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«BUILDING – BASE» SYSTEM BOUNDARY DEFORMATIONS EXCEEDING PROBABILISTIC ESTIMATION METHODOLOGY

In the paper the method is proposed and the algorithm is developed for solving the problem of «building – base» system exceeding boundary deformations in reliability parametric theory framework probability (risk) determination. For calculations, the method of statistical tests (Monte-Carlo) was used. Using the powerful Mathcad complex, the computer program has been developed to implement the proposed calculation method has been developed. The calculations of the existing «building-base» system have been performed from determination of this system exceeding boundary deformations probability (risk). Analysis of the probability calculation indicates the need to improve existing approaches to determination the probability of deformations exceeding boundary value, because new methods will increase the reliability of solving geotechnical problems.

Keywords: *probability, system reliability theory, statistical test method, distribution function of random variable distribution, «building – base» system, deformation of the base, calculation of deformations by the method of layer summing.*

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МЕТОДИКА ЙМОВІРНІСНОЇ ОЦІНЮВАННЯ ПЕРЕВИЩЕННЯ ГРАНИЧНИХ ДЕФОРМАЦІЙ СИСТЕМИ «БУДІВЛЯ – ОСНОВА»

Запропоновано методику та розроблено алгоритм вирішення задачі з визначення ймовірності (ризику) перевищення граничних деформацій системи «будівля – основа» в рамках параметричної теорії надійності. У процесі розрахунків застосовано метод статистичних випробувань (Монте-Карло). Розроблено комп'ютерну програму з використанням потужного комплексу Mathcad, вона реалізує запропоновану методику розрахунків. Виконано розрахунки існуючої системи «будівля – основа» з визначення ймовірності (ризику) перевищення граничних деформацій цієї системи. З'ясовано, що аналіз імовірнісного розрахунку вказує на необхідність удосконалення існуючих підходів до визначення ймовірності перевищення граничного значення деформацій, тому що нові методики дозволять підвищити надійність рішення геотехнічних задач.

Ключові слова: *ймовірність, системна теорія надійності, метод статистичних випробувань, функція розподілу випадкової величини, система «будівля – споруда», деформація основи, розрахунок осідань методом пошарового підсумовування.*

Introduction. At present, calculations of foundation bases in accordance with normative documents are carried out by the method of boundary states. To estimate the reliability, a deterministic approach based on the application of partial reliability coefficients is used, which cases does not give an objective assessment in all cases. All the parameters included in the «base-building» system are random, and therefore the development of calculation techniques associated with the use of probabilistic methods for estimating the reliability of such a system is an urgent task.

The latest sources of research and publications analysis. The works of such scientists as Yu.L. Vynnykov [1], B.A. Garagash [2], N.N. Ermolaev and V.V. Mikheev [3] with their fundamental work «Reliability of structures foundations», A.P. Pshenichkin [4], V.A. Pshenichkina [5], A.N. Trofimchuk [6], V.M. Ulitsky [7], A.V. School [8] are devoted to the evaluation of the «base – building» system reliability. A comprehensive assessment of hydraulic structures reliability and safety was proposed by A.I. Weinberg [9]. Foreign researchers, such as – Beacher G.B [10], Honjo Y. [11], Shahin M.A. [12], C. Cherubini [13], Pereira C., also considered some geotechnical problems, solved with the help of probabilistic methods.

Isolation of previously unresolved parts of a mutual problem. The value of base deformation is random and it depends on a number of random variables: the characteristics of building materials, the acting loads and impacts, base deformation characteristics etc. The use of probabilistic methods for estimating foundation reliability by the normative method is an insufficiently studied problem.

Formulation of the problem. To develop calculating base deformations method, which allows probabilistic assessment of base boundary state occurrence by deformations.

Main material and results. Calculation of base deformations according to DBN B.2.1-10-2009 [14] is carried out with the aim of limiting the object (foundation) absolute or relative displacements, together both with the base, and with such boundaries that ensure the object performance and durability, become impossible manifestations of inadmissible deformations, ups, crevices, etc.

In order to estimate the risk (probability) of a particular species boundary state occurrence, it is necessary to solve the problem of parametric reliability theory with the use of probability theory apparatus. As a result of solving the problem, the value of the «base-building» system exceeding boundary deformations probability can be found. The following stages of calculation can be distinguished.

1. To compile the equations of connection between input parameters (loads and effects, properties of materials and soils, etc.) and output (the results of calculation) parameters, considering the system elements. Such an equation can be compiled on the basis of calculated dependencies analysis governed by design standards.

2. To prepare the initial calculation data which input parameters are distinguished into random and nonrandom (deterministic).

3. To distribute parameters of random variables considering determined initial data.

4. To determinate system exceeding boundary deformation value probability (risk) on the statistical dynamics corresponding solution basis.

