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Eligiusz Mieloszyk; Anita Milewska; Mariusz Wyroślak

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Assessment of Subsoil Subsidence Under the Railway Surface with the Use of Fuzzy Sets

Eligiusz Mieloszyk [1], Anita Milewska [1], Mariusz Wyroślak [1, a)]

[1] *Gdansk University of Technology, Faculty of Civil and Environmental Engineering, 80-233 Gdańsk, ul. Narutowicza 11/12, Poland*

[a)] Corresponding author: mariusz.wyroslak@pg.edu.pl

Abstract. The cause of the subsidence of the railway track is the subsidence of the track bed itself and it is often related to the subsidence of the subsoil. Such settlement leads to: uneven longitudinal railways and track twist. These phenomena have a negative impact on the comfort and safety of driving, and in extreme cases lead to a train derailment. It has been shown that the magnitude of these settlements is determined by many parameters characterizing the subgrade and subsoil as well as dynamic interactions (vibrations) generated by passing rail vehicles. The propagation of these vibrations in the subgrade and the subsoil is related to the propagation of the generated elastic waves as mechanical waves in the elastic medium which is the subgrade and further the subsoil. Fuzzy sets, operations on them and their properties were used to assess the subsidence of the subsoil under the railway surface. Using the created membership functions $\mu_{X_i}, i = 1, 2, \ldots, n$ their linear combination is determined. The coefficients of this combination are selected by the AHP method. Practical applications of the created linear combination (created models) were indicated.

INTRODUCTION

During the daily operation of the railway track, its deformation occurs. The causes of deformations are, among others, high track loads - figure 1.

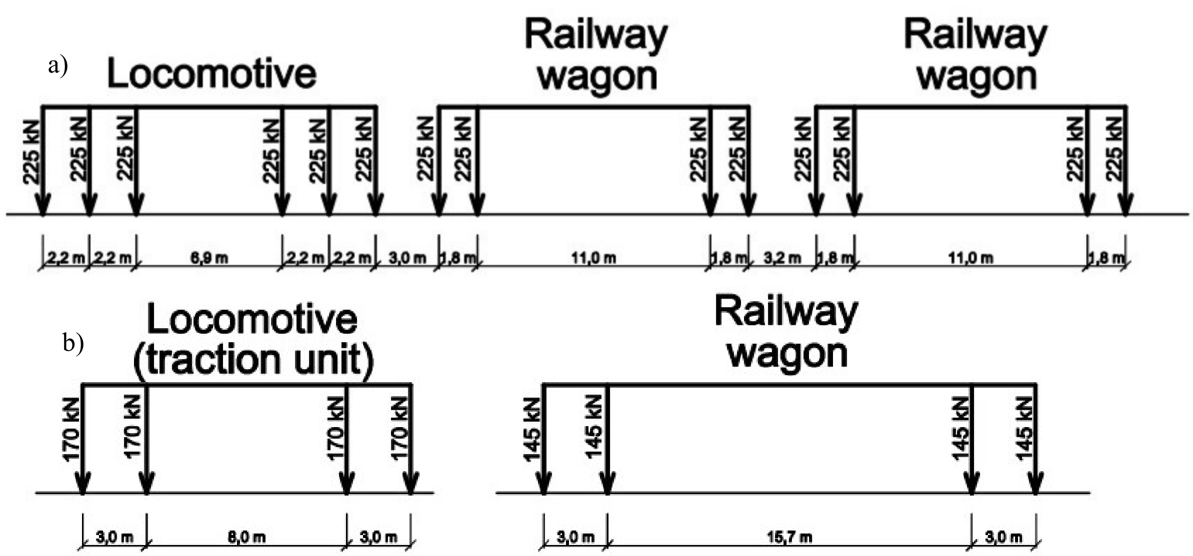

FIGURE 1. Scheme loads for: a) cargo train, b) passenger train on the TGV railway line.

