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Application of the fuzzy logic theory in the problem prediction values of the technical coefficient

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Abstract. The agricultural work demands prediction of loss of the mound stability. The mound under certain conditions may lose its stability, and transfer from the static equilibrium state to the state of motion. The article is devoted to prediction of loss of the mound stability in respect to the stability coefficient, by using an artificial intelligence system. This problem can be solved by introduction of the computer monitoring systems that can be quickly adapted in the course of work. The analysis of the literature showed that nowadays there is no computer system for monitoring the mound stability which would allow the units to react quickly to extreme conditions and adapt to them. The authors suggest a concept of the computer system, mainly creating an automatic fuzzy system. This approach is implemented with the help of a software package, the observation data are applied to the system input, which makes a decision about a danger of instability occurrence. The fuzzy logic methods are proposed to predict the coefficient that affects stability. A linguistic variable being constructed takes some values, the membership function is built for the terms, the knowledge base is created, fuzzification and defuzzification is carried out, some prognostic values are obtained. The algorithm of appearance of instability is calculated, and rapid reaction of the operator to this phenomenon is predicted, that is, the sequence of actions necessary to avoid danger is indicated.

1. Introduction
Mound materials include soil, snow, ore, grain, powder, sand, fertilizers, granulated mixed fodders, medicines, etc. Loose mound materials are involved in production processes, so the theory of their study is one of the most interesting and developing sections of mechanics. Only in the 20th century the scientists understood that mound materials could behave like solid, liquid or gas matter, and this distinguishes them from other substances. By the end of the 20th century, mound media began to be studied within the framework of a special science – soil mechanics. Simulations of the soil dynamics used a model of continuous medium. A great contribution in this area was made by the Soviet scientists ([1–3] and others).

The modern methods of computer simulation of the dynamics of mound materials rely primarily on the concept of discrete representation of the matter. The family of such methods is united under a common name – the method of discrete elements. The method of discrete elements was first applied by Cundall in 1971 when solving problems of rock mechanics. In particular, in 1985 some of them demonstrated that the method of discrete elements can be considered as a generalization of the finite element method. Many of the theoretical aspects of the method were put forward in the provisions of international conferences. The current
directions in the field of the method of discrete elements are indicated in some articles. The combination of the method of discrete elements with the finite element method is considered in the book [4].

In recent decades, several varieties of the discrete element method have appeared: the method of individual elements, the generalized discrete element method, the discrete deformation analysis, and the finite discrete elements method [4]. In Russia, the method of discrete elements has developed only in recent years. For the first time it was used by Yu. M. Levkin and I. M. Iofis for real calculations. In the number of works the method of discrete elements was applied to free-flowing media (G. N. Khan, A. A. Baryakh, E. N. Dyachenko, S. O. Dorofeenko, S. V. Klishin, V. A. Andronova, I. G. Dik).

The method of discrete elements allows to calculate the motion of a large number of particles – molecules, grains, gravel, pebbles and other granular media. For the first time this method was applied in the mechanics of rocks. The modeling processes by the method of discrete elements begins with the indication of the following data – the initial positions of particles and velocities. The method of discrete elements has a limitation set by the requirements for PC computational resources. However, thanks to the appearance of distributed algorithms, it is possible to accelerate significantly the computational experiment, to increase the initial number of particles in it.

Currently the discrete element method is implemented by the following program complexes: YADE, LIGGGHTS, Chute Maven (Hustrulid Technologies Inc.), PFC2D, PFC3D, EDEM (DEM Solutions Ltd.), GROMOS 96, ELFEN, MIMES. These software products allow calculation of particle motion, however, any of them allows to obtain an average picture of the process [5].

2. The definition problem
To calculate the stability of the loose mound f rotation, the method of circular-cylindrical sliding surfaces is used [1–6]. In this paper, the task is to predict the stability of a loose mound. Let us suppose the data changing the stability coefficient at the last n moments as shown in figure 1.

Further, it is necessary to analyze the experimental data in order to develop a predictive model based on fuzzy logic methods.

