Application of numerical methods in research of deformation anisotropy soil

O A Korobova¹, L A Maksimenko², I Yu Solovyanova¹

¹Department of engineering Geology, bases and foundations, Novosibirsk state university of architecture and civil engineering (Sibstrin), 113, Leningradskaya Str., Novosibirsk 630008, Russia
²Department of Geomatics and real estate infrastructure, Siberian State University of Geosystems and Technologies, 10, Plakhotny Str., Novosibirsk 630108, Russia

E-mail: maksimenko_la@mail.ru

Abstract. The article provides a methodology for conducting studies of the effect of the deformation anisotropy on the stress and strain state of foundation soil provided. The investigation of the stress-strain state of a wide range of soil bases was performed by a finite element analysis with the application of method of mathematical experiment design techniques. The character of the stress change component depending on the variation for each factor considered characteristic zones subgrade as well, estimated effect on each component of the stress properties of the medium degree of meandering from the isotropic state. The efficiency of taking into account the deformation anisotropy of the soil in the calculations of the bases is estimated.

1. Introduction

Normative documents for the calculation of soil bases (SP 22.13330.2011 “Foundations of buildings and structures. The updated version of SNiP 2.02.01—83*” [1]) recommends to take into account the deformation anisotropy of soils, which will undoubtedly increase the accuracy of their calculation on deformations and allow taking into account the real properties of soils, but until now, due to some reasons, it was not done. The successful solution of this problem is impossible without the use of numerical and mathematical methods in the formation of the computational model, one of the components of which is the study of the stress-strain state (SSS) of anisotropic soil bases.

2. The relevance of research

Due to the fact that the main problem of modern construction is safe, reliable and accurate prediction of SSS, accounting for deformation anisotropy not only allows the most accurate calculation of sediment foundations, but also to predict the degree of approximation of the stress state of the soil bases to the limit.

Data for SSS of the anisotropic soil foundation are not without great practical interest [1-11]. Taking into account the anisotropy of the soil leads to a change in the size of the shear zones and the value of the calculated resistance of the soil R, which results in the need to adjust the size of the foundations in comparison with the dimensions established without it. In the characteristic regions of the stress state of the anisotropic base with a change in the index α, there is a significant change in the
horizontal stresses $\sigma_x$ and tangent $\tau_{zx}$, which affects the degree of approximation of the stress state of these zones to the ultimate strength, especially with an increase in the index $\alpha$. In this regard, the account of deformation anisotropy and prediction of the ultimate stress state of anisotropic soil bases is an urgent task and has scientific novelty.

3. Formulation of the problem

Application of methods of mathematical planning of experiment allows to receive much bigger volume of information, than at usual experiment. At the same time, it is possible to estimate the effect of each of the anisotropy parameters on the response (stress) functions and to some extent justify the possibility and admissibility of the simplifications adopted by various authors in terms of reducing the number of independent parameters of the deformation anisotropy of the medium in the calculations of its SSS.

4. Theoretical part

For these purposes, the authors have made the appropriate calculations with application of method element analysis [12, 13] and conducted a quantitative estimate of the impact of the induced anisotropy of the environment and each of its parameters on SSS transversely isotropic homogeneous linearly elastic half-plane. Changing the state of stress half-plane is investigated in its three characteristic zones - in the zone I (future shifts zone located below the edge of the half-plane of the loaded portion), in the zone II (a potential region of compacted plug is located under the middle part of the loaded section), in the zone III (region located under the peak potential of the soil plug). Stress state of each of the zones was evaluated fairied values component, $\sigma_z$, $\sigma_x$, $\tau_{zx}$, which was calculated for finite elements, constituting the respective zone. Effect of changes in environmental parameters induced anisotropy ($E_z$, $E_x$, $\nu_{zx}$, $\nu_{yx}$) on the state of stress characteristic of the half-plane zones was studied with the help of the methodology mathematical experiment design techniques [14, 15]. As a variation factors was taken induced anisotropy parameters of the environment, and each of this was varied at three levels. Levels and variation interval were given in Table 1.