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These deformations are related to the settlement of the railway surface. The main cause of subsidence of the railway surface is the subsidence of the track bed itself, as well as subsidence of the subsoil. There are many factors that determine the subsidence of a railway track - figure 2.

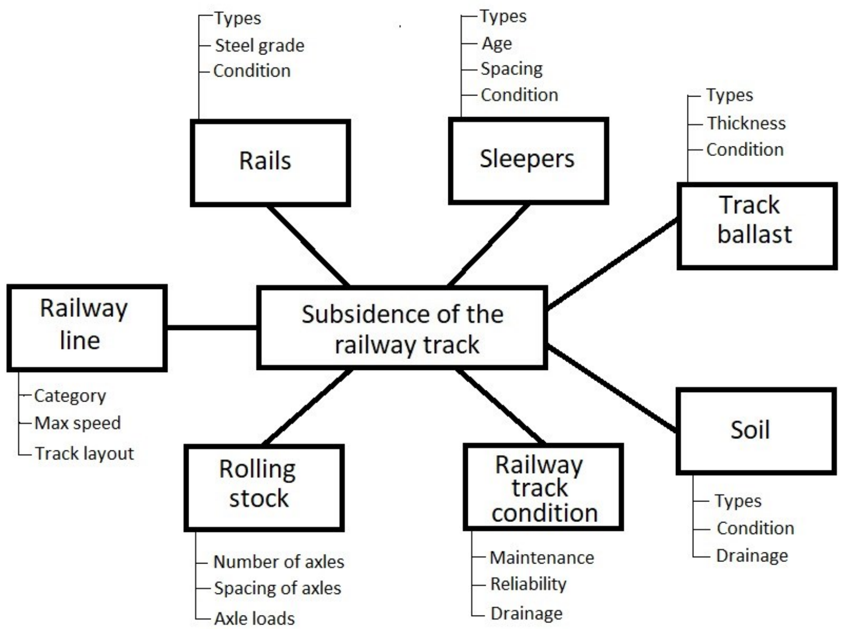

FIGURE 2. Factors influencing subsidence of the railway structure.

The subsoil is the direct support of an engineering structure, which is a railroad in this case. This subsoil can be used for engineering ground structures (excavations, canals, drainage ditches, tunnels, etc.). The subsoil, as intact natural soil, can also be a building material - embankments, backfills, etc. The subsoil may be weak - it must be then improved or strengthened, for example, by piling, dynamic compaction, using the microblasting (blasting charges) method [1].

In the case of subsoil subsidence, this applies to the subsidence of its elements: the track, protective layer (its thickness), embankments (their height), excavations (their depth), drainage ditches. In the case of, for example, embankments, the type of soil from which they are made is additionally important.

The primary cause of these settlements are the dynamic interactions generated by running trains. Vibrations in a given ground medium [2] are caused by a passing rail vehicle [3].

This is related to the propagation of the generated elastic waves as mechanical waves in the elastic medium which is the subgrade and further the subsoil. The generation of these waves is influenced by: train speeds, track geometry, etc.

Elastic waves are volume waves propagating in the ground and surface waves propagating along the surfaces separating media with different properties, including waves propagating on the ground surface.

The longitudinal volume waves P cause a deflection of vibration in a direction parallel to the direction of wave propagation. They cause compression and stretching of the medium. Transverse volume waves S arrive from the source to the vibration recorder (to the "target") after the P wave [4]. The velocities of the P and S waves depend on the value of elastic parameters of the medium (subgrade, subsoil). Along with the change of these parameters, these velocities may vary significantly, and these changes may be especially related to e.g. an increase in depth in the ground.

Surface waves: Rayleigh R and Love L waves have long periods and vary in amplitude, with the amplitude of their vibrations decreasing exponentially with increasing depth.

Surface Rayleigh R waves propagate horizontally and cause both vertical and horizontal, but not often transverse movements of the ground surface - figure 1, with the vertical and horizontal components being opposite in phase, so that the movement of the particles is elliptical - takes place in an ellipse vertically oriented and perpendicular to the direction of the wave.

