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FORECASTING OF RAILWAY TRACK TAMPING BASED ON SETTLEMENT OF SLEEPERS USING FUZZY LOGIC

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ABSTRACT

The sleepers in a railway track transfer vertical, transverse and longitudinal loads to the track ballast and subgrade. The sleepers allow for keeping the distance between the rails constant. The thickness of ballast should be between 16 and 35 cm depending on the design standard of the track, and it should be densified where the ballast supports the sleeper.

The exploitation causes contamination of the ballast, crushing the material under cyclic dynamic loads, which results in the settlement of sleepers. Consequently, the thickness of ballast is not sufficient and the effects such as longitudinal unevenness of rails and track twist appear. Those effects have negative impact on the comfort and travel safety, in the extreme cases leading to the derailment.

The parameters like ballast thickness, degree of its contamination, its density and sleepers' settlement are difficult to measure so that they can be considered as 'fuzzy'. Therefore, the fuzzy sets and transfer functions are used to determine those parameters. The cause and effect relationships and their impact on the reliability of the system will be analyzed in the fuzzy sets' domain. Special attention will be paid to use this concept in forecasting the track tamping to enhance the interaction of the track surface with the soil ground and to increase safety.

Key words: subsidence of railway sleepers, tamping ties, fuzzy logic

ON NON-UNIFORM SETTLEMENTS OF SOIL GROUND, TRACK BED AND TRACK

The acceptance criterion for a particular train velocity on a train line includes the track unevenness and the track width (Bałuch, 1997). The track stability depends on: the resistance of the ballast against the displacement of the track frame, the stiffness of the track frame, vertical and horizontal track unevenness, the condition of track bed and soil ground.

A proper preparation of both track bed and soil ground (Lechowicz & Wrzesiński, 2013) affects the track settlement, which is usually non-uniform, and it leads to the generation of track unevenness.

Different examples/cases can be observed during practical exploitation. The plots in Figure 1 demonstrate the temporal changes in the settlement in the selected points of the railroad embankment and the enhanced soil. The settlement rate depends on the distance from the pile.

In the other example, an increased track settlement of the range of 20–35 mm in the period of 15–20 days was detected in the observed segment. The reason for that was that the track bed in a given region (segment of the length of 250 m) was made of cohesive soil (Głuchowski, Sas, Bąkowski & Szymański, 2016). As a consequence, unevenness up to 24 mm and track twist appeared in that segment.

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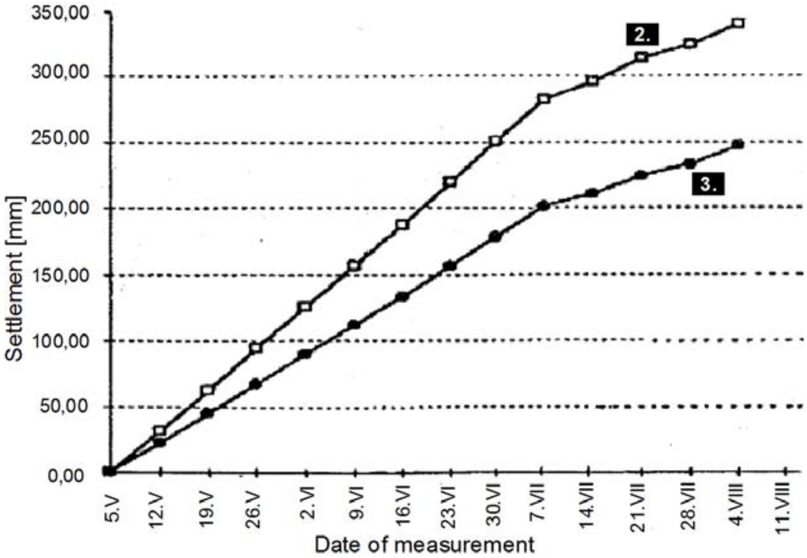