| Factors of variation $x_i$ | Levels of variation | unit interval |
|---------------------------|---------------------|--------------|
|                           | lower | null | upper |               |
| $E_z$, MPa                | $x_1$ | 5    | 22.5  | 40  17.5 |
| $E_x$, MPa                | $x_2$ | 5    | 22.5  | 40  17.5 |
| $\nu_{zx}$                | $x_3$ | 0.25 | 0.30  | 0.35 0.05 |
| $\nu_{yx}$                | $x_4$ | 0.25 | 0.30  | 0.35 0.05 |

Matrix of the experiment design techniques in non-dimensional and natural values of factors was given in Table 2.
Table 2. Information matrix of the experimental design techniques in non-dimensional and natural values of factors.

| Experience number | Plan of an experiment | Natural values of factors |
|-------------------|-----------------------|--------------------------|
|                   | $x_1$     | $x_2$     | $x_3$     | $x_4$ | $x_1$ | $x_2$ | $x_3$ | $x_4$ |
| 1                 | -1       | -1        | -1        | -1    | 5.0   | 5.0   | 0.25  | 0.25  |
| 2                 | +1       | -1        | -1        | -1    | 40.0  | 5.0   | 0.25  | 0.25  |
| 3                 | -1       | +1        | -1        | -1    | 5.0   | 40.0  | 0.25  | 0.25  |
| 4                 | 1        | 1         | -1        | -1    | 40.0  | 40.0  | 0.25  | 0.25  |
| 5                 | -1       | -1        | +1        | -1    | 5.0   | 5.0   | 0.35  | 0.25  |
| 6                 | +1       | -1        | +1        | -1    | 40.0  | 5.0   | 0.35  | 0.25  |
| 7                 | -1       | +1        | +1        | -1    | 5.0   | 40.0  | 0.35  | 0.25  |
| 8                 | +1       | +1        | +1        | -1    | 40.0  | 40.0  | 0.35  | 0.25  |
| 9                 | -1       | -1        | -1        | +1    | 5.0   | 5.0   | 0.25  | 0.35  |
| 10                | +1       | -1        | -1        | +1    | 40.0  | 5.0   | 0.25  | 0.35  |
| 11                | -1       | +1        | -1        | +1    | 5.0   | 40.0  | 0.25  | 0.35  |
| 12                | +1       | +1        | -1        | +1    | 40.0  | 40.0  | 0.25  | 0.35  |
| 13                | -1       | -1        | +1        | +1    | 5.0   | 5.0   | 0.35  | 0.35  |
| 14                | +1       | -1        | +1        | +1    | 40.0  | 5.0   | 0.35  | 0.35  |
| 15                | -1       | +1        | +1        | +1    | 40.0  | 5.0   | 0.35  | 0.35  |
| 16                | +1       | +1        | +1        | +1    | 40.0  | 5.0   | 0.35  | 0.35  |
| 17                | -1       | 0         | 0         | 0     | 5.0   | 22.5  | 0.30  | 0.30  |
| 18                | +1       | 0         | 0         | 0     | 22.5  | 22.5  | 0.30  | 0.30  |
| 19                | 0        | -1        | 0         | 0     | 22.5  | 5.0   | 0.30  | 0.30  |
| 20                | 0        | +1        | 0         | 0     | 22.5  | 40.0  | 0.30  | 0.30  |
| 21                | 0        | 0         | -1        | 0     | 22.5  | 22.5  | 0.25  | 0.30  |
| 22                | 0        | 0         | +1        | 0     | 22.5  | 22.5  | 0.35  | 0.30  |
| 23                | 0        | 0         | 0         | -1    | 22.5  | 22.5  | 0.30  | 0.25  |
| 24                | 0        | 0         | 0         | +1    | 22.5  | 22.5  | 0.30  | 0.35  |

Regression equations were obtained for each of response functions under consideration ($\sigma_x, \sigma_z, \tau_{zx}$). As for the zone I, they are written as:

$$\hat{\sigma}_z = -1.61 + 0.01 \cdot (x_1^2 + x_2^2 + x_3^2 + x_4^2);$$  \hfill (1)

$$\hat{\sigma}_x = -0.40 + 0.74x_1 - 0.69x_2 - 0.06x_3 + 0.57x_1x_2 + 0.03x_1x_3 - 0.03x_2x_3 + 0.61x_1^2 + 0.02(x_2^2 - x_3^2 - x_4^2);$$  \hfill (2)

$$\hat{\tau}_{zx} = -0.64 + 0.29x_1 - 0.27x_2 + 0.03x_3 + 0.13x_1x_2 - 0.04x_1x_4 + 0.04x_1x_3 - 0.22x_1^2 + 0.06x_2^2 + 0.02x_3^2 + 0.04x_4^2.$$  \hfill (3)

