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IDENTIFICATION OF CARRYING CAPACITY OF PILES BY METHODS OF FUZZY LOGIC AND METHOD BOUNDARY ELEMENTS

The paper considers identification by numerical method of boundary elements using fuzzy knowledge bases of nonlinear task of geomechanics-forecasting of bearing ability of building piles depending on physicomechanical properties of soil and lengths of a pile. For solution of this problem genetic algorithms of optimization, as more effective are used for the search of global minimum

Keywords: *method of boundary elements, intense-deformed condition, fuzzy logic, training sample, genetic algorithms, soil, bearing ability of a pile.*

The introduction

One of the primary goals which appears at designing of building objects is the estimation of carrying capacity of foundation of the construction, in particular piles. Resistance of piles to static loadings causes many discussions.

Presence in the mass of non-uniform ground of inclusions in the form of foundation construction results in redistribution and a curvature of stresses of free field of ground. Due to complexity and bad conditionality of this problem its geomechanics is impossible to describe by exact analytical dependences. Therefore for its solution (sacrificing the accuracy) it is necessary to apply fuzzy approximate but qualitative solutions. These are methods of decision-making on the basis of fuzzy logic. These methods are developed, used in different branches of human activity and nowadays are actual and perspective due to fast development of computing facilities. Application of laws of logic reasoning along with computing facilities have allowed to create artificial intelligence systems operating on expert level .

Modern intellectual technologies of decision-making open opportunities for using new approaches for calculations and designing of the bases of constructions. The problem of forecasting of carrying capacity of building piles is a typical nonlinear problem of mechanics of soils because of multifactorial influence on carrying capacity of physicomechanical properties of soil and lengths of piles. The paper considers the model of identification of this nonlinear object with the help of fuzzy bases of knowledge of decision making concerning carrying capacity of piles and comparison of results with the solution of this problem applying numerical method of boundary elements (MBE).

The problem of definition of carrying capacity of a pile under definite soil conditions is solved due to association of advantages of the fuzzy logic, allowing to use expert knowledge of object as linguistic statements such as "if", and genetic (evolutionary) algorithms which enable to search for the optimal solution of the problem simultaneously from several index points. Thus, construction of model of object occurs in two stages. At the first stage called rough adjustment, expert knowledge of the structure of object is obtained: amount of input and target variables, their ranges and linguistic estimations. At the second stage called thin adjustment, the problem of optimization of parameters of fuzzy base of knowledge is solved appling genetic algorithm.

The generalized fuzzy model is considered as aproximator of nonlinear dependence between carrying capacity of piles, their length and numerous characteristics of soil foundation .

Initial preconditions. Statement of the problem.

The solution of a nonlinear problem of geomechanics is closely connected with the study of stressed - deformed condition of the soil and meets difficulties due to dispersity of the soil and a great number of factors influencing their behavior.

Variability of soil deformation process of construction foundation was investigated in the paper by numerical MBE applying dilatational mathematical model [1]. The basic equations of the theory of elasticity which describe the behavior of fundamental construction – piles in the soil in MBE are reduced to the integrated equation reciveded by K. Brebbija, Z. Tellesom [2]:

$$c_{ij} \cdot u_j + \int_{\Gamma} p^*{}_{ij} u_{ij} d\Gamma = \int_{\Gamma} u_{ij}{}^* p_i d\Gamma + \int_{\Omega} \sigma^* \varepsilon_{jk}{}^p d\Omega\,, \tag{1}$$

where u - preset vector of displacement on the edge of a pile; p - a required vector of stresses on the edge of a pile; u *, p *, σ * - nuclei of boundary equation – R. Mindlin's solutions at P=1 in semispace for displacement, stresses and derivatives from stresses; c_{ij} - matrix, is defined from conditions of movement of a body as the whole; Γ, ξ, x – correspondingly: border, a point of force application P=1, a point of supervision.

The equation (1) represents the boundary integrated equation relatively values of required functions on the border of the object under investigation (the surface of a pile). This important circumstance gives the greatest attraction to this equation which becomes rather suitable for research using the numerical methods.