Fig. 1. Settlement of the railroad embankment and the enhanced soil in points 2 and 3 (Mieloszyk, 2003)

Similar situations are observed during modernization of railway lines. The peat was found in the soil at both sides of the existing railroad embankment. The soil was stabilized using columns of gravel and crushed stone. Additionally, static consolidation was realized, which was based on burdening of the constructed embankment with the sand layer (of the thickness of 1.25 m) above the upper surface of the embankment for 30 days. The exploitation showed that the settlement existed even after few years and achieved 25 mm per month. In order to avoid reduction of train speed, the track was constantly tamped and crushed stone was deposited, which generated costs and troubles with railway traffic.

Fig. 2. Negative impact of the incorrect drainage on the condition of embankment slope (registered in March 2017)

Inadequate drainage of the track could also cause the settlement. Figure 2 demonstrates how the water affects the trackbed and soil ground.

In each case, the dynamic loads lead to the displacements of the sleepers in time, and those effects are visible in the track, as illustrated in Figure 3.

Fig. 3. Displacements of the sleepers in the track

The scheme of the loads and displacements of sleepers is shown in Figure 4. It is important to note that the displacements observed in Figures 3–4 are different during train passage. Once the track is unloaded, the track comes back to the location in Figure 3, however, those displacements get larger, which results in track degradation. The displacements depend on many factors, are difficult to be measured and should not exceed the limits. It is necessary to perform diagnostics of the situation, complete the track tamping, and deposit the ballast to avoid further displacements of the sleepers and to provide safety. When do these actions should be taken when it is difficult to determine the displacements precisely? It is difficult to perform the measurements for the selected segments of the track and for the selected sleeper. Therefore, the theory of fuzzy set could be used here in decision making. Additional difficulty comes from the fact that the track exploitation improves its stabilization. According to many studies, the resistance levels between the sleeper and the ballast become constant after 18 months, as indicated in Figure 5.

DIFFERENTIAL MODEL

Different models can be developed to describe the behavior of the railroad surface, its elements and its enhancement. The railroad surface can be considered as a beam on an elastic foundation (Huber, 1988), a beam with variable cross-section (Milewska, 2011), a base or a group of foundations (Meyer, 2012), or a group of foundations loaded cyclically (Huber, 1988; Dembicki, 1997; Hall, 2000; Dembicki, 2004).

Let us consider the system consisting of a sleeper connected to the rails and the ballast interacting with