Love L waves also propagate horizontally, causing transverse, horizontal movements of particles - figure 3.

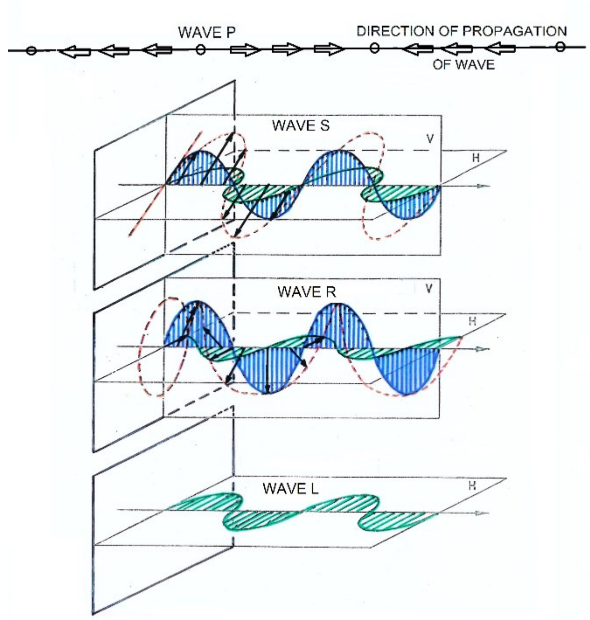

FIGURE 3. Waves [4].

These waves cause vibrations of the track, subgrade and subsoil and directly depend on the speed of passing trains. The analysis of models and measurements carried out on the lines in operation shows that along with the increase in the speed of trains, the vibrations of the track, subgrade and subsoil significantly increase and permanent track deformations increase rapidly [2]. For example, the amplitudes of vertical vibrations of the track at the train speed of 200 km / h are about 0.6 mm under the rail and in the track axis 0.6-0.8 mm, the amplitudes of horizontal vibrations are 0.2 mm and 0.3-0.4 mm, respectively [5], [6]. At the edge of the track, the vibration amplitudes constitute 22-43% of the vibration amplitudes in the section under the rail and decrease to 10-20% when the movement takes place on the adjacent track. The frequency of the highest amplitudes at train speeds of 140-200 km / h is 3-40 Hz on the track, 35-60 Hz on its edge and 25-50 Hz at a distance of 4 m from the track axis.

Vibrations in the railway surface, subgrade, subsoil generated by a passing rail vehicle may occur even after the rail vehicle leaves a given track section. This extends the time of their negative impact on the entire railroad. However, these vibrations do not oscillate infinitely long due to the presence of dissipative forces. Vibrations from passing trains have a negative effect on the mechanical properties of the soil. For example, dynamic loads from a train weighing 4,200 t and of a length of 800 m reduce the shear strength of clay sands by 46-48%, sandy clays by 39-42% and clays by 36-38%. For a passenger train, these values are respectively 20-21%, 16-17% and 13-15%. The reason for these changes in strength in cohesive soils is the possibility of the phenomenon of thixotropy. These unfavorable movements of soil and reduction of its strength are the cause of the increase of unevenness in the track and consequently lead to the twist of the track.

Subsoil subsidence caused by the propagation of waves in the ground under the influence of dynamic effects of passing trains may, in extreme cases, lead to a derailment of the train. Therefore, this difficult and complex phenomenon of subsidence must be tracked, assessed, and then reduced and prevented. Fuzzy sets can be helpful in these activities.

After first paragraph, other paragraphs are indented as you can see in this paragraph. After Introduction, divide your article into clearly defined and numbered sections.

