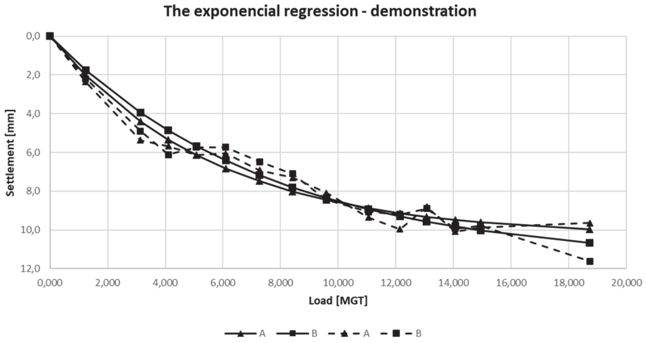

Figure 2 Demonstration of applicability of the exponential regression

The graph in Fig. 3 demonstrates the evolution of the settlement in all areas of one selected turnout. In this case, it is a P3-UNB turnout equipped with USPs along the entire length of the turnout (zones B, C and D). A transition area to the standard ballasted track was established both in front of and behind the turnout, consisting of a section with higher stiffness USPs (A and E). The connectiong plain track sections without USPs (A' and E') were also monitored.
It is evident from the graph that the fastest settlement was found in the zones behind the turnout. This is due to the problems in the track subgrade that were evidenced at this station. However, it can be seen that even the establishment of the USP transition zone had a significant positive effect on the development of settlement (comparison of curves E and E'). The turnout itself settled in a broadly consistent manner compared to the area before the front and behind the turnout, which can also be assessed positively. Of the areas B, C and D, the crossing panel settled the most, which is a natural phenomenon in all fixed crossings due to the occurrence of the largest dynamic load in the turnout. An interesting observation can also be made in the zone in front of the turnout (curves A' and A). It is evident that the tamping performed in the passed load of about 60 MGT had a very short-term effect. It is possible to conclude that after another 20 MGT, the benefit of tamping was completely lost and the theoretical curve of what the development of settlement could look like if the tamping had not been performed would most likely almost merge with the curve measured after tamping.

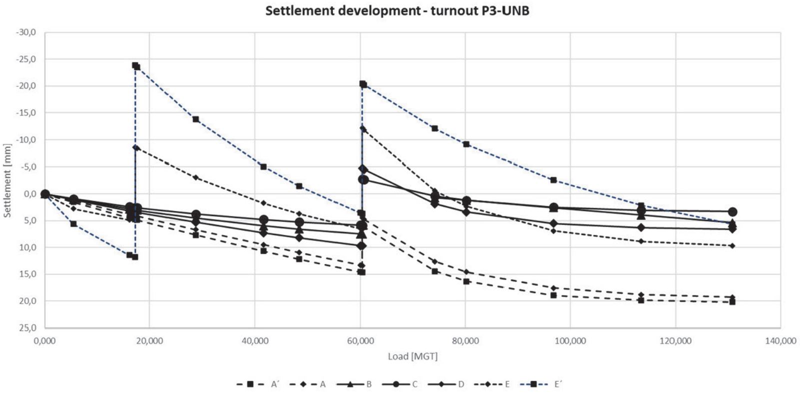

Figure 3 Demonstration of settlement development of all zones at the turnout with USPs

5 Mutual comparison

Due to the limited scope of the paper, the comparison of the observed turnouts was focused on the crossing panel of the turnout (i.e. area D) as the most important zone in terms of dynamic load. Therefore, possible modifications leading to a reduction of dynamic load may also be most evident. A graph presenting the development of the settlement of all the subject turnouts in area D is shown in the following Fig. 4. The parameters of the regression functions used for the crossing panel of the turnouts under study are summarized in Tab. 2. Periods 1, 2, and 3 correspond to the time periods between the tamping interventions. That is, if a turnout was tamped twice during the monitoring period, three regression curves were calculated, and therefore parameters shown in Tab. 2 are for the three periods. If the turnout was tamped once, regression parameters for two periods are given; if the turnout was not tamped during the monitored period, parameters only for one period are given. The comparison of the settlement trends was based on the parameters of the regressions (see Table 2).

The parameter k, which determines the slope of the regression curve of settlement at the point after the track tamping, represents the rate of settlement; the parameter S_{inf} corresponds to the relative magnitude of the steady state settlement of the track, i.e. it represents the value of settlement to which the curve with initial settlement value S_0 = 0 mm asymptotically approaches. The absolute settlement value, which can be read from the graph in Fig. 4, is obtained by adding the value of S_0 to the value of S_{inf} in the corresponding period. The quality of the regression model was also considered in the evaluation, as assessed by the R^2 determination index. If R^2 › 0,85, then the regression performed was assessed as appropriate. If it was less, the parameters of function (1) were not considered in the evaluation (indicated by note 1) in Table 2). If the regression gave a large S_{inf} parameter (in thousands of mm), the exponential regression did not make good sense and was replaced by a linear regression with a resulting regression line directive k (indicated by note 2) in Table 2).