Compiling the equations of connection.

To ensure operational reliability by the normative method, it is necessary to perform a calculation on the bases deformation where the following condition must be fulfilled:

$$s \le s_u, \tag{1}$$

where s the base and structure joint deformation, which is determined by one of the DBN methods ; while for foundation pits with a depth of less than 5 m it is:

$$s = \beta \sum_{i=1}^{n} \frac{(\sigma_{zp,i} - \sigma_{z\gamma,i}) \cdot h_i}{E_i} , \quad (2)$$

where β is a dimensionless coefficient equal to 0.8;

E_i – the deformation modulus of the *i*-th soil layer along the primary loading branch, kPa;

h_i is the thickness of the elementary layer;

n is the number of layers within the compressible thickness H_c;

average stresses in the elementary layer:

$$\sigma_{zp,i} = \frac{\sigma_{zi} + \sigma_{z,i+1}}{2} , \quad (3)$$

$$\sigma_{z\gamma,i} = \frac{\sigma_{\gamma i} + \sigma_{\gamma,i+1}}{2} . \quad (4)$$

Here $\sigma_{zp,i}$ are additional stresses from the external load at a depth of z:

$$\sigma_{zp} = \alpha \cdot p , \quad (5)$$

where $p = p_{ap}$ is the average pressure below the base of the foundation, equal to:

$$p_{ap} = \frac{N}{b \cdot l} + \gamma_{mt} \cdot d + q , \quad (6)$$

N – vertical load at the level of the foundation upper cutoff;

b, l – dimensions of the foundation base, m;

γ_{mt} – the average value of the foundation specific weights, the soil and the floor located above the base of foundation, assumed to be 20 kN/m^3,

d – depth of the deposit, m;

q – load on the floor;

α is the coefficient of stresses attenuation depending on of the relative depth $\zeta = \frac{2 \cdot z}{b}$ and ratio foundation sides $\eta = l/b$;

$\sigma_{z\gamma}$ are the vertical stresses from the own weight of the soil taken in the foundation pit up to the level of the foundation base, at a depth of z:

$$\sigma_{z\gamma} = \alpha_{\kappa} \cdot \sigma'_{zg,0} , \quad (7)$$

where $\alpha_{к}$ is found in Table B.6 of DBN and depends on the relations $\zeta = \frac{2 \cdot z}{B_{\kappa}}$ and $\eta = l/b$;

B_{κ} – width of the pit;

$\sigma'_{zg,0}$ – vertical stress from the own weight of the soil taken from the foundation pit at the level of the foundation base and equal to $\sigma'_{zg,0} = \gamma_{гр} \cdot d_n$,

d_n – the depth of foundation laying in relation to the level of natural relief;

s_u – the boundary value of the foundation and structure joint deformation, governed by the norms.

When performing such calculations according to the normative methodology, the exploitation reliability of the «base-building» system is considered to be ensured if inequality (1) is satisfied. It is noted that the work does not consider the nonlinear work of the base soil.

Preparation of initial data

All directly or indirectly entering components of equation (1) are random, but some quantities can be assumed deterministic. In the present work, the following quantities are considered to be deterministic:

1) geometric characteristics of the foundation construction – b, l, d, d_n;
2) geometric characteristics of the enclosing structure;
3) geometric size of brick partitions and the thickness of the overlap;
4) the average specific weight of the foundation and soil on its edges γ_{mt};
5) the load on the floor q;
6) specific weight of backfill material and base soil.

Estimated soil resistance is determined deterministically.

All other parameters of the connection equation are considered random variables. These parameters include:

1) physical and strength characteristics of the enclosing structure materials (brick walls), overlapping, partitions;
2) deformation characteristics of the base soil (modulus of deformation E);
3) the vertical load on the foundation N, composed of the structures own weight G, the snow S and the payload Q, which are also random variables;
4) the average pressure under the foundation base p_{cp};
5) the stresses from the additional load σ_{zp};
6) deformations s.

The following distribution laws for random input parameters are adopted in the work.

1. The distributions $P_{\gamma b} = P_{\gamma b}(\gamma_b)$ and $P_{\gamma kk} = P_{\gamma kk}(\gamma_{kk})$ of random variables – the specific weights of concrete and brickwork, which are assumed to be normal with the mathematical expectations $m_{\gamma b}$ and $m_{\gamma kk}$, correspondingly, and the mean-square deviations $\sigma_{\gamma b}$ and $\sigma_{\gamma kk}$. The values of these parameters are determined by the tests results or by design standards.

2. The distributions $P_Q = P_Q(Q)$ and $P_S = P_S(S)$of random variables – payload and snow load, which are assumed to be normal with the mathematical expectations m_Q and m_S, correspondingly, and the standard deviations σ_Q and σ_S. These parameters values can be determined on the analysis basis of water reserves observation arrays in the snow cover, analysis of data on the residential and public fund premises survey, or adopted in accordance with design standards.