Use in nonlinear problems of geomechanics as fundamental solutions the dependences of R.Mindlin for semispace does not require representation in the discrete form of boundary surface of the soil, this considerably reduces volume of computations. What is more, due to the symmetry of examined area (pile) relatively the vertical axis it is necessary discrete and to consider only half of the pile (Fig. 1).

Definition of carrying capacity of a pile in the paper is carried out taking into account presence of areas of boundary state of dispersed soil which develop under loadings. Behaviour of the soil in a plastic stage was described by the theory of plastic flow. For the account of dissipative effects of the soil to the equation (1) were added: a) - criterion of transition in a plastic state - conditions of fluidity Misess-Gubkin-Botkin(assumes destruction on octahedronic platforms); b) – physical equations - dependence between stresses and deformations for plastic state of the soil – non-associative law of flow:

$$d\varepsilon_{ij}^{p} = d\lambda \frac{dF}{d\sigma_{ij}}\,,\ F \neq f\,, \tag{2}$$

where F – plastic potential (dissipative function of porous environment of the soil), f – criterion of transition to plastic state, $d\lambda$ – scalar multiplier.

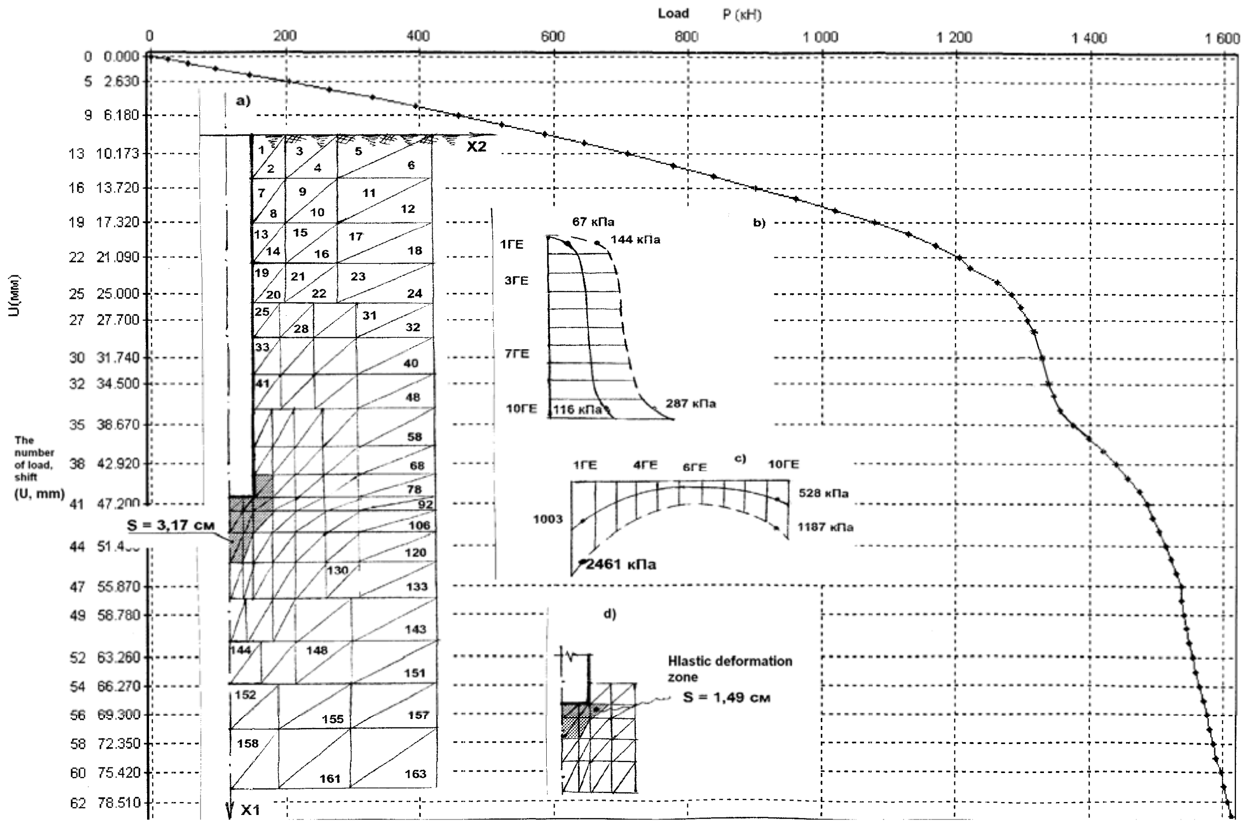

Fig. 1. a) Scheme of digitization of active zone of friction pile L=10 m; in, b,c) – tangent curves of stresses on lateral surface; normal stresses on edge of a pile; d) - zone of plastic deformations at S=1.49cm.

For correction of misalignment of stress tensors and deformation tensors at work of the basis in plastic stage V. N. Nikolaevsky, I. P. Bojko dilatation theory [3, 4] was used. The suggested dilatation model combines calculation of foundations on both boundary conditions (by deformations and carrying capacity) within the framework of the uniform calculation scheme. In Fig. 1 within the framework of the suggested model carrying capacity of a pile of 10 m of length for given soil conditions is predicted. In order to control the parameters of the algorithm and estimation of discrepancies of result comparison of calculation data for MBE with experiment is carried out, Table5.

In recent years due to the growth of price of construction field research of piles became expensive and it is not always possible to carry out such research. Even when they are carried out in conditions of the construction site, geological conditions of the site differ. Thus, in correctly put model not correct initial data are substituted. In the paper we suggest the approach, based on the description of relationships between risk factors (reasons) which influence carrying capacity of piles and the given forecast (consequence) in the form of expressions of natural speech. In such conditions of uncertainty for modeling of such relationships fuzzy logic and genetic algorithms were used [5].

