Investigation of the effect of the deformation anisotropy on the stress-strain state of the of soil basement

L'investigation de l'effet de la déformation anisotrope sur la base d'état de contrainte-déformation du sol de fondation

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ABSTRACT: The article analyses the stress-strain state of soil basement, folded anisotropic soils on the basis of the numerical experiment. To evaluate a stress-strain state of soil basement, ANSYS software system was used. Calculations were carried out using a model of elastic linear material strain. Strain properties of environment are determined by strain module E and Poisson's ratio μ. It should be noted that in advance we tested the effect of Poisson's ratio and modulus of soil deformation on the stress-deformed state of isotropic and anisotropic soil basement, also we considered different calculation schemes "the foundation - the basement". Analysis of the data suggests that the Poisson's ratio has a significant effect on the calculation results, while the regulatory calculation methods of foundation settlement do not consider that fact. By analyzing the results of numerical experiments, we derived correction factors for the calculation of foundation settlement. The paper presents the calculation method of the deformations of soil basement, which consider the anisotropic properties of the soil and allow improving the forecast accuracy.

RÉSUMÉ: L'article analyse l'état de contrainte-déformation du sol de fondation, des plié sols anisotropes sur la base de l'expérimentation numérique. Pour évaluation l'état de contrainte-déformation du sol de fondation, le système de logiciel ANSYS a été utilisé. Les calculs ont été effectués au moyen du modèle de raccourcissement élastique de matériau. Les propriétés de contrainte de l'environnement sont déterminées par le module d'élasticité E et le coefficient de Poisson μ. Il convient de noter qu'à l'avance nous avons testé l'effet du coefficient de Poisson et des modules de déformation du sol sur l'état de contrainte-déformation du sol de fondation isotrope et anisotrope. En plus, nous avons considéré les différents schémas de calcul «le fondement - le sol de fondation». L'analyse des données suggère que le ratio de Poisson a un effet significatif sur les résultats de calcul, tandis que les méthodes de calcul normatives du tassement de la fondation ne considèrent pas ce fait. En analysant les résultats des expériences numériques, nous avons déterminé des facteurs de correction pour le calcul du tassement de la fondation. L'article présente la méthode de calcul des déformations du sol de fondation, qui considèrent des propriétés anisotropes du sol et permettent d'améliorer la précision des prévisions.

KEYWORDS: stress-strain state, anisotropic soils, foundation settlements, deformations of soil basement

1 INTRODUCTION

Anisotropic soils are very widespread in the planet. They cover very large area on the territory of Russia, Ukraine, Kazakhstan, Central Asia and other countries. Not without reason many researchers express opinion that all the dispersed soils has the anisotropic properties in a varying degree. It is explained by complex loading soils were experienced more or less while formation in the past geological epochs, that's why heterogeneous and anisotropic stress state was formed.

Soils and rocks can have a mechanical (strength and deformation) anisotropy, anisotropy of filtration properties, thermal conductivity, swelling and other properties.

The most important to design of foundations on the soil basement is the property of deformation anisotropy, which can have a significant influence on the stress-strain state of the base.

2 NUMERICAL INVESTIGATIONS OF DEFORMATION ANISOTROPY OF SOIL BASEMENT

To analyze the influence of deformation anisotropy on the stress-strain state of the soil basement was used the model of linearly deformable medium using ANSYS software system. The correctness of the researches was ensured by the load limitation on the foundation, for which the plastic zone did not achieve the depth of 0,25 of the foundation width. Strain properties of environment are determined by strain module *E* and Poisson's ratio μ. Degree of stress-strain anisotropy was evaluated based on ratio of deformation modules in vertical E_z and horizontal E_x directions. Possible soil anisotropy in the horizontal plane is not considered, $E_x = E_y$. Taking into account results of many years of experimental researches, conducted by department of geological engineering, soil basements and foundations of the Novosibirsk state architecture and civil engineering university (Sibstrin) a range of most probable indicator of anisotropy $k_a=E_z/E_x$ is assumed from 0.5 to 2.

Deformation modules of soil were determined by known laboratory and field methods. As Poisson's ratios were set average values: to sand – 0,27; silty clay – 0,30; lean clay – 0,35 and clay – 0,40.