3. Distribution $P_E = P_E(E)$ –of the soil deformation modulus random value accepted to be normal with mathematical expectation m_E and the mean-square deviation σ_E. The values of this parameter are determined by analyzing the results of soil tests.

All calculations are performed for the estimated service life T.

Determination of exceeding boundary deformations probability by the Monte Carlo statistical test method

To determine the probability of exceeding the boundary deformations of the «base-building» system, it is advisable to use the method of statistical tests (Monte Carlo) using the normative method of deformations calculation by the layerwise summation method.

According to this method, N statistical tests are performed. For each test, calculations are performed according to the following algorithm.

1. It is set the random probability of the parameters uniformly distributed in the interval from 0 to 1:

1.1. specific weight of concrete $P_{\gamma b}$;
1.2. specific weight of brickwork $P_{\gamma kk}$;
1.3. payload intensity P_Q;
1.4. snow load intensity P_S;
1.5. soil deformation modulus E.

2. Using the values of the probabilities it can be found quantiles – the values of the corresponding parameters from the known distribution functions:

2.1. concrete specific weight $P_{\gamma b}$;

2.2. brickwork specific weight $P_{\gamma kk}$;

2.3. payload intensity P_Q;

2.4. snow load intensity P_S;

2.5. soil deformation modulus E.

3. The random values of the vertical load N are determined depending on the loads values from the own weight G, snow S, payload Q.

4. The random mean values of the mean pressure under the foundation base p_{cp} are determined from formula (6).

5. The calculated resistance of the foundation soil is determined, and the boundaries of layer-by-layer summation method applicability ($p_{ap} \le R$) are delineated.

6. Stresses from the own soil weight σ_{zg}, stresses from the own soil weight taken in the pit basin $\sigma_{zy,}$ are determined by the formula (7), and the stresses $0,2\sigma_{zg}$ are determined.

7. The random values of the stresses from the additional load σ_{zp} are determined by the formula (5).

8. The random values of vertical deformations s_i in each elementary layer and the total value of s are determined by formula (2).

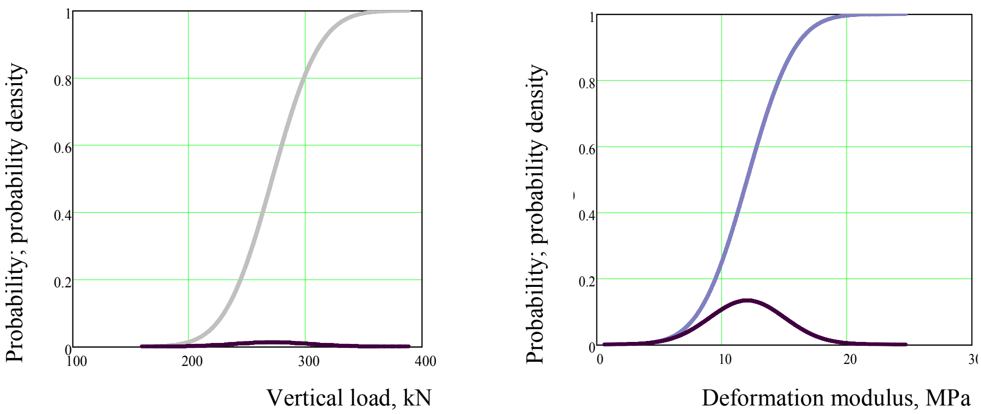
9. In each case, condition (1) is checked.

10. After all N tests being completed, the risk (probability) of exceeding the boundary deformations during the estimated service life P_T is calculated as the number of tests ratio*n* where $Y = s_u - s < 0,$ to the number of all tests N.

The number of tests N should be increased to more accurately determine the value of Y more accurately, in this case the number of tests was taken as $N = 1\text{x}10^4$. The author has developed the computer program for performing calculations to determine the risk of exceeding boundary deformations in the Mathcad environment.

Example of the calculation. As an illustration of the proposed methodology application using the developed computer program, calculation was performed to determine the probability of exceeding boundary deformations in the example of an ordinary five-story brick building. Consequences (responsibility) class of the building are CC2, the responsibility category of the construction is A. Table 1 shows the deterministic values, in Table 2 – the probabilistic characteristics of the random variables normal distribution functions.