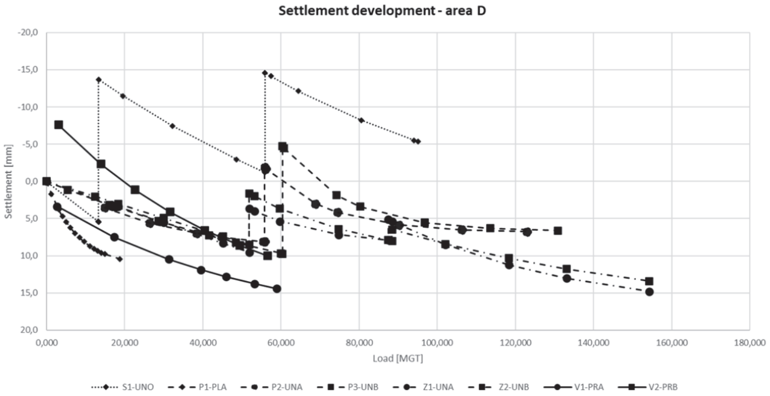

Figure 4 Settlement development of all monitored turnouts in area D (crossing panel)

Table 2 Parameters of the regression functions for the zone D (crossing panel)

Period		**1.**				**2.**				**3.**		
Regression parameters	S_o	**k**	S_{inf}	R^2	S_o	**k**	S_{inf}	R^2	S_o	**k**	S_{inf}	R^2
S1-UNO	0	0,41	10000$^{2)}$	1,000	-13,7	0,37	34,3	0,988	-14,6	0,31	21,8	0,992
P1-PLA	0	1,47	11,5	0,987								
P2-UNA	0	0,22	5,8	0,990	-1,7	0,53$^{1)}$	8,6$^{1)}$	0,734$^{1)}$				
P3-UNB	0	0,21	22,0	0,935	-4,5	0,69	11,2	0,925				
Z1-UNA	0	0,18	648620$^{2)}$	0,969	3,7	0,26	5,0	0,922	5,1	0,27	13,0	0,932
Z2-UNB	0	0,16	239359$^{2)}$	0,927	1,6	0,29	9,3	0,994	8,4	0,13	10,4	0,853
V1-PRA	0	0,33	16,4	0,973								
V2-PRB	0	0,55	26,2	0,903								

The parameter k describes the settlement rate of the track immediately after installing or after tamping. It is therefore more beneficial for the settlement evolution to keep the parameter k as small as possible. The long-term settlement evolution is represented by the parameter S_{inf}. A lower value of S_{inf} means a smaller amount of settlement. These parameters should be considered simultaneously when interpreting the measurement results; they complement each other.

The Z1-UNA and Z2-UNB turnouts equipped by the elastic fastening system show the lowest values of the parameter k in all periods. A slightly higher value can be observed for the P2-UNA and P3-UNB turnouts with USPs, but it has tripled after tamping. However, in terms of settlement (S_{inf}) the development is beneficial, and all four turnouts are comparable in this parameter. The P1-PLA turnouts with USPs came out negatively in terms of parameter k. The value of the k parameter is much higher, which is however expected in view of the unstable construction of the track substructure, manifested by large and irregular settlement of the track and related local defects of the geometric parameters of the track behind the turnout. This section is located on a line with less traffic load (compared to the other sections presented here). It has been monitored and measured for about 8 years. Despite the high settlement speed at the beginning, the steady state settlement value reaches a magnitude of 11,5 mm, which is comparable to the switches described above. The high-speed V1-PRA and V2-PRB turnouts with crossing with movable parts perform similarly to the fixed-heart turnout.

The effect of tamping must also be considered in the comparison. Some sections have not been tamped at all, others have been tamped twice. The amount of lifting level during tamping, the number of tamping and the spacing of the individual interventions in the track height position have an influence on the development of settlement. It is not easy to define the extent to which the interventions made contribute to the development and final settlement of the track. In the switches Z1-UNA and Z2-UNA, the last tamping was carried out to adjust the level by 1,6 mm and 3,7 mm respectively. In the following period, an ineffective to negative effect of tamping can be observed. The development of settlement was significantly worse, with the absolute value of the settlement before the last tamping being 8,7 mm and 10,9 mm, respectively; after the tamping, the settlement development showed a settlement of 18,1 mm and 18,8 mm, respectively. However, the results clearly show that the elastic support, either by USPs or by the elastic fastening system, has a clear positive effect on the development of settlement.

6 Conclusion

This paper describes a summary turnouts evaluation of various modifications, which have been regularly measured in the last 10 years by the geodetic method of levelling. Over time, the turnouts have mostly been evaluated separately, so the idea of looking at all the measured data collectively was suggested. Attention was focused on the development of settlement of individual areas of the turnouts, and due to the scope of the article, only the crossing panel as the most dynamically loaded part was discussed in detail. Different turnouts with structural improvements leading to a reduction of dynamic load or leading to a reduction of the negative consequences of dynamic loading (USP, elastic fastening system, movable crossings) and standard turnouts without such improvements were compared.

The evaluation focused on the parameters of the regression curves of settlement development. The turnouts equipped by USPs and the elastic fastening systems came out very well from this comparison. As expected, the standard turnout without longitudinal optimization of track stiffness performed worse. Movable crossings also did not perform very well, which was not directly expected.

The interpretation of the results is influenced by other factors, especially the condition of the track subgrade or the effect of adjusting the height position of the track by tamping. It is difficult to quantify these influences and therefore a comparison of the settlement development of individual turnouts is not fully representative. For a more reliable interpretation of the results, a larger sample of turnouts would be required, which is not possible due to the time required for this measurement. However, the presented evaluation shows certain patterns in the development of settlement that can be used for further evaluation and research.

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