As for the zone II:

$$\hat{\sigma}_z = -3.13 - 0.07x_1 + 0.07x_2 + 0.05x_3 - 0.07x_1x_2 - 0.05x_1x_3 + 0.05x_2x_3 + 0.04x_1^2 + 0.02 \cdot (x_2^2 + x_3^2 + x_4^2);$$  \hfill (4)
\[
\hat{\sigma}_z = -1,16 + 1,71x_1 - 1,60x_4 - 0,11x_3 + 1,21x_5 + \\
+0,08x_6x_7 - 0,08x_5x_3 - 1,33x_1^2 + 0,08x_7^2 + 0,04 \cdot (x_3^2 + x_7^2); \\
\hat{\tau}_{zx} = 0,01 - 0,06x_1 + 0,06x_5 + 0,05x_1 - 0,06x_5x_2 - 0,05x_3x_4 + \\
+0,05x_6x_7 + 0,03x_1^2 + 0,01x_3^2 + 0,02 \cdot (x_3^2 + x_7^2).
\]

as for the zone III:

\[
\hat{\sigma}_z = -3,13 - 0,18x_1 + 0,17x_2 + 0,06x_3 - 0,15x_5x_2 - 0,06x_5x_3 + \\
+0,06x_6x_7 + 0,12x_1^2 + 0,02 \cdot (x_3^2 + x_7^2); \\
\hat{\sigma}_x = -0,36 + 0,65x_1 - 0,60x_2 - 0,13x_3 + 0,50x_4x_2 + \\
+0,11x_6x_7 - 0,11x_2x_3 - 0,50x_1^2 + 0,01x_3^2; \\
\hat{\tau}_{zx} = 0,01 + 0,13x_1 - 0,12x_2 + 0,09x_5x_2 - 0,10x_7^2.
\]

where \(x_1, x_2, x_3, x_4\) - coded values of the variables (Table 1).

Analysis of the equation of regression, which was obtained for all zones, showed that \(\nu_{zx}\) (\(x_z\) factor) has practically no effect on the response function. Also it was found that \(E_x, E_z, \nu_{zx}\) (Factors \(x_1, \ldots, x_3\)) have a weak affect on the magnitude of the stress \(\sigma_z\).

The values of \(\sigma_z\) by increasing \(x_1\) from -1 to +1 in the zone I decrease from 100% (level -1) to 30% (level 0) and up to 16% (level 1). With increasing of \(x_2\) from -1 to +1, values \(\sigma_z\) increased to 120% (1). Increasing of \(x_3\) from -1 to 1 leads to an increase up to 130\% \(\sigma_z\) (0) and up to 140\% (1); increase of \(x_4\) leads to a decrease \(\tau_{zx}\) up to 50\% (0) and up to 20\% (1); increase of \(x_5\) leads to an increase \(\tau_{zx}\) up to 140\% (0) and up to 200\% (1); increase of \(x_7\) has the external impact in the magnitude of \(\tau_{zx}\). The pattern of changes in the stress components in the zone III is qualitatively the same as in the zone I, with some quantitative differences.

In addition to analyzing the effect of each of the components of the stress factors \(E_i, (x_1, x_2)\) and \(v_i\) \((x_3, x_4)\), also evaluated the impact on each component of the stress properties of the medium degree of deviation from the isotropic state; the last one was estimated by index anisotropy \(\alpha = E_x / E_z\). (Where \(E_x\) and \(E_z\) – Moduli of deformation in the vertical and horizontal directions are respectively. The estimates were made for each of the zones I ... III.

In zone I the change of \(\alpha\) has hardly affects on the value of \(\sigma_z\) at any value of index \(\sigma_z\). Maximum deviations in the direction of decreasing \(\sigma_z\) compared with the case of \(\alpha = 1\), is 2.5\% (with \(\alpha = 0.13\)), and in the direction of increasing \(\sigma_z\) - 1\% \((\alpha = 8)\) [16], [17].