FUZZY SETS AS A TOOL OF DESCRIPTION AND ANALYSIS

In engineering practice, it is difficult to measure all parameters influencing subsidence on a regular basis. It is also difficult to establish the mutual correlations between these parameters and to establish their influence on this settlement. This impact can be small, medium, large, for example. Thus, there appeared fuzzy concepts in this field, also known as fuzzy concepts. For example, even with the speed of trains, as a parameter, it is difficult to clearly define when it is high, when it is average, and when it is very high. The question is not what the speed is formally, but what it is from the point of view of the analysed problem (phenomenon).

A railroad is a certain engineering structure and, like any such structure, it must be safe. The safety qualification of the structure includes the identification of: structure loads, parameters of the materials used, parameters of the subsoil [7] combined with the performance of control calculations. The safety assessment also consists in comparing the existing state of the entire facility with the desired state. This assessment may include: subsoil, subgrade, railway track and its elements or the entire structure. Here, the actual state can be assessed, for example, as very bad, bad, sufficient, good, very good. These are also "fuzzy" concepts.

Let U be a set of all elements due to some property, and let f assign each element from the set X⊂U a number from the interval <0,1>.

In the fuzzy set theory [8], the membership function $\mu_X(x)$ is defined as follows:

$$\mu_X(x) = \begin{cases} f(x) & for\ \ x \in X \\ 0 & for\ x \notin X \end{cases} \quad , x \in U\ , \tag{1}$$

because an element may belong “partially” to a given set. For example, the function of membership of a fuzzy set - the settlement of the subsoil under the railway surface is approximately d_0, and it can be determined as in figure 4.

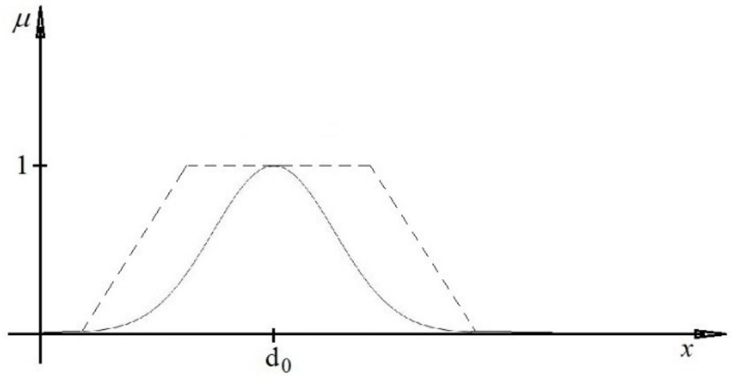

FIGURE 4. Examples of membership functions for a fuzzy set - subsidence of the subsoil under the railway surface.

Note. In the case of e.g. finite sets, the membership function is defined differently.

Membership functions presented in figure 4 are subjective in nature, as they are usually assumed arbitrarily.

For creating the membership function, you can use e.g. any non-negative constrained function $g(x)$. Under these assumptions, the membership function can be defined by a formula:

$$\mu_X(x) = \frac{g(x)}{max g(x)}\ . \tag{2}$$

In practice, it is more convenient to use the membership functions in the shape of broken lines - figure 4. A pair (set, membership function) is called a fuzzy set, i.e. the pair $(X, \mu_X(x))$ is a fuzzy set.

Note. Often the fuzzy set $(X, \mu_X(x))$is briefly denoted by X

Fuzzy sets, as already mentioned, are used to formally define "fuzzy", imprecise or ambiguous terms, such as "high subsidence of the subsoil".

The common part of the fuzzy sets and their sum $\left(X_1, \mu_{X_1}(x)\right)$, $\left(X_2, \mu_{X_2}(x)\right)$ are defined on the fuzzy sets. These operations are defined by the membership functions as follows:

$$\mu_{X_1 \cap X_2}(x) = \min\left[\mu_{X_1}(x)\ , \mu_{X_2}(x)\right], \tag{3}$$

$$\mu_{X_1 \cup X_2}(x) = \max\left[\mu_{X_1}(x)\ , \mu_{X_2}(x)\right] \quad \text{for } x \in U. \tag{4}$$

Figure 5 shows the membership function of the product and the sum of two fuzzy sets.