Figure 1 illustrates the function and density of random variables distribution N – the vertical load on the foundation and E – the modulus of the base soil deformation.



a) b)

Figure 1 – Function and density of distribution of random variables:
a) ***N*** – vertical load on the foundation and b) ***E*** – deformation modulus of the base soil

Table 1 – Deterministic values

№	Name of the parameter	Designation	Units of measurement	Value
1	Width of foundation	A	m	1,0
2	Length of foundation	L	m	1,0
3	Depth of foundation	D	m	1,5
4	Brick wall thickness	H	m	0,51
6	Thickness of overlap	T	m	0,25
7	Height of the storey	H	m	3,0
8	Freight area	A	m^2	3,0
9	The average specific weight of the foundation and soil on its edges	γ_{mt}	kN/m^3	20,0
10	Load on the floor	Q	kN/m^2	10,0
11	Specific weight of backfill material	γ_I	kN/m^3	16,0
12	Specific weight of foundation soil	Γ	kN/m^3	18,0
13	Estimated soil resistance	R	kPa	314,057

Table 2 – Probabilistic characteristics of the normal distribution functions

№	Name of the parameter	Designation	Units of measurement	Probabilistic characteristics	
				mathematical expectation m	mean-square deviation σ
1	Specific weight of concrete	γ_b	kN/m^3	25,0	0,75
2	Specific weight of brickwork of walls and partitions	γ_{kk}	kN/m^3	18,844	0,517
3	Payload on the overlap	P_{pol}	kN/m^2	0,9	0,315
4	Snow load	S_m	kN/m^2	0,46	0,069
5	Soil deformation modulus	E	MPa	12,0	3,0
6	Average pressure under the base of the foundation	P_{ap}	kPa	233,276	28,82

Using the developed program, calculations were performed to determine the probability of base exceeding boundary deformation. The results of the calculations are shown in Fig. 2 and in Tables 3 and 4.

Table 3 – Statistical parameters of base boundary deformation random value distribution density

Parameters	Values
Mean value (mathematical expectation), m	0,049
The coefficient of variation	0,173
Maximum value, m	0,466
Minimum value, m	0,036

Table 4 – Results probability calculations of base exceeding boundary deformation

Name of the parameters	Values
The probability of base exceeding boundary deformation	$2x10^{-3}$
The permissible probability of foundation exceeding boundary deformation according to DBN B.1.2-14-2002	$1x10^{-4}$

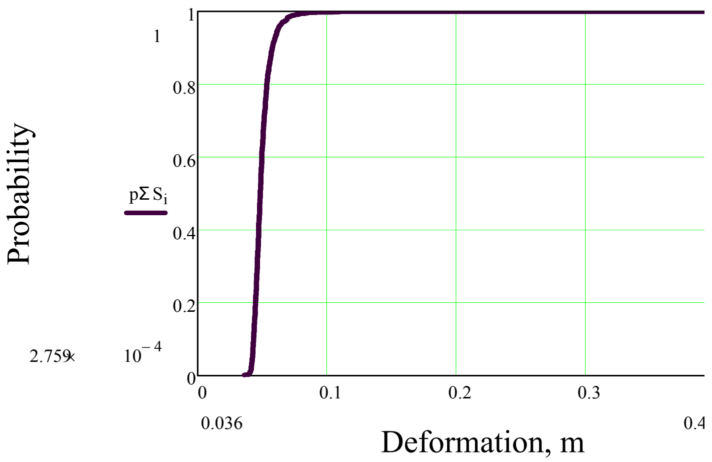


Figure 2 – Distribution function of the random value of deformations (s)

Conclusions. The method is proposed and the algorithm for solving the problem of determining the probability (risk) of exceeding the «base – building» system boundary deformation is developed within the framework of the parametric reliability theory using the method of statistical tests (Monte-Carlo).

A computer program that implements the proposed method of calculations has been developed.

Calculations have been performed to determine the probability (risk) of exceeding the boundary deformation of the «base-building» system for an ordinary residential brick building. The value of exceeding boundary deformation probability, equal to $2x10^{-3}$, is obtained. This value exceeds the normative, governed by DBN B.1.2-14-2009 (Table 3). The value of the deformations, determined by deterministic calculation according to the normative method, is 0,049 m, which is much less than the DBN B.2.1-10-2009 for this type of building (0,1 m). It can be stated that DBN B.1.2-14-2009 has a high level of reliability, and to satisfy this condition, the value of the deformations should be about 9 – 10 times lower than the normative one.

It is obvious that the optimal value of the risk should be in the range of $1x10^{-2}$ ... $5x10^{-3}$, which corresponds to the optimal reliability value of 0,99 ... 0,995 and agrees with the work of N.N. Mikheyev. In the normative document DBN B.2.4-3: 2010, the following values of the probabilities of accidents occurrence on pressure hydraulic structures of class CC2 $3x10^{-3}$ 1/year (for CC2-2) and $5x10^{-4}$ 1/year (for CC2-1), i.e for the entire service life (50 and 100 years correspondently) they should be not more than $15x10^{-2}$ and $5x10^{-2}$.

Analysis of probabilistic calculation shows the need to improve existing approaches to determining the probability of deformation exceeding boundary value, because new methods will improve the reliability of geotechnical problems.

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