At the changing \(\alpha\) values \(\sigma_z\) vary quite significantly, increasing to 300\% at \(\alpha = 0.13\) and decreases to 9\% when \(\alpha = 8\) (the case of \(\alpha = 1\)). For most of ground coats as is well known are marked by induced weak anisotropy \((2 \geq \alpha \geq 0.5)\), so that in this case it is possible to increase \(\sigma_z\) and 210\% reduction to 30\%; \(\tau_{zx}\) influence of parameter in this case is negligible.

Effect of changes \(\alpha\) on the amount \(\tau_{zx}\) is also quite markedly: when \(\alpha = 0.13\) \(\tau_{zx}\) value is 200\% ... 250\%, and if \(\alpha = 8\), \(\tau_{zx}\) halved in comparison with their value at \(\alpha = 1\). With a decrease of \(\alpha\) in range \((2 \geq \alpha \geq 0.5)\) the values \(\tau_{zx}\) vary, constituting 70\% ... 135\% of the \(\tau_{zx}\), corresponding to an isotropic medium. Parameter of \(v_{zx}\) has a negligible impact on the calculation results of influence.

In zone II influence of change \(\alpha\) on the amount \(\sigma_z\) is weak: increase \(\alpha\) with enhancement of \(\sigma_z\) is not in excess of 0.3\%. The greatest influence of index of anisotropy is set at \(\alpha = 0.13\) and \(\nu_{zx} = 0.35\), when the values \(\sigma_z\) are reduced, constituting 84\% of the magnitude, which is peculiar to the isotropic medium. In zone II the values \(\sigma_z\), as in zone I, at a deviation parameter \(\alpha\) from unity, vary quite significantly, increasing sixfold at \(\alpha = 0.13\) and decreasing sevenfold when \(\alpha = 8\) in comparison with
the value $\sigma_z$ with $\alpha = 1$. In the range change ($2 \geq \alpha \geq 0.5$) is set $\sigma_z$ smooth increase to 190% ($\alpha = 0.5$) and the reduction to 35% ($\alpha = 2$) from the value $\sigma_z$, corresponding to $\alpha = 1$.

In zone II the subjecting to stress $\tau_{zx}$ with $\alpha \geq 1$ are characterized by a constant value, whereas when $\alpha < 1$ change substantially and gradually increases with decreasing $\alpha$. Thus, the value $\alpha = 0.5$ corresponds $\tau_{zx}$ increase in 1.5 ... 1.6 times, and the value $\alpha = 0.13 - 2.4 ... 3.5$ times in comparison with the case of an isotropic medium. Influence of the parameter $\nu_{zx}$ on the value $\sigma_z$ and $\tau_{zx}$ has relatively weak effect.

In the zone III effect of changes $\alpha$ on an amount $\sigma_z$ is manifested negligible: increase $\sigma_z$ measures up only 2% compared to the $\sigma_z$ value at $\alpha = 1$. The greatest influence $\alpha$, as for zone II, is detected with $\alpha = 0.13$ and $\nu_{zx} = 0.35$. In this case, the values of stress $\sigma_z$, when it is decreasing, constitute 70% of the magnitude which it is peculiar to the isotropic medium.

Values $\sigma_z$ on turn of $\alpha$, as for zones I and II, at a deviation parameter $\alpha$ from unity, vary quite significantly, incremental sevenfold at $\alpha = 0.13$ and decreasing sixfold when $\alpha = 8$ in comparison with the value $\sigma_z$ when $\alpha = 1$. In the range ($2 \geq \alpha \geq 0.5$) is marked increase $\sigma_z$ to 190% ($\alpha = 0.5$) and the reduction to 38% ($\alpha = 2$) from the value $\sigma_z$ when $\alpha = 1$.

A change in $\alpha$ has significantly affect on the value of $\tau_{zx}$ stresses as when $\alpha > 1$ - up to 200% ($\alpha = 8$), and in particular when $\alpha < 1$ - increasing more than 10 times. Value of $\alpha = 0.5$ corresponds to an increase $\tau_{zx}$ 3.5 ... 3.9 times, and the value $\alpha = 2$ - an increase of 1.0 ... 1.2 times compared with the case of an isotropic medium. Parameter $\nu_{zx}$ has a negligible effect on the calculation results.