In the majority of countries carrying capacity of piles on the soil is defined applying two-component scheme depending on the length of a pile and physicomechanical properties of the soil. Wide variation of definition of carrying capacity of piles by both theoretical and experimental methods (static and dynamic) shows the necessity of improvement of methods of calculation of piles in order to increase the accuracy, profitability, reliability of design. Statement of the problem is the following: the vector of fixed values of input variables (physicomechanical properties soil G and length of pile L) is given.

$$F = f(G, L)\ . \tag{3}$$

On the basis of the information regarding the input vector it is necessary to define the output-carrying capacity of pile F. For formation of dependence (3) input and output variables as linguistic variables are considered:

$$G = f_G(P, D, Sr);\ \ P = f_P(E, \rho, \upsilon);\ \ D = f_D(e, c, \varphi); \tag{4, 5, 6}$$

where P – durability characteristics of the soil; D – deformation characteristics of the soil; E – module of soil deformation (MPa): [75-6]; υ – Poison factor (lateral expansion of the soil): [0.27-0.42]; ρ – density of the soil (g/cm2) [1.54-2.76]; C – coefficient of cohesion (kPa): [0.5-90]; φ – angle of internal friction (radians): [0.122-0.75]; Sr – degree of humidity of the soil: [0-1]; e – factor of porosity (Vpor/Vsol): [0.45-1.05].

The interval of change of input data is specified in square brackets.

The model of the object of diagnostics is constructed on the basis of the fuzzy logic equations which connect terms of membership functions of input parameters.

Advantages of application of fuzzy sets is that they allow to apply to construction of the model the expert knowledge, expressed in the natural language verbal form.

The first stage of construction of fuzzy model of the object (phasing of variables) comprises the definition of linguistic estimation of variables and corresponding membership functions . The structure of model of pile carrying capacity forecast is shown in Fig. 2 as a tree of logic interrelation which represents the graph, representing classification of reasons which influence the forecast of parameter F.