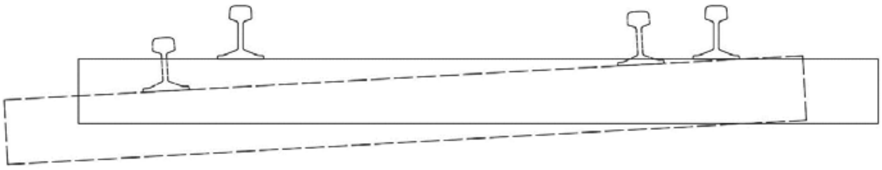

Fig. 4. Schematic of the sleeper displacement

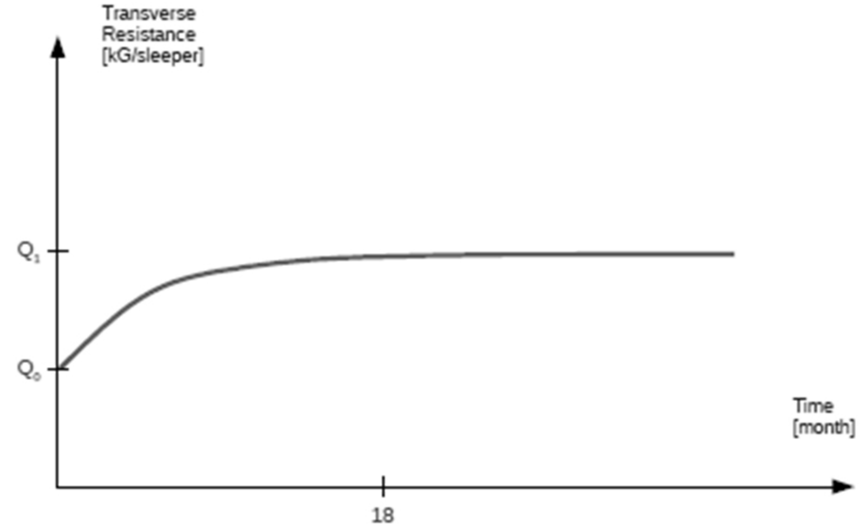

Fig. 5. Dependence and stabilization of lateral resistance below the sleeper. The data based on references and experiments of Authors. $Q_0 \in (220; 550)$ $Q_1 \in (350; 700)$, Q_0, Q_1 depend on the sleeper and the ballast materials (Samavedam, 1995; Funke, 1981; Hunt & Yu, 1998; Woldringh & New, 1999)

the vibrating sleeper. For a given excitation signal $F(t)$ coming from the passing vehicle, the following differential equation can be written (Koc & Mieloszyk, 1988):

$$m\ddot{y} + c\dot{y} + ky = F(t) \tag{1}$$

where: m – indicates the mass of the system;
c – coefficient of damping;
k – coefficient of elasticity.

In Eq. (1), the driving signal can be also distribution signals.

If we define:

$$2h = \frac{c}{m}, \qquad \alpha^2 = \frac{k}{m}$$

Eq. (1) can be rewritten in the form:

$$\ddot{y} + 2h\dot{y} + \alpha^2 y = \frac{F(t)}{m} \tag{2}$$

which indicates that the system is a special case of the generalized oscillation term (Mieloszyk, 2008), whose transfer function $G(p_q)$ is given by (Mieloszyk, 2008):

$$G(p_q) = \frac{id}{p_q^2 + 2hp_q + \alpha^2 id} \tag{3}$$

When $h^2 - \alpha^2 < 0$ the Eigen modes of the free system (2) are described by damped harmonic signals of variable amplitude Ae^{-ht}, A – const.

For this type of damped vibrations, the coefficient defined by:

$$\ln\left|\frac{Ae^{-ht}}{Ae^{-h\left(t+\frac{T}{2}\right)}}\right|, \text{ where } T = \frac{2\pi}{\sqrt{a^2 - h^2}}$$

is called logarythmic decrement, which is used to assess the damping of vibrations. This metrics is used to qualitatively analyze the reaction of the entire system or its components to special signals – excitations (Lechowicz & Wrzesiński, 2013). When the homogenous segment of line (the characteristics of its components, i.e. rails, sleepers, material and thickness of ballast etc. are constant) is analyzed, the changes in logarithmic decrement indicate the incorrect cross-tie tamping or the sleeper settlement.

It is also possible to consider a random character of the effect. Then, the defined dynamic system could be considered as deterministic with random excitations and reactions. Now, the Eq. (2) is equivalent to random differential equation:

$$\ddot{Y}_t + 2h\dot{Y}_t + \alpha^2 Y_t = F_t \tag{4}$$

in which: Y_t, F_t – stochastic processes.

The transfer function (3) can be used to determine the reaction Y_t of the system. As we mentioned before, the deterministic and random models can be used to perform qualitative analysis of the sleeper settlement or the degree of tamping but it is difficult to take practical decision based on those data since the models enable extraction information on the character of those effects.

FUZZY MODEL

In our everyday lives as well as in the engineering practice, we operate with the 'fuzzy' terms. The 'fuzzy' terms in civil engineering include e.g. requirements for the construction safety, safety-in-use, noise control and vibration control (Mieloszyk & Grulkowski, 2018). Therefore, safety assessment includes identification of at least static schemes, structure load, parameters of the materials used, parameters of the soil ground (Meyer, 2012) along with making the control calculations to ensure that all standards and regulations of structure design are met. The condition of the existing structure is also compared with the desired (expected) condition, which corresponds to the soil ground (Dembicki, 2004; Lechowicz & Wrzesiński, 2013), trackbed, railroad surface and its components as well as the entire structure. The actual condition can be rated as very bad, bad, satisfactory, good, very good, which are 'fuzzy' terms.