The stated above explorations include the expanded area of raft with anisotropy’s parameters $\alpha = 0.13 ... 8$. The degree of anisotropy of the natural ground is not so high. Within this context messiness have been conducted that allow us to provide insight into the dependence of the stress components at change index anisotropy in the range $\alpha = 0.22 ... 3$ [18]. In Tables 3 - 5 the percentage values of the subjecting to stress $\sigma_z$, $\sigma_x$ and $\tau_{zx}$ is listed for $\alpha$ anisotropic medium to the respective values of voltages $\sigma_z$, $\sigma_x$ and $\tau_{zx}$ isotropic options. The calculation is performed for the zones I ... III at $\nu_{zx} = 0.30$.

Graphs of change of the voltage’s significant component at the changing index of anisotropy $\alpha$ are listed in Figure 1.

### Table 3. The average estimate of the subjecting to stress $\sigma_z$

| №  | $\alpha = E_z / E_x$ | zone I | zone II | zone III |
|----|----------------------|--------|---------|----------|
| 1  | 0.22                 | 1.59   | 98.9%   | 3.07     | 98.7%    | 2.86     | 92.0%    |
| 2  | 0.50                 | 1.60   | 99.4%   | 3.10     | 99.7%    | 3.03     | 97.4%    |
| 3  | 0.56                 | 1.60   | 99.4%   | 3.10     | 99.7%    | 3.05     | 8.1%     |
| 4  | 1.00                 | 1.61   | 100.0%  | 3.12     | 0.03%    | 3.15     | 100.3%   |
| 5  | 1.78                 | 1.61   | 100.0%  | 3.12     | 0.3%     | 3.16     | 100.6%   |
| 6  | 3.00                 | 1.61   | 100.0%  | 3.12     | 0.03%    | 3.16     | 100.6%   |

### Table 4. The average estimate of the subjecting to stress $\sigma_z$

| №  | $\alpha = E_z / E_x$ | zone I | zone II | zone III |
|----|----------------------|--------|---------|----------|
| 1  | 0.22                 | 1.81   | 89%     | 4.32     | 385%     | 1.50     | 411%     |
| 2  | 0.50                 | 0.78   | 11%     | 2.09     | 187%     | 0.68     | 186%     |
| 3  | 0.56                 | 0.68   | 84%     | 1.88     | 168%     | 0.61     | 167%     |
| 4  | 1.00                 | 0.37   | 100%    | 1.12     | 100%     | 0.37     | 100%     |
| 5  | 1.78                 | 0.20   | 54%     | 0.66     | 59%      | 0.22     | 60%      |
| 6  | 3.00                 | 0.11   | 13%     | 0.40     | 36%      | 0.14     | 38%      |
Table 5. The average estimate of the subjecting to stress $\sigma_z$

| №  | $\alpha = \frac{E_z}{E_x}$ | zone I  | zone II | zone III |
|----|-----------------------------|---------|---------|----------|
|    |                             | $10 \sigma_z$, MPa % | $10 \sigma_z$, MPa % | $10 \sigma_z$, MPa % |
| 1  | 0.22                        | 1.21    | 200     | 0.05     | 250      | 0.26     | 1040 |
| 2  | 0.50                        | 0.83    | 137     | 0.03     | 150      | 0.09     | 383  |
| 3  | 0.56                        | 0.79    | 131     | 0.03     | 150      | 0.08     | 320  |
| 4  | 1.00                        | 0.61    | 100     | 0.02     | 100      | 0.03     | 100  |
| 5  | 1.78                        | 0.51    | 84      | 0.02     | 100      | 0.01     | 40   |
| 6  | 3.00                        | 0.43    | 71      | 0.02     | 100      | 0.01     | 14   |

Figure 1. Graphs change of subjecting to stresses at the changing of index anisotropy $\alpha = \frac{E_z}{E_x}$. Zone I, $v_{zx} = 0.25$ (a); Zone I, $v_{zx} = 0.30$ (b); zone I, $v_{zx} = 0.25$ (c); zone III, $v_{zx} = 0.30$ (d).