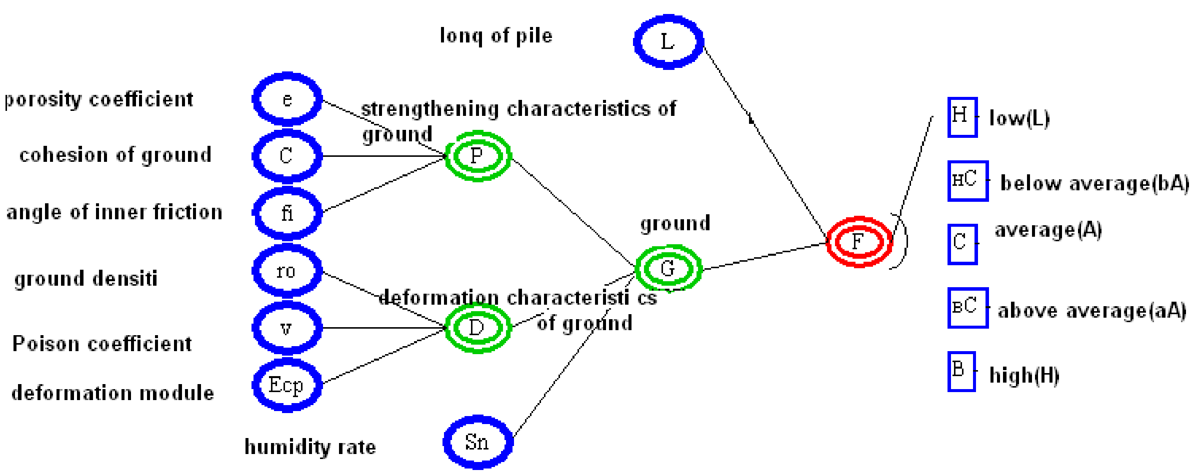

Fig. 2. Hierarchical classification of fuzzy logic model

Graph corresponds to the relations (3-6). For evaluation of linguistic variables L, G, P, D values the scale of qualitative terms is used: H-low, C-average, B- high. The range of change of target variable F was digitized in 5 levels. Each qualitative linguistic term represents fuzzy set specified with the help of membership functions, transforming the linguistic information in the form, suitable for computer processing.

The following step of modeling – compiling of expert base of knowledge. The fuzzy base of knowledge is the carrier of the expert information on relationships between the input and output parameters. Using the entered qualitative terms and knowledge of experts, ratios 3-6 are presented in the form of fuzzy hierarchical bases of knowledge presented in Tables 1-4. These matrixes correspond to fuzzy rules "if-then", composed on the basis of expert knowledge [5]. Nonlinear dependences "if-then" represent concentration of experience of the expert and play determining role in practice of the solution of applied problems by the man.

Tables 1-4

Expert bases of knowledge for functions F, G, P, D

L	G	F
H	H	
H	C	H
HC	H	
H	B	HC
HC	C	
C	H	
HC	B	C
C	C	
BP	H	
B	H	
C	B	BP
BP	C	
B	C	
BP	B	B
B	B	

P	D	S_R	G
H	H	B	
H	C	C	
H	C	B	H
H	B	H	
H	B	C	
H	B	B	
C	C	B	
C	B	C	
C	B	B	
B	B	B	
H	H	H	
H	H	C	
H	C	H	
C	H	B	
C	C	H	
C	C	C	
C	B	H	
B	H	B	C
B	C	C	
B	C	B	
B	B	H	
B	B	C	
C	H	H	
C	H	C	
B	H	H	B
B	H	C	
B	C	H	

e	c	φ	P
H	B	H	
C	C	H	
C	B	H	
C	B	C	
B	H	H	H
B	H	C	
B	C	H	
B	C	C	
B	C	B	
B	B	H	
B	B	C	
B	B	B	
H	C	H	
H	B	C	
C	H	H	
C	C	C	C
C	B	B	
B	H	B	
H	H	H	
H	H	C	
H	H	B	
H	C	C	B
H	C	B	
H	B	B	
C	H	C	
C	H	B	

E	ρ	ν	D
C	B	H	
C	B	C	
B	H	H	
B	H	C	
B	C	H	
B	C	C	
B	B	H	H
B	B	C	
B	B	B	
H	C	H	
H	B	H	
H	B	C	
C	H	H	
C	H	C	
C	C	H	
C	C	C	
C	C	B	
C	B	B	C
B	H	B	
B	C	B	
H	H	H	
H	H	C	
H	H	B	
H	C	C	
H	C	B	B
H	B	B	
C	H	B	