The ‘fuzzy’ logic along with the fuzzy inference system are useful in decision making in engineering, especially when the unambiguous assessment is hard to complete or it is difficult to do the measurements: low settlement of the soil ground, low rail wear, long exploitation time, short closure period, many rail defects of particular type, compacted density and contamination of the ballast – low/high. Such unambiguous and subjective information indicates imprecision and fuzziness of described effects. Therefore, the transformation from elements with a fuzzy feature to another fuzzy feature should be progressive. This can be enabled by the theory of fuzzy sets, which is based on the concept of a fuzzy set (Kacprzyk, 2001).

Let U be the set of all elements with a particular feature, and f assigns the number in the range <0, 1> to each element from the set $X \subset U$.

In the theory of fuzzy sets, the membership function $\mu_X(x)$ is defined as:

$$\mu_X(x) = \begin{matrix} f(x) & \text{for } x \in X \\ 0 & \text{for } x \in X \end{matrix} \qquad x \in U$$

since the element can ‘partially’ belong to the set. Figure 6 shows the example of the membership function of the fuzzy set – the crushed stone thickness below the sleeper is around q_0.

However, it is easier when the membership functions have the form of polygonal curve (Fig. 6).

The membership functions presented in Figure 6 were determined arbitrarily and have subjective character.

As mentioned before, the fuzzy sets allow a formal description of imprecise and ambiguous terms such as ‘huge contamination of the ballast’. The pair (set, membership function) is called a fuzzy set.

Using the fuzzy sets $\left(X_1, \mu_{X_1}(x)\right)$, $\left(X_1, \mu_{X_2}(x)\right)$, it is possible to define the intersection and the union. Those sets are defined by the corresponding membership functions.

Attention: The fuzzy set $\left(X, \mu_X(x)\right)$ is usually denoted shortly by X.

Let us introduce different membership functions for sleepers’ settlement taking into account: the contamination of the ballast, the ballast thickness, the ballast compactness (Fig. 7).

Let us define the following function

$$Z = \sum_{i=1}^{n} w_i \left[\mu_i(x)\right]^2 \tag{5}$$

where: w_i – weights assigned by the expert depending on the importance of the factor i.

The weights were determined using Analytic Hierarchy Process (AHP) method (Saaty, 1980, 1982), in which the scale range 1–9 was taken. The importance of the factor is assessed with respect to another factor in an ordered pair of factors. As an example, the score 3 indicates that the first factor is slightly more important than the second factor. The scores 2, 4, 6, 8 are intermediate scores between uneven scores. The score 1 indicates the same importance of the factors in a pair. When the direction of factors

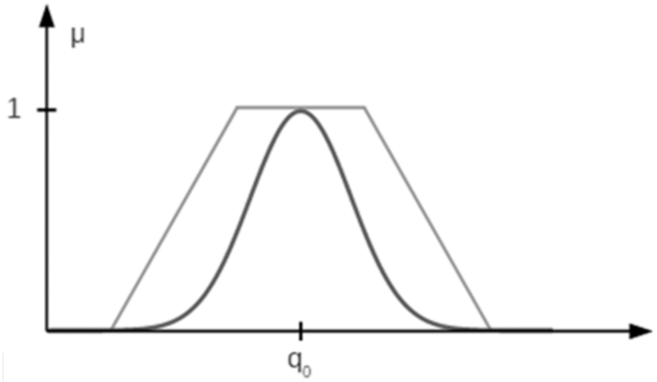

Fig. 6. Membership function for the fuzzy set – crushed stone thickness below the sleeper