In addition to studying the influence of variability of environmental parameters on the SSS, a study was conducted to assess the degree of approximation of the stress state of the soil base to the limit [19]. To do this, in each characteristic zone as a whole, as well as for each point within the selected zone, the values of the main stresses were calculated, the $\theta_{\text{max}}$ is the angle of the greatest deviation of the total pressure from the normal to the site on which it acts was determined. The values of $\theta_{\text{max}}$ calculated according to the equation:

$$\sin \theta_{\text{max}} = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2 + 2 \cdot c \cdot \tan \phi}$$

(10)

where $\sigma_1$ and $\sigma_3$ are the averaged values of the principal stresses in the rectangular finite elements of zone I.

The stresses $\sigma_1$ and $\sigma_3$ are calculated from the known dependences of the theory of averaged stresses (for each zone I...III) stress values $\sigma_z$, $\sigma_x$ и $\tau_{zx}$. In the case of non-cohesive soil specific adhesion in the soil $c = 0$. 

6
The dependence of the ratio $\theta_{\text{max}} / \theta_{\text{max}}$ on the anisotropy index $\alpha$ at $p = 0.1$ and $0.5$ MPa is shown in figures 2 and 3. As shown above, the values of $\sigma_z$ are practically unchanged (with the change $\alpha$), the values of $\sigma_x$ (zone I...III) correspond to the increasing (at $\alpha < 1$) or decreasing (at $\alpha > 1$) values of $\sigma_x$ and $\tau_{xz}$ compared to the isotropic solution. This fact increases or decreases the tendency for shifts in these zones. Thus, the calculation found that the values of $\alpha = 1; 2$ and $0.5$ ($\nu_{xz} = \nu_{yx} = 0.30$) the mean for zone I is the angle of greatest deviation $\theta_{\text{max}} = 63^\circ, 77^\circ$ and $51^\circ$ respectively. This means that, ceteris paribus, the indicator $\alpha = 2$ will correspond to the reduced value of the calculated resistance of the soil base $R$, and the indicator $\alpha = 0.5$ - increased, compared with the calculated resistance set for the isotropic half-plane.

In zone II values $\alpha = 1; 2$ and $0.5$ correspond to values $\theta_{\text{max}} = 27^\circ, 41^\circ$ and $11^\circ$; in zone III $\theta_{\text{max}} = 52^\circ, 60^\circ$ and $39^\circ$.

As can be seen, in each of the zones the influence of $\alpha$ change on the value of $\theta_{\text{max}}$ is qualitatively the same. However, for any value of $\alpha$, the angle $\theta_{\text{max}}$ in zone I is greater than in other zones, in zone II - it is minimal. These data are in good agreement with the experimental results [20], indicating the development of shear regions in zone I and the appearance of a compacted core in zone II, where the stress state is far from the limit [20,21].
5. Results
The results of the analysis of the influence of individual parameters of anisotropy allowed to simplify the design of the initial physical dependencies (Hooke's law for anisotropic medium).

A computational and theoretical apparatus designed to assess the stress-strain state of anisotropic soil bases has been developed. The stress components obtained by the calculation are sufficient for a complete assessment of the stress state of the half-plane and for revealing the tendency to hardening or destruction of the anisotropic medium in each of the considered characteristic zones of the stress state when the anisotropy index changes. The availability of the results of calculations of the stress state for an unevenly distributed external loads allows you to make the appropriate calculations sediment grounds again-personal view of the embankments and other structures. The influence of the full adhesion of soil with the lateral surface of foundations on the amount of pressure on their soles and, consequently, on the amount of precipitation is estimated.

The results of the research were applied in the calculation of the sediment foundations of several residential and industrial buildings in Barnaul and Novosibirsk, in the company «ProektStroj» (Novosibirsk), etc.

6. Conclusions
The stress-deformed state of half-loaded that was imported by the uniform load, is quite different at same values of $E_z$ and various $\alpha < 1$. At $\alpha = 0,13$ difference in $\sigma_z$ the subjecting to stress can be double, $\sigma_x$ can be seven- or tenfold at separate points of the half-plane. If $\alpha > 1$ anisotropy influence on the stress state of the half-plane is significant less than at $\alpha < 1$. The influence of $\alpha_1$ on the stress state of the half-plane is relatively insignificant in many cases. When $E_z = \text{const}$ and $\alpha < 1$ vertical half-plane’s displacement is less, and if $\alpha > 1$ more than at $\alpha = 1$.