3. The process of fuzzy logic prediction
Suppose that the variable reflecting the value of the stability coefficient can take a value from the range from 0.96 to 1.04 [1–6] at particular time. Each value of the stability coefficient from the range from 0.96 to 1.04 can be associated with a certain number, from zero to one. This number determines the degree of belonging of a given physical value of quantity to a particular term of the linguistic variable according to the provisions of the theory of fuzzy sets [7–14]. We obtain a universal set G by dividing the whole numerical axis of the values of the variable. This set can be represented as:

\[ G = \{g_1, g_2, \ldots, g_n\}, \]

this is the interval of the numerical axis, made up of intervals \(g_i\), \(i = 1, \ldots, n\). One can define a fuzzy set \(Z\) as follows on the basis of the universal set \(G\):

\[ Z = \{(\nu_z(g_1), g_1), (\nu_z(g_2), g_2), \ldots, (\nu_z(g_n), g_n)\}, \quad g_i \in G, \quad \nu_z(g_i) \in [0, 1]. \]

where \(\nu_z(g_i)\) is the membership function. The linguistic variable is determined by the membership function the belonging of each exact value to one of the terms. It shows the degree of belonging \(g\) to the set \(Z\) in the problem under consideration:

Thus, the linguistic variable "the value of the coefficient of stability" can be described with the aid of the terms shown in figure 2, which are statements in natural language. You can see
Figure 1. Data on the change in the coefficient of stability

Figure 2. The determination of the linguistic variable "the value of the stability coefficient"

some expert-linguistic patterns that will later help us to build a prediction model. It can be seen that the retention of the stability factor at one level is 3 units at time, its decrease is 3 units at time, and the increase is longer – 5 units at time following the points of the graph [7–14].

The cyclic constructions are denoted as follows:

$$\ldots, x_{10}^{i-1}, x_{11}^{i-1}\{x_1^i, x_2^i, x_3^i, x_4^i, x_5^i, x_6^i, x_7^i, x_8^i, x_9^i, x_{10}^i, x_{11}^i\} \{x_1^{i+1}, x_2^{i+1}, \ldots$$

The knowledge base is represented in the form of eleven expert statements in natural language in accordance with the regularity observed in figure 2, and the point template of the cyclic construction. The statements are represented by the rules "IF-TO" and connect the value of the coefficient of stability in the $i$-th and $(i + 1)$-th cycles [7–14].
A network of dependencies is compiled according to the rules $F_1 - F_{11}$. It shows that the last two values $(i - 1)$-th cycle can predict all the values $i$-th of the cycle, figure 3.

\[ F_{11} \rightarrow x_{11}^i \]
\[ F_{10} \rightarrow x_{10}^i \]
\[ F_9 \rightarrow x_{9}^i \]
\[ F_8 \rightarrow x_{8}^i \]
\[ F_7 \rightarrow x_{7}^i \]
\[ F_6 \rightarrow x_{6}^i \]
\[ F_5 \rightarrow x_{5}^i \]
\[ F_4 \rightarrow x_{4}^i \]
\[ F_3 \rightarrow x_{3}^i \]
\[ F_2 \rightarrow x_{2}^i \]
\[ F_1 \rightarrow x_{1}^i \]

**Figure 3.** Dependent net for prediction

The apparatus of the theory of fuzzy sets is applied to the rules $F_1 - F_{11}$. The following analytical model of the function the membership of a variable $x$ ("the value of the coefficient of stability") of an arbitrary fuzzy term $T$ is defined in order to formalize the "HIGH" (H), "ABOVE AVERAGE" (AA), "MID" (M), "BELOW AVERAGE" (BA) and "LOW" (L):

\[ \mu_T(x) = \frac{1}{1 + \left( \frac{x - b}{c} \right)^2} \]

where $b$ and $c$ are tuning parameters. Parameter $b$ is coordinate the maximum of the function ($\mu_T(b) = 1$). Parameter $c$ is the concentration-expansion coefficient of the function. Number $b$ represents the most possible value of a variable $x$ for a fuzzy term $T$. 
The parameters $b$ and $c$ for different linguistic estimates are selected by an expert.

To convert the obtained membership functions to clear values, the defuzzification formula is applied, in the given problem having the form:

$$x_i = \frac{\sum_{j=1}^{K_A} k_j \mu^A(x_i)}{\sum_{j=1}^{K_A} \mu^A(x_i)},$$

where $x_i$ is an accurate value of the coefficient of stability; $\mu^A$ is the function of the attribution of a clear meaning to the term under consideration; $K_A$ is the number of constituted membership functions for the rule $F_i$.

The coefficients $k_j$ The range of possible values of the stability factor is divided into five parts in accordance with the terms H, AA, M, BA, L introduced in the present problem. Then the coefficients will take the values $k_j$ of the stability coefficients at the term boundaries. The set of values $[k_1, k_6]$ of the coefficient of stability contained in the segment will be the base set.

