Sequence of calculation of anisotropic soil foundations on deformation

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Abstract. The article presents the sequence of calculation of ground bases for deformations, taking into account their deformation anisotropy. The calculations were performed by the finite element method using the mathematical planning of the experiment. It is established that after determining the index of the deformation anisotropy of the soil, you can use the results of the numerical experiment and the tables of the coefficients of the soil anisotropy influence, calculate the sediment of the soil base and layers of different thickness by any of the currently existing methods, taking into account their deformation anisotropy. It was revealed that the nature of the deformation anisotropy of the studied soil types is different. With an increase in the compressive load, the values of \( \alpha \) increase, and with an increase in \( \alpha \) value, the values of the sediment of the foundations increase as well. Taking into account the natural anisotropy of soils makes it possible to more reasonably prescribe the dimensions of the base of the foundations and determine their draft, and in some cases obtain a noticeable economic effect.

1. Introduction

One of the most important issues in the study of stress-strain state is the question of taking into account the deformation anisotropy of soils in the calculations of the grounds. Since numerous studies indicate that all natural non-rocky soils have the property of deformation anisotropy, the degree and nature of which are quite different: they are clearly expressed in a layered or columnar texture (for example, in compacted bulk soils, loess soils, etc.) and less in sandy and clay soils of natural composition.

Regulatory documents for the calculation of ground bases recommend [1] to take into account the anisotropy of soils, which is often associated with difficulties in the absence of simple and effective methods for accounting for deformation anisotropy, as well as determine the design parameters of anisotropic soil. 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 of anisotropic soil bases.

The development of a reliable apparatus for calculating soil foundations acquires particular relevance at the present time when the available data on the stress-strain state (SSS) of soil foundations mainly confirm the provisions of the calculation methods described in [1]. However, in some cases it is necessary to adjust the standard methods for calculating the sediment of the ground.
basis of foundations. An important issue in the study of SSS is the consideration of deformation anisotropy in the calculations of ground massifs, which is recommended to take into account modern regulatory documents on the calculation of ground bases [1].

2. The relevance of research
The actual problem of modern construction is the reliable prediction of the SSS of the soil foundations, which makes it possible to make fuller use of the opportunities that they possess. That is, to obtain the most economical options for foundations and structures from the ground while ensuring sufficient safety during their operation, which is possible on the basis of conducting comprehensive studies. Computational models can be considered reliable and economical only if they sufficiently fully reflect the real properties of soils and the phenomena occurring in the soil under the action of external loads. The development of a reliable theory of calculating soil grounds is of particular relevance now, when many buildings and structures for some reason or other are in disrepair and require repair or reconstruction. It should be noted that the study of deformation anisotropy, both experimental and theoretical, including using computers, is the work of many authors [2-10], etc. The successful solution of this task is to develop mechanisms for correcting the method for calculating the sediment of foundations based on the use of the linearly deformable half-space scheme according to [1], which so far has not been done.

3. Formulation of the problem
To achieve this goal, the following tasks were set:

- to study the status of the issue of taking into account the factor of the deformation anisotropy of the soil in the study of the stress-strain state of the soil bases;
- experimentally investigate externally homogeneous non-rocky and loess-like subsidence soils in order to identify the degree of deformation anisotropy and the nature of their deformability;
- develop a theoretical design unit (applied to the finite element method) for studying the SSS of a wide range of anisotropic soils using the theory of mathematical planning of an experiment;
- to study the effect of deformation anisotropy on the magnitude and nature of the distribution of stresses and strains of linearly deformable bases in the form of layers of different thickness (and half-plane) under the action of uniform and non-uniform band loads and hard (non-buried and submerged) punches, with the implementation of the above tasks on a computer;
- assess the effectiveness of taking into account the deformation anisotropy of the soil in the calculations of the bases;
- to develop recommendations for the calculation of sediment foundations taking into account the deformation anisotropy of soils;
- to introduce the results of experimental and theoretical studies in the practice of design.