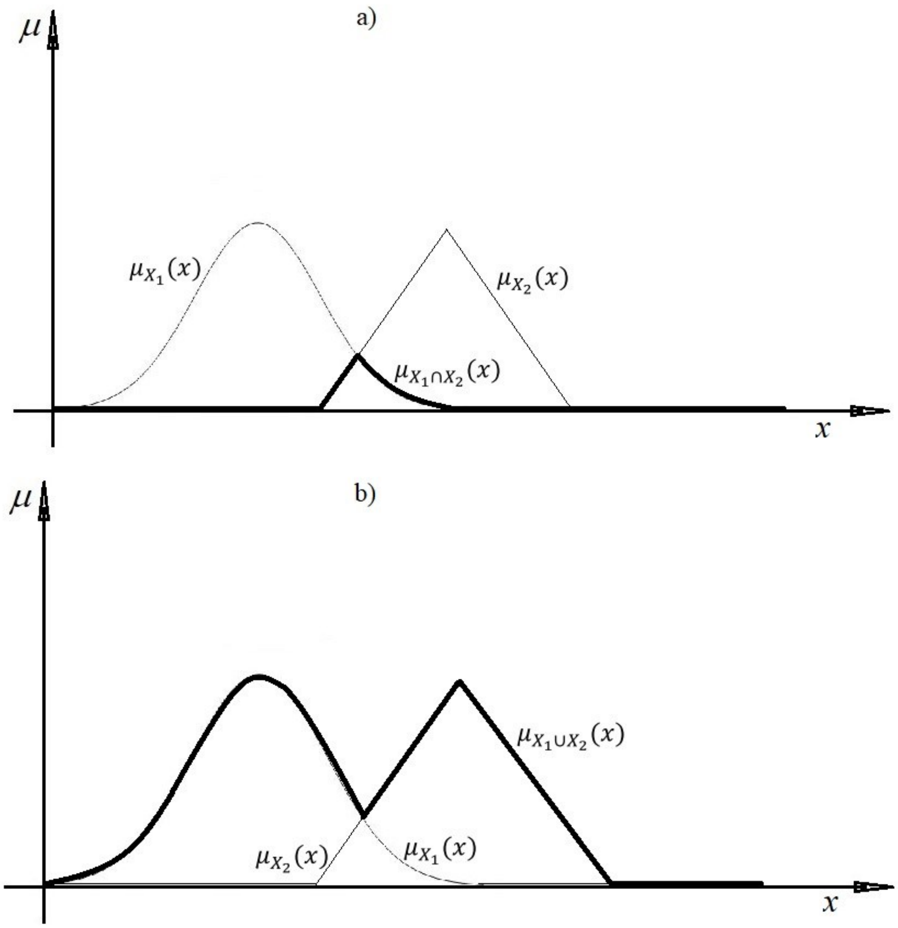

FIGURE 5. Membership functions for: a) product, b) sum of two fuzzy sets.

Note. It is important that the defined operations of the sum and the product of fuzzy sets do not extend beyond the family of fuzzy sets.

Note. Generally, formulas (3) and (4) can be extended to n sets $X_1, X_2, \ldots, X_n$.

Taking into account the following factors: train speeds and their changes (speed changes), soil type, drainage (soil), different membership functions are created for soil subsidence, as presented in figure 6.

Note. Assuming membership functions as in figure 4, it is indicated here that, according to the formula (2), the common part of individual fuzzy sets should be determined by a non-zero membership function. Using membership functions, one can define the function in the form:

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

where w_i are the appropriate expert-assigned weights depending on the importance of the factor i.

In formula (5), for example, membership functions presented in figure 6 can be practically used. Weights w_i can be determined using the AHP (Analytic Hierarchy Process) - [9, 10, 11] method.