The stress components $\sigma_z$, $\sigma_x$ and $\tau_{zx}$ obtained by the calculation are sufficient for a complete assessment of the stress state of the half-plane and for revealing the tendency to hardening or destruction of the anisotropic medium in each of the considered zones I - III with index in the anisotropy $\alpha$.

References
[1] Aliev M M and Geniev G A 2001 Calculation of the bearing capacity of anisotropic structures bases News universities. Construction (Novosibirsk) 6 18–22
[2] Artem’ev I T 1991 Some basic questions of the theory of anisotropic ideally plastic media (Cheboksary) p 35
[3] Batugin S A 1988 Anisotropy of the rock mass (Novosibirsk: Nauka) p 86
[4] Bugrov A K and Golubev A I 1993 Anisotropic soils and foundation structures (SPb.: Nedra) p 245
[5] Vinokurov E F, Kuz’mickij V A, Byhovcev V E and SHulika L G 1973 Computer-aided calculation of elastic anisotropic bases Proc. to the VIII International Congress (Moscow: Strojizdat) pp 220–224
[6] Vinokurov E F and Mikulich V A 1975 Investigations of the stress-strain state of inhomogeneous and layered soil bases Proc. of the Institute of Construction and Architecture. Foundations and foundations 5 34–37
[7] Vinokurov E F 1977 Investigations of the stress-strain state of inhomogeneous and layered soil bases Proc. of the Institute of Construction and Architecture. Foundations and foundations (Minsk: Gosstroi BSSR) 16 3–9
[8] Vinokurov E F 1977 The current state and problems of calculating complex soil bases Interniversity collection (Novocherkassk) pp 3–11
[9] Vinokurov E F, Mikulich V A and Taleckij V V 1989 About the definition of constant ratios of elasticity of an anisotropic alluvial soils Bases and foundations (Kiev) 22 21–5
[10] Krivorotov A P and Korobova O A 1987 Influence of the deformation anisotropy of the soil on the sediments of rig-id foundations Information sheet on scientific and technical achievements (Novosibirsk) 87-19 p 5

[11] Pisanenko V P 1977 About clay soil deformation anisotropy of the Novosibirsk’s Ob area Proc. of the Novosibirsk Institute of railway engineers (Novosibirsk) 180 80–83

[12] Vinokurov E F 1972 Iterative method of calculation of bases and foundations using a computer (Minsk: Science and technology) p 248

[13] Vinokurov E F and Mikulich V A 1975 Investigation of the stress-strain state of the buried strip Foundation by the finite element method Bases, foundations and soil mechanics 5 35–37

[14] Voznesensky V A 1981 Statistical methods of planning experiments in technical and economic research Finance and statistics (Moscow) 1 263

[15] Montgomery D K 1980 Experiment planning and analysis data's (Leningrad: Shipbuilding) p 384

[16] Korobova O A and Maksimenko L A 2015 Improvements to the calculation sediment of soil bases Interexpo Geo-Siberia: Sat. materials XI Intern. Scientific Conf. 13-25 April 2015 (Novosibirsk: SSUGT) 1 194–199

[17] Korobova O A and Maksimenko L A 2016 Methods for improving the calculation of sediments of soil bases (Novosibirsk: SSUGT) Interexpo Geo-Siberia: Sat. materials XII Intern. Scientific Conf. 18-22 April 2016 2 125–131

[18] Korobova O A 2002 A comprehensive study of the stress state and of deformability of anisotropic soil bases (Barnaul: AltGTU) p 341

[19] Korobova O A and Birjukova O A 2012 Laboratory investigations of deformation anisotropy of soils during engineering-geological surveys Engineering survey (Moscow) pp 24–32

[20] Golubev A I 1983 On the limit stress state of anisotropic soils News VNIIG 165 37–40

[21] Korobova O A, Maksimenko L A and Shesternyova A A 2017 On the problem of predicting the limit stress state of anisotropic soil bases News universities. Construction 7 21–28