In carrying out the numerical experiment (simulation in the ANSYS software system) the values of shear modulus G_{xz} is determined by the formula:

$$G_{xz} = \frac{E_x E_z}{E_x(1+\mu_z)+E_z(1+\mu_x)} \qquad (1)$$

where E_z и E_x – deformation modulus of vertical and horizontal directions;
μ_z и μ_x – Poisson's ratio correspondingly.

As under side foundation pressure p was assumed as equal to reference resistance of soil *R*, when determining the strain, occurrence and development of plastic strain was not taken into account.

2.1 *Application of ANSYS software system for calculation of soil basements*

As one of the research purposes is an evaluation of possible use of the software when designing basements and foundations, several tasks of various interaction schemes basement-foundation were concerned.

For flexible foundation, results are evenly distributed stress to depth, most corresponding to scheme of linear strained semi-space. The greatest divergence of stress of soil basement with hard and flexible foundation may be observed in area close to foundation underside.

It is known that if foundation hardness is concerned, there is stress redistribution on foundation underside with endlessly big contact stress concentrated on foundation circuit. But in this case, strain values of soil basement are close to settlement values, determined using layer-by-layer summing method

2.2 *Comparison of the results of solving the problem in 2D and 3D setting.*

It should be noted that for continuous foundation with isotropic soil in its basement analysis of stress-strain state there is a plain 2D setting. Calculation results (presented in Figure 1) are in accordance with the data received and published by famous researchers earlier.

Analysis of the data received indicates that flat task solution give sin creased (up to 44 %) values of soil basement stress compared to volume task solution. A good coincidence of results was received for volume task solution (3D setting) with data of layer-by-layer summing method, recommended Russian geotechnical design standards for calculations of foundations basements of buildings and structures.

It is worth noting that besides the above said an effect of Poisson's ratio μ and deformation modulus *E* were tested for stress-strain state of isotropic and anisotropic soil basement. Analysis of data received indicates that Poisson's ratio has a sufficient influence on calculation results, while Russian regulatory methods of the settlement forecasting and evaluation do not take it into account. Given Poisson's ratio μ=0,42 stress values were received corresponding mostly to reference scheme of linear-stressed semi-space, stated in SP. Difference of results received makes up to 31% for pier and up to 45% for continuous foundations at other values of Poisson's ratio. Poisson's ratio has influence on deformation of soil basement. When μ=0.42 there are minimal values of settlement both for pier, as well as for continuous foundation. At other values of Poisson's ratio settlements increase to 1.13 times for pier foundation and up to 1.2 for continuous foundation.

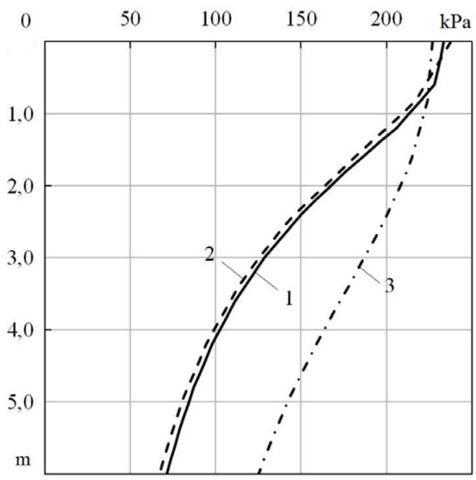

Figure 1. Stress distribution σ_{zp} of pier foundation: 1 according to layer-by-layer summing method (SP); 2 – results calculated in ANSYS; 3 – results calculated in ANSYS (2D).

Deformation modulus, as expected, does not influence stress distribution in ground mass.

2.3 *Influence of deformation anisotropy on the stress-strain state of basement*

Resulting from calculation experiments, transverse-isotropic environments were concerned with coefficients of stress-strain anisotropy ka=0,50; 0,75; 1,33; 2 et al. Here stress to depth distribution were concerned for continuous foundations, square, rectangular and round in plain view.

Given below are stress distributions σ_{zp} for isotropic and anisotropic soil basements of continuous foundations, square and rectangular in plain view (Figure 1 & 2).

Based on processed results correction coefficients were received α_a or α′ for determination of normal stress σ_{zp} from external loading anisotropic soil basement including different deformability of soil in vertical and horizontal dimensions.