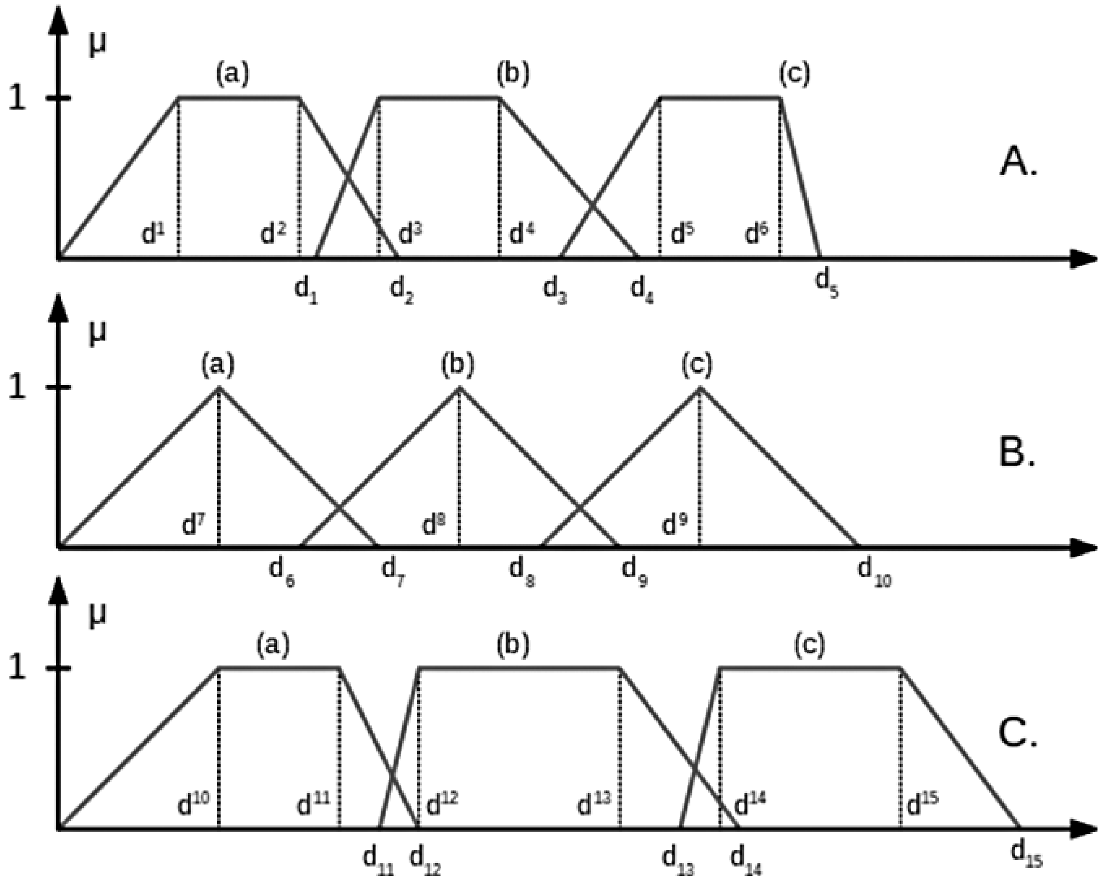

Fig. 7. Membership functions, e.g.: A. – ballast thickness, B. – ballast contamination, C. – ballast density, (a) – little, (b) – intermediary, (c) – high and d_i, d_i = const, $i = 1, 2, \ldots, 15$

is reversed during assessment, the score becomes reciprocal of the obtained score, e.g. the score 3 becomes 1/3.

Table 1 presents the scores (in pairs) of three factors affecting the sleepers' settlement. The scoring was done using literature, considerations in Section 2 and the experience of the Authors.

Using the data in Table 1, we determine the weights w_i, $i = 1, 2, 3$ as the components of the vector collinear to the vector that is created by the transformation with the transformation matrix **A** with the elements from Table 1. This vector satisfies the equation $\mathbf{A}\vec{w} = \lambda\vec{w}$. For $\lambda_{mai} = 3$ we obtained the weights shown in Table 2.