For this purpose, the assessment was made in accordance with the 1 to 9 rating scale adopted in the AHP method. This scale assesses the importance of one factor in relation to another, in ordered pairs of factors. For example, a rating of 3 means that the first factor is slightly more important than the second. Ratings: 2, 4, 6, 8 are intermediate ratings between adjacent odd ratings. Obviously, a rating of 1 means that the pairing factors are equally important. When changing the order of factors in scoring, the grade is now the opposite of the accepted grade. For example, on a rating of 3, it would be 1/3.

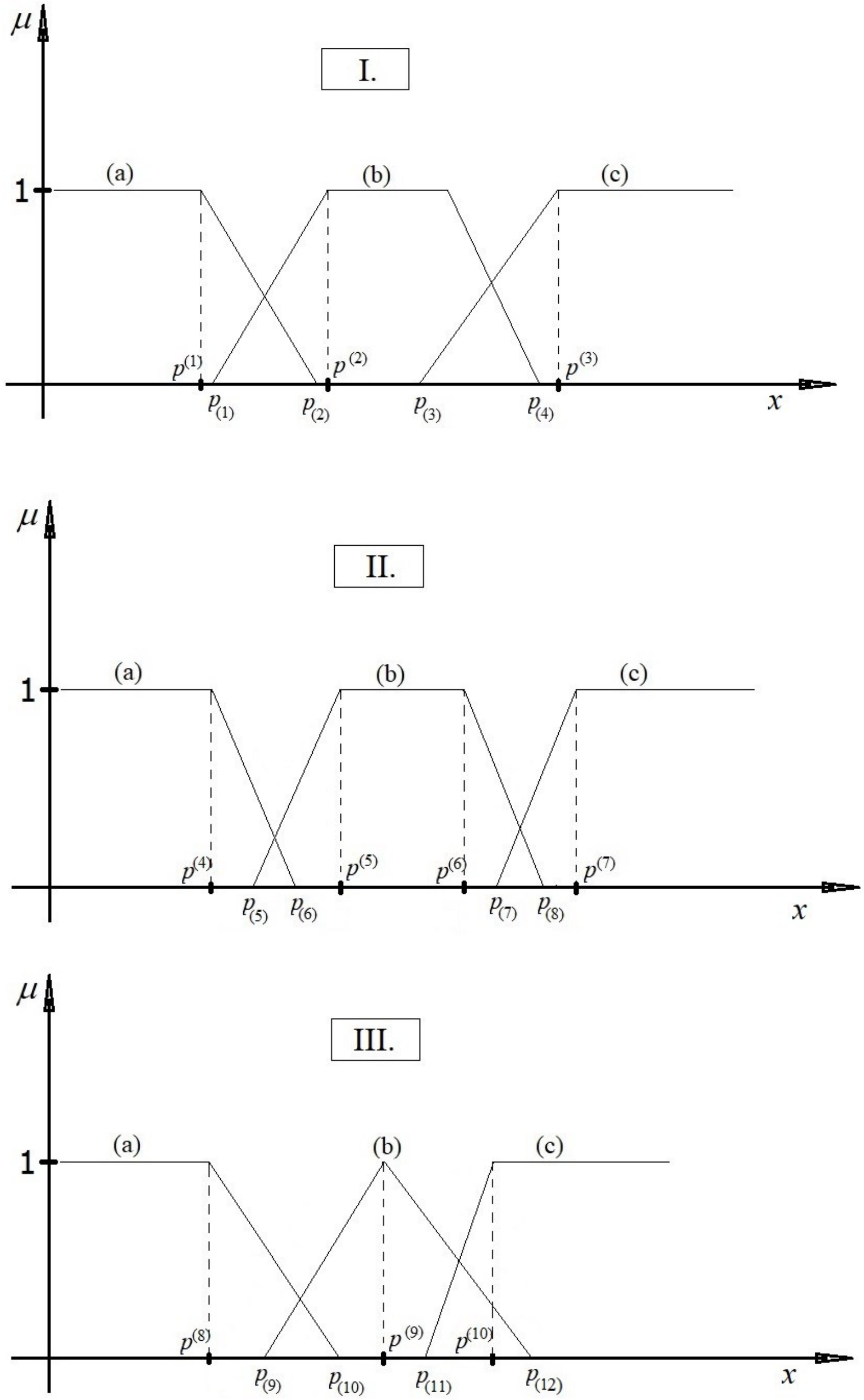

FIGURE 6. Examples of membership functions for: I. - train speeds and their changes, II. - type of soil, III. - drainage (of soil), with the following markings: (a) - small, (b) - medium, (c) - large and $p_{(i)} = const,\ i = 1, 2, \dots, 12$, $p^{(i)} = const,\ i = 1, 2, \dots, 10$.

Table 1 presents the results of expert assessments (in pairs) of three factors influencing the subsidence of the subsoil. These assessments were made using the literature data, considerations from point 1 and the expert experience of the authors.

TABLE 1. Ratings for the subsoil settlement criterion.

Subsoil subsidence	Train speeds and their changes (changes in speed)	Type of ground	Drainage (ground)
Train speeds and their changes (changes in speed)	1	1/5	1/7
Type of ground	5	1	1/3
Drainage (ground)	7	3	1

The information contained in table 1 allows us to determine the weights w_i, $i = 1,2,3$ as the $\vec{w}$ vector coordinates. This vector is collinear with the vector which is its image with the linear transformation represented by matrix $\boldsymbol{A}$. It is the matrix of the form:

$$\boldsymbol{A} = \begin{bmatrix} 1 & \frac{1}{5} & \frac{1}{7} \\ 5 & 1 & \frac{1}{3} \\ 7 & 3 & 1 \end{bmatrix}.$$

This matrix was created from the elements of table 1.

The vector $\vec{w}$ is a vector that satisfies the equation $\boldsymbol{A}\vec{w} = \lambda\vec{w}$. As a result of the calculations for $\lambda_{max} = 3,065$, the weights presented in table 2 were obtained.

TABLE 2. Weights for the factors considered.

Factors	**Weights**
Train speeds and their changes (changes in speed)	0.101
Type of ground	0.393