3 METHOD OF CALCULATION OF DEFORMATION OF ANISOTROPIC SOIL BASEMENT

Based on the research we propose a method for calculating the deformation of foundations soil basement, taking into account the soil anisotropic properties which is well correlated with the Russian construction standards for isotropic basement. Foundation basement settlements is recommended to determine using scheme of linear deformed semi-spaces at average pressure under the foundation base *p*, not exceeding calculated soil resistance *R*. Soil basement is divided into separate layers but no more than 0,4 of the width of the foundation base concerned. It is preferably to define a thickness of layers equal 0.2 m which normally corresponds the module definition intervals in the field by the stress relaxation method using wedding dilatometer WD-100 (Nuzhdin 2013). Then stress from external loading $\sigma_{zp,i}$ and stress of its own weight of soil $\sigma_{zg,i}$ are determined in each layer.

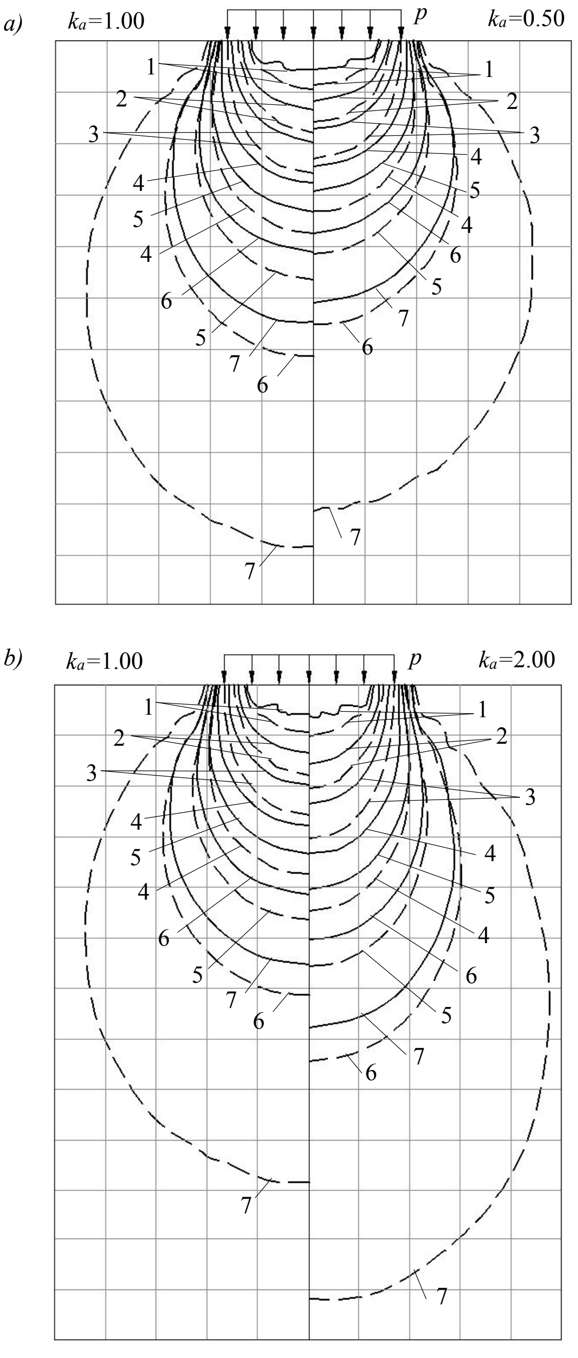

Figure 2. Stress distribution σ_{zp} of square (solid line) and rectangular (l/b = 1,4; dash line) foundation in isotropic (left, k_a = 1,0) and anisotropic (right) soils: *a* – with anisotropic indication k_a = 0.5; *b* – with k_a = 2.0; 1 – 0.9*p*; 2 – 0.8*p*; 3 – 0.5*p*; 4 – 0.4*p*; 5 – 0.35*p*; 6 – 0.25*p*; 7 – 0.15*p*.

Vertical stress from external loads σ_{zp} depend on the size, shape and depth of the foundation, the pressure distribution on the soil at its base and the properties of the basement.

Values of the stress at the depth *z* under the foundation base the vertical line passing through the center of the bottom foundation are calculated by formula

$$\sigma_{zp}=\alpha' \times p \qquad (2)$$

where α' – coefficient for round, square, rectangular (l/b = 1,4; 1,8; 2,4; 3,2; 5) and continue ($l/b \geq 10$) foundation, depending on the relative depth ξ equal $2z/b$ and taking into account the deformation anisotropy of soil basement depending $k_a = E_z/E_y$ (e.g., see Tables 1 and 2);

p – average pressure of foundation underside.