Table 1. Scores for the criterion 'settlement of sleepers'

Settlement of sleepers	Ballast compactness	Ballast thickness below sleeper	Contamination of ballast
Ballast compactness	1	4	8
Ballast thickness below sleeper	1/4	1	2
Contamination of ballast	1/8	1/2	1

Table 2. Weights for considered factors

Factor	Weight
Ballast compactness	0.72
Ballast thickness below sleeper	0.19
Contamination of ballast	0.09

Inserting the obtained weights to formula for Z, we obtain $Z = 0.72\ \mu_1(x) + 0.19\ \mu_2(x) + 0.09\ \mu_3(x)$, where $\mu_i(x)$, $i = 1, 2, 3$ are the membership functions either shown in Figure 7 or other prepared. The maximum or minimum of the function Z provides fuzzy information on the settlement of sleepers. That information allows to recommend if and when the track should be tamped.

CONCLUSIONS

It is difficult to forecast the maintenance works for the railroad surface, track bed and soil ground but it affects the safety of railway traffic.

The demonstrated methods of fuzzy logic can be useful in decision making in the field of rail engineering, where the 'fuzzy terms or quantities' are taken into account. This is realized when the decision is actually a trade-off. Example: Do we need to reduce the speed in the selected line? Do we need to start current maintenance works or major repairs? If yes, when? Should the components of the track be exchanged, repaired or regenerated after set exploitation duration?

The presented example could be extended to account for additional factors influencing the sleepers' settlement. However, the advanced model should be developed by a group of experts, especially during derivation of transfer function and determination of the results.

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PROGNOZOWANIE PODBICIA TORU KOLEJOWEGO NA PODSTAWIE OSIADANIA PODKŁADÓW Z WYKORZYSTANIEM LOGIKI ROZMYTEJ

STRESZCZENIE

Zadaniem podkładów kolejowych jest przejęcie zmiennych i różnorodnych obciążeń: pionowych, poprzecznych i podłużnych oraz przeniesienie ich na podsypkę, a dalej na podtorze i podłoże gruntowe. Dodatkowo pozwalają one na utrzymywanie stałej odległości między tokami szynowymi. Grubość warstwy podsypki pod podkładem powinna wynosić od 16 do 35 cm w zależności od standardu konstrukcyjnego toru i powinna być zagęszczona pod podkładem w strefach podparcia.

W wyniku eksploatacji następuje zanieczyszczenie podsypki, rozkruszanie jej ziaren pod wpływem cyklicznych obciążeń dynamicznych, a tym samym następuje niekorzystne osiadanie podkładów. Prowadzi to w konsekwencji do niespełnienia warunku dotyczącego grubości podsypki i powoduje powstawanie zjawisk: nierówności podłużnych toków szynowych i wichrowatości toru. Zjawiska te mają negatywny wpływ na komfort i bezpieczeństwo jazdy, a w przypadkach skrajnych prowadzą do wykolejenia się pociągu.

Wspomniane już wielkości: grubość podsypki pod podkładem, stopień jej zanieczyszczenia i zagęszczenia oraz osiadanie podkładów są wielkościami trudno mierzalnymi, a więc nieostrymi, rozmytymi. W związku z tym do ich określenia i wykorzystania zostaną zastosowane zbiory rozmyte i funkcje przynależności. W dziedzinie zbiorów rozmytych analizowane będą stany zaobserwowanych i ocenionych zjawisk przyczynowo-skutkowych, ich wpływ na niezawodność całej konstrukcji ze szczególnym uwzględnieniem zastosowania stworzonej koncepcji do prognozowania podbić toru w celu polepszenia współpracy nawierzchni kolejowej z podłożem gruntowym dla zwiększenia bezpieczeństwa (Dembicki, 1997), (Wiłun, 2005).

Słowa kluczowe: osiadanie podkładów kolejowych, podbijanie podkładów kolejowych, logika rozmyta