It is possible to explicitly record the forecasting model in explicit form as follows with the help of fuzzy logic operations “AND” (min), “OR” (max) and defuzzification operations:

$$F_1 : \begin{cases} 
\mu^{BC}(x_1^1) = \max \left( \min \left( \mu^B(x_{10}^{i-1}), \mu^B(x_{11}^{i-1}) \right), \right. \\
\left. \min \left( \mu^C(x_{10}^{i-1}), \mu^{BC}(x_{11}^{i-1}) \right) \right), \\
x_1^1 = \frac{k_4 \cdot \mu^{BC}(x_1^1)}{\mu^{BC}(x_1^1)}. 
\end{cases}$$

$$F_2 : \begin{cases} 
\mu^B(x_2^1) = \min \left( \mu^B(x_{10}^{i-1}), \mu^B(x_{11}^{i-1}) \right), \\
\mu^{BC}(x_2^1) = \min \left( \mu^C(x_{10}^{i-1}), \mu^{BC}(x_{11}^{i-1}) \right), \\
x_2^1 = \frac{k_5 \cdot \mu^B(x_2^1) + k_4 \cdot \mu^{BC}(x_2^1)}{\mu^B(x_2^1) + \mu^{BC}(x_2^1)}. 
\end{cases}$$

$$F_3 : \begin{cases} 
\mu^B(x_3^1) = \mu^B(x_2^1), \\
\mu^{BC}(x_3^1) = \mu^{BC}(x_2^1), \\
x_3^1 = \frac{k_5 \cdot \mu^B(x_3^1) + k_4 \cdot \mu^{BC}(x_3^1)}{\mu^B(x_3^1) + \mu^{BC}(x_3^1)}. 
\end{cases}$$

$$F_4 : \begin{cases} 
\mu^{BC}(x_4^1) = \min \left( \mu^B(x_2^1), \mu^B(x_3^1) \right), \\
\mu^C(x_4^1) = \min \left( \mu^{BC}(x_2^1), \mu^{BC}(x_3^1) \right), \\
x_4^1 = \frac{k_4 \cdot \mu^{BC}(x_4^1) + k_3 \cdot \mu^C(x_4^1)}{\mu^{BC}(x_4^1) + \mu^C(x_4^1)}. 
\end{cases}$$

$$F_5 : \begin{cases} 
\mu^H(x_5^1) = \max \left( \min \left( \mu^B(x_3^1), \mu^{BC}(x_4^1) \right), \right. \\
\left. \min \left( \mu^{BC}(x_3^1), \mu^C(x_4^1) \right) \right), \\
x_5^1 = \frac{k_1 \cdot \mu^H(x_5^1)}{\mu^H(x_5^1)}. 
\end{cases}$$
The rules allow prediction changes in the value of the stability coefficient for some time ahead, which is the most important indicator of the effectiveness of the model being developed. Of course, the prediction error with each iteration will increase, but this can be corrected, having large volumes of experimental data accumulated in the course of the process.

4. Practical results

In figure 4, the black graph reflects the actual value of the stability factor, and the red graph shows the value of the stability factor obtained as a result of the prediction algorithm based on fuzzy logic. Also, the deviation of the prediction results from real data is obvious. The error is calculated by the formula [15–17].

\[
E_i = \left| \frac{N_{actual} - N_{predictable}}{K_{max} - K_{max}} \right| \cdot 100 \%
\]

where \(E_i\) is at the \(i\)-th the reduced error in predicting the stability coefficient at \(i\) time moment. The numerator contains the corresponding absolute error, and in the denominator there is a confidence interval that depends on the type of scale and is equal to the width of the range of
measurements of the predicted value. The mean reduced error is taken as the arithmetic average of the reduced errors for \( i \) units at time, and is calculated by the formula:

\[
E = \frac{\sum_{i=P_1}^{P_n} E_i}{P},
\]

where \( P \) is the number of forecasted values, \( P_1 \) is the moment of the beginning of the forecast, and \( P_n \) is the last forecasted moment.

The error is calculated in percent within the scope of the problem being solved. Thus, prior to applying the adjustment, the reduced prediction error for the selected parameters is about 10.5%.

The tasks considered in this paper are solved using PHP, MySQL, HTML. The module for predicting the stability factor of a soil massif is described by the file PROGNOZ.PHP. The implementation of this module is carried out in several steps. The structure of the module is shown in figure 5. It is possible to predict the change in the value of the stability factor of a loose mound in the future to predict the phenomenon of instability with the help of programming complex in figure 5.

5. Conclusion
1. A model for predicting the coefficient of stability by means of the formalization “limiting state” is developed. The theory of fuzzy logic is applied.
2. The description of the program module for predicting the stability value of the soil mass is given.
3. It is possible to predict a change the value of the stability, using the model and the program complex. The structure program complex is shown in figure 5. It is possible to predict the phenomenon of instability.
Figure 5. Scheme of the prediction module

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