Table 1. Correction coefficients values α' for rectangular foundations with sides proportion $\eta = l/b = 1$.

$\xi = 2z/b$	Correction coefficient α' with anisotropy coefficient k_a, value			
	0.5	0.75	1.33	2
0	1,035	1,035	1,032	1,031
0,4	0,889	0,910	0,936	0,952
0,8	0,705	0,742	0,797	0,834
1,2	0,511	0,556	0,632	0,690
1,6	0,363	0,402	0,477	0,543
2,0	0,270	0,302	0,369	0,432
2,4	0,203	0,228	0,285	0,342
2,8	0,154	0,174	0,221	0,272
3,2	0,123	0,139	0,179	0,222
3,6	0,100	0,113	0,146	0,184
4,0	0,082	0,092	0,121	0,154
4,4	0,069	0,077	0,101	0,130
4,8	0,059	0,065	0,086	0,111
5,2	0,050	0,056	0,074	0,096
5,6	0,044	0,048	0,064	0,084
6,0	0,039	0,042	0,056	0,074
6,4	0,035	0,037	0,050	0,066
6,8	0,031	0,033	0,044	0,059
7,2	0,028	0,030	0,039	0,053
7,6	0,026	0,027	0,036	0,048
8,0	0,024	0,025	0,032	0,044
8,4	0,022	0,022	0,029	0,040
8,8	0,020	0,021	0,027	0,037
9,2	0,019	0,019	0,025	0,034
9,6	0,017	0,018	0,023	0,032
10,0	0,016	0,016	0,021	0,030
10,4	0,015	0,015	0,020	0,028
10,8	0,014	0,014	0,019	0,026
11,2	0,013	0,013	0,017	0,025
11,6	0,013	0,012	0,016	0,023
12,0	0,012	0,012	0,015	0,022

Table 2. Correction coefficients values α' for tape foundations ($\eta = l/b \geq 10$).

ξ=2z/b	Correction coefficient α' with anisotropy coefficient k_a, value			
	0.5	0.75	1.33	2
0	0,982	0,982	0,980	0,973
0,4	0,848	0,871	0,900	0,915
0,8	0,660	0,698	0,756	0,797
1,2	0,456	0,499	0,577	0,641
1,6	0,312	0,347	0,419	0,486
2,0	0,227	0,255	0,316	0,377
2,4	0,168	0,189	0,239	0,292
2,8	0,126	0,142	0,183	0,228
3,2	0,100	0,113	0,146	0,184
3,6	0,081	0,091	0,119	0,151

4,0	0,066	0,074	0,097	0,125
4,4	0,055	0,062	0,081	0,105
4,8	0,047	0,052	0,069	0,090
5,2	0,040	0,045	0,059	0,077
5,6	0,035	0,038	0,051	0,067
6,0	0,031	0,034	0,045	0,059
6,4	0,027	0,030	0,039	0,052
6,8	0,025	0,026	0,035	0,047
7,2	0,022	0,024	0,031	0,042
7,6	0,020	0,021	0,028	0,038
8,0	0,019	0,019	0,026	0,035
8,4	0,017	0,018	0,023	0,032
8,8	0,016	0,016	0,021	0,029
9,2	0,015	0,015	0,020	0,027
9,6	0,014	0,014	0,018	0,025
10,0	0,013	0,013	0,017	0,023
10,4	0,012	0,012	0,016	0,022
10,8	0,011	0,011	0,015	0,021
11,2	0,011	0,010	0,014	0,019
11,6	0,010	0,010	0,013	0,018
12,0	0,009	0,090	0,012	0,017

Vertical stress of its own weight of soil at the level of the foundation bottom are determined by formula

$$\sigma_{zg,0}=\gamma \times d \quad (3)$$

where γ' – the specific gravity of the soil, which is located above the bottom of the basement;

d – depth of laying the foundation.

To determine the natural stress $\sigma_{zg,i}$ at a depth z from the foundation bottom using the

$$\sigma_{zg,i}=\sigma_{zg,0}+\sum_{i=1}^{n}\gamma_i \times h_i \quad (4)$$

where γ_i – the specific gravity of the soil of the i-th layer;

h_i – thickness of the i-th layer.