Drainage (ground)	0.914

By inserting the obtained weights into the formula (4), the following function was obtained

$$Z = 0,101[\mu_1]^2 + 0,393[\mu_2]^2 + 0,914[\mu_3]^2, \tag{6}$$

where $\mu_i(x)$, $i = 1, 2, 3$ are membership functions e.g. presented in figure 4 or other created.

Using the formula (2), the functions defined by the formula (6) can be introduced into the family of membership functions.

By analysing in detail the various Z functions obtained (different models - for different μ), a lot of valuable information can be obtained. They include information on the fuzzy assessment of subsidence of the subsoil of the railway track. In addition, it is possible to read the total fuzzy influence of the factors included in the analysis. This information can be successfully used in making decisions, including decisions in the field of broadly understood rail engineering. This is important, especially in cases where the decision has to be a compromise. This compromise may concern: reducing the speed on a given line, increasing the speed, deadline for completion on the current or major line repair, etc.

RESULTS AND DISCUSSIONS

Similar problems concern tram lines and can be analysed using the methods presented here as special cases of railway lines.

The aforementioned waves cause vibrations of the track, subgrade and subsoil and directly depend on the speed of passing trains, etc.

As the speed of trains increases, the vibrations of the track, subgrade and subsoil significantly increase and permanent track deformations and subsidence increase rapidly.

Subsoil subsidence caused by the propagation of waves in the ground under the influence of dynamic effects of passing trains and other factors may, in extreme cases, lead to a derailment of the train.

Fuzzy logic supported by the AHP method turned out to be helpful in the assessment and analysis of subsoil subsidence under the railway track. This settlement, under the influence of various factors, can be assessed and forecasted as, for example, small, medium, large, i.e. in the category of "fuzzy" terms.

One of the methods of improving such an assessment is the improvement of the subsoil or its strengthening, e.g. by blasting charges [1].

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