Synthesis of set of rules " if-then, or ", composed according to Tables 1-4 give 13 logic equations representing fuzzy base of knowledge.

$$\mu^{B}(F)=\mu^{BC}(L)*\mu^{B}(G)*\mu^{B}(L)*\mu^{B}(G);$$

$$\mu^{BC}(F)=\mu^{C}(L)*\mu^{B}(G)*\mu^{BC}(L)*\mu^{C}(G)*\mu^{B}(L)*\mu^{C}(G);$$

. . . . (7)

$$\mu^{H}(D)=\mu^{C}(E)*\mu^{B}(\rho)*\mu^{H}(\upsilon)*\mu^{C}(E)*\mu^{B}(\rho)*\mu^{C}(\upsilon)*\mu^{B}(E)*\mu^{H}(\rho)*\mu^{H}(\upsilon)*\mu^{B}(E)*\mu^{H}(\rho)*\mu^{C}(\upsilon)*$$
$$\mu^{B}(E)*\mu^{C}(\rho)*\mu^{H}(\upsilon)*\mu^{B}(E)*\mu^{C}(\rho)*\mu^{C}(\upsilon)*\mu^{B}(E)*\mu^{B}(\rho)*\mu^{H}(\upsilon)*\mu^{B}(E)*\mu^{B}(\rho)*\mu^{H}(\upsilon)*$$
$$\mu^{B}(E)*\mu^{B}(\rho)*\mu^{H}(\upsilon)*\mu^{B}(E)*\mu^{B}(\rho)*\mu^{C}(\upsilon)*\mu^{B}(E)*\mu^{B}(\rho)*\mu^{B}(\upsilon).$$

The following approximation of studied object [1] corresponds to fuzzy knowledge base:

$$F=\sum_{i}^{5}F_i\mu_i^T\,/\sum_{i}^{5}\mu_i^T\ ;\ \ \mu^{jp}(x_i)=\frac{1}{1+[\frac{x_i-b_i^{jp}}{c_i^{jp}}]^2}\ ; \tag{8,9}$$

where $\mu^{dj}(F)$ – membership function of target variable F to class $d_j \in [F_{j-1}, F_j]$; $\mu^{jp}(x_i)$ – membership of input variable Xi to a term; b_i^{jp}, c_i^{jp} – setting parameters of membership functions , their interpretation: b-coordinates of a maximum $\mu(b)=1$; c – parameter of concentration (compression-tension).

The essence of forecast model setting is-- selection of such parameters of membership function (b, c) and weights of fuzzy rules (w) which provide minimum of deviation between the modeling data and the data of training sample.

The mechanism of training of fuzzy model is realized by carrying out of nonlinear optimization of mean-square error and modeling results of value of output of fuzzy model. For the solution of the problem of nonlinear optimization genetic algorithms are used. Simulating processes of wildlife, they are more effective in search of global optimum, allow to conduct search from different points while classical methods of linear programming are focused on search of local optimum. As a result of training values of parameters of membership functions of fuzzy terms and weight factors of rules of knowledge base (Fig. 3) which provide a divergence between the experimental and modeling data not greater than 8,54 % are obtained.