Specific weight of soils, lying below the level of underground water, but higher waterproof layer, must be taken into account with a weighting of water action. It is necessary to take into account the pressure of the water column, located above a depth consideration, while determining σ_{zg} in a waterproof layer. Vertical natural stress of soils, taken out from the pit, at a depth z from the foundation bottom is determine similarly

$$\sigma_{z\gamma,i}=\alpha' \times \sigma_{zg,0} \quad (5)$$

where α' – also, in the formula 2 (in this case it is necessary to use dimensions in terms not foundation, but pit).

Depth z is taken as the border of compressed thickness H_c, if it meets the equality condition $\sigma_{zp} = 0,5\sigma_{zg}$, or for weak soils (with $E \leq 7$ MPa) $\sigma_{zp} = 0,2\sigma_{zg}$.

Settlement of anisotropic foundation basement is depending by formula

$$S=\beta\sum_{i=1}^{n}\frac{(\sigma_{zp,a,i}-\sigma_{z\gamma,i})h_i}{E_i}+\beta\sum_{i=1}^{n}\frac{\sigma_{z\gamma,i}h_i}{E_{e,i}} \quad (6)$$

where β – dimensionless ratio, equal 0,8;

σ_{zpi} – average value of the vertical normal stress from the external load in the i-layer anisotropic soil on vertical passing through the center of the foundation bottom;

h_i – thickness of the i-th layer, is taking no more than 0,4 of the width of the foundation base;

E_i – deformation modulus of the i-th layer of the primary branches of loading;

$\sigma_{z\gamma,i}$ – average value of vertical natural stress of soils, taken out from the pit, in the i-layer on vertical passing through the center of the foundation bottom;

$E_{e,i}$ – deformation modulus of the i-th layer of the secondary branches of loading.

The second term in (6) may be ignored, when calculating the sediment of foundations erected in the pits depth less than 5 m.

4 EXPERIMENTAL VERIFICATION OF RESULTS

Result of numerical experiment and proposed method of calculation of foundation settlements of basement, folded by anisotropic soils, were tested experimentally according to the instrumental observations of settlements of foundations in different sizes, erected on the anisotropic soil basement in Novosibirsk, Barnaul and Perm. The analysis shows a fairly good convergence of obtained calculated results with the actual deformations of soil basements.

5 CONCLUSIONS

Conducted researches shows that taking into account anisotropic properties of soils can improve the forecast accuracy of foundation settlements. It should be noted that at the deformation anisotropy coefficients k_a >1 real settlements exceeds values, calculated by SP 22.13330.2011 and, in some cases, it may even be necessary to increase the size of the foundation in plane. Neglect of anisotropy in the calculation by SP 22.13330.2011 leads to increase of the calculated settlements when anisotropic indication k_a < 1. In this case, the correct assessment of the stress-strain state of anisotropic soil basement may provide a more cost-effective technical solutions of the foundation.

Even marginally accounting of deformation anisotropy of natural addition of soil can lead to the refinement of the estimated settlements of foundations on 10 ... 40%.

It is particularly important to consider deformation anisotropy when design of reinforced soil basement with the creation of induced anisotropy, including construction new facilities near existing building.

6 REFERENCES

Ambartsumyan S.A. 1982. *Multimodulus theory of elasticity*. Moscow: Nauka Publishers. Main editorial board of physics and mathematics literature.

Nuzhdin L., Nuzhdin M., Kozminykh X., et al. 2013a. Evaluation of deformation properties of soils using a wedge dilatometer and improvement of forecast accuracy of buildings settlemen . *Challenges and innovations in Geotechnics*: Proc. of ATC7 Workshop, 18ICSMGE. Paris: Presses des Ponts, 68-75.

Nuzhdin L.V., Nuzhdin M.L. and Kozminykh K.V. 2013b. Improvement of forecast accuracy of foundations based on field research deformability of the soil wedge dilatometer. *Scientific works: edition: Indus-trial Engineering & Construction.* Issue 3 (38).V. 2. Poltava: PoltNTU, 258-273.

Nuzhdin L.V, Korobova O.A. and Nuzhdin M.L. 2014. The practical calculation method of foundation settlements with regard strain anisotropy of the soil. *Deep foundations and problems of underground space development*: collected works of All-Russian conference with international participation Part 4. Perm: PNRPU, 154-162.

Nuzhdin L.V. and Pavlyuk K.V. 2016. Analysis of stress-strain state of anisotropic soil basement. *Challenges and Innovations in Geotechnics*: Proc. of the 8th Asian young geotechnical engineers conf. CRC Press: Balkema, 277-283.