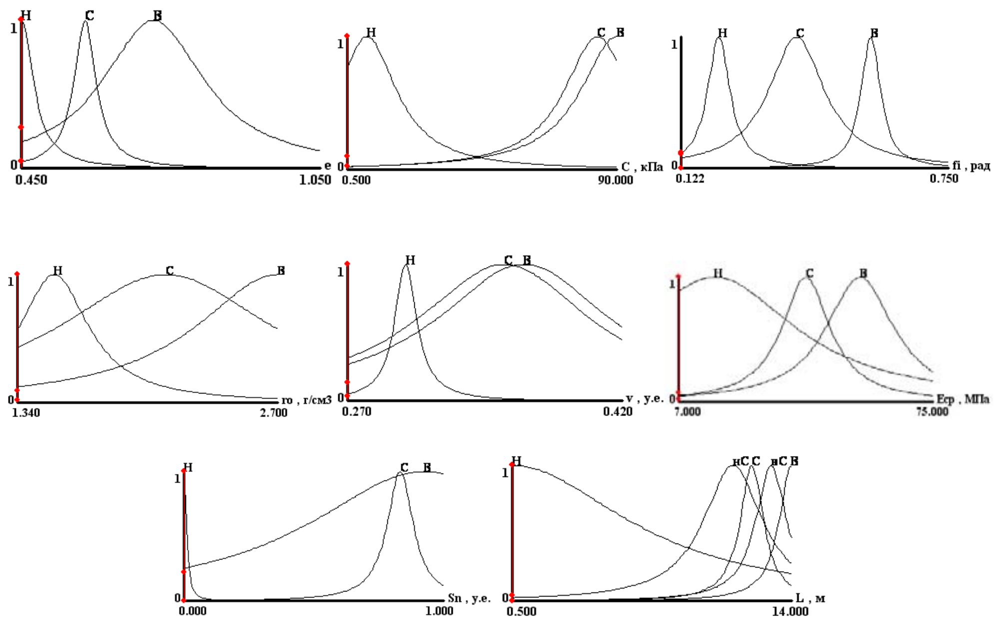

Fig. 3. Form membership functions of input terms after training

For setting and testing of fuzzy model of forecast model the training sample composed by the data of experiments and results of numerical modeling applying the method of finite elements (MFE) and method of boundary elements (NBE) was used. The fragment of sample testing is shown in Table 5, in last column the results of forecasting of carrying capacity of a pile after training of fuzzy network are given.

Table 5

Training sample

№	L (m)	E (MPa)	ν	C (kPa)	φ (rad)	S Sr	ρ($\frac{g}{sm^3}$)	e	Fexp (kN)	Fmod (kN)
1	3	8	0,35	12	0,331	0,1	1,45	0,85	329,35	353,6
2	4	60	0,3	0,5	0,593	0,283	1,67	0,45	400	407,75
3	4,65	30	0,3	16	0,61	0,425	1,68	0,64	668	600,7
4	7	14,5	0,37	21,5	0,314	1	2,65	0,72	450	583,56
5	8,5	30,91	0,3	9,56	0,54	0,482	2,68	0,55	630	686,83
6	9,5	16	0,37	12	0,349	0,524	2,68	0,89	720	710,91
7	10	15,47	0,394	27	0,213	0,498	1,931	0,55	1160	1151,34
8	12,7	16,93	0,382	17	0,348	0,953	1,96	0,69	830	1109,95
9	13	17,19	0,39	18	0,348	0,875	1,98	0,72	1060	1167,96
10	14	22,84	0,382	20	0,349	0,978	1,96	0,70	1680	1480,03
11	9	8,87	0,3	1,488	0,2093	1	1,663	0,684	1008	876,8
.	.	.	.	.	.	.	.	.	.	.
22	6	36	0,3	7,2	0,584	0,3	2,67	0,55	400	407,75
23	6	16,74	0,334	13,17	0,414	1	2,25	0,65	610	526,12
24	6	21	0,42	16	0,75	0,23	1,74	0,5	1375	1231,1
25	9	8,87	0,3	1,49	0,209	1	1,66	0,673	840	877,78

The problem is realized on the basis of program environment Fuzzy Expert. Time of problem setting by genetic algorithm was 30 minutes and required 55000 iterations.

Conclusions

The accuracy of diagnostics of carrying capacity of piles applying the method of boundary elements and methods of the theory of fuzzy logic makes 7-10 % it is acceptable for solution of practical problems. The main task of the model of fuzzy logic – identification of nonlinear dependence of carrying capacity of a pile according to its length and physicomechanical properties of soil by means of fuzzy base of knowledge. Valid results of modeling are obtained by adjustment of fuzzy rules according to the data of training sample, that is, by the choice of parameters of membership functions of fuzzy terms and weights of rules by optimization using genetic algorithms.

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