4. Theoretical part
The algorithm developed by the authors for taking into account the deformation anisotropy in calculating the soil bases consists of four main stages. At the first stage (preparatory), soil is sampled from the monolith or directly at the construction site in two mutually perpendicular directions: perpendicular and parallel to the bedding (Figure 1).

[Figure 1. Scheme of soil sampling (a - vertical position of the rings; b – side).]
Soil samples were taken from the sites presented in Table 1.

Table 1. Characteristics of the studied soils.

| No | Name of soil | \(\gamma\) kN/m³ | \(W\), % | \(I_p\), % | \(I_l\), % | Location of sample ground |
|----|--------------|----------------|--------|----------|---------|-------------------------|
| 1  | Silt sandy fluid loam | 18.7 | 31 | 4 | 1.2 | Kemerovo city, plant "Himvolokno" |
| 2  | Soft sandy loam | 17.2 | 38 | 6 | 1.0 | Kemerovo city, plant "Siblitmash" |
| 3  | Soft sandy loam (plain deformation \(\sigma_1 = \sigma_3\)) | 17.7 | 18 | 6 | 0.6 | Novosibirsk city, Leninskiy region |
| 4  | Soft sandy loam | 19.2 | 18 | 3 | 0.4 | Novosibirsk city, Dzerzhinskij region |
| 5  | Solid sandy loam | 17.4 | 18 | 1 | 0 | Novosibirsk city, Opera theatre |
| 6  | Light loam, silty, semi-hard | 17.5 | 20 | 13 | 0.1 | Kemerovo city, plant "Himvolokno" |
| 7  | Dense sand | 17.2 | 3 | — | — | Novosibirsk city, Kirovskij region |
| 8  | Sand of middle density | 18.2 | 9 | — | — | Novosibirsk city, Oktjabr’skij region |
| 9  | Sand of middle density \((\sigma_1 = \sigma_3)\) | 15.6 | 3 | — | — | Novosibirsk city |
| 10 | Sand of middle density \((\sigma_1 = \sigma_2 = \sigma_3)\) | 15.6 | 3 | — | — | Novosibirsk city |
| 11 | Dense sand \((\sigma_1 = \sigma_3)\) | 18.0 | 3 | — | — | Novosibirsk city |
| 12 | Sand dense \((\sigma_1 = \sigma_3)\) | 18.0 | 3 | — | — | Novosibirsk city |
| 13 | Clay loam, tamped with heavy load (weight 10 tons) | 19 | 16 | 10 | <0 | Barnaul, 2001 block |
| 14 | Loam, light, solid, subsiding | 15.5 | 6 | 10 | <0 | Barnaul, 2001 block |
| 15 | Sandy loam, silty, solid, subsiding | 21.4 | 10 | 2.5 | <0 | Barnaul, House of models |
| 16 | Sandy loam, silty, solid, subsiding | 20.3 | 15 | 6 | <0 | Barnaul |
| 17 | Clay loam, solid, subsiding | 17.4 | 19 | 11 | <0 | Barnaul, River station |
| 18 | Clay loam, solid, subsiding | 17.2 | 18 | 7.5 | <0 | Novosibirsk region |
| 19 | Clay loam, solid, subsiding | 17.1 | 15 | 13 | <0 | Novosibirsk city region |
| 20 | Clay loam, solid | 17.0 | 18 | 11 | <0 | Novosibirsk city region |

Then, at the second stage (experimental) in the laboratory, samples are tested according to the existing standard methods. In our case, the deformations of soil samples 1–8, as well as 13–20 (Table 1) in the vertical and horizontal directions were determined in the compression conditions - in the compactors of the “Hydroproject” system. Soils 9 and 11 (Table 1) were tested in the PTS of the system of A. Kryzhanovsky (a device of triaxial compression with independent control of variables of the main stresses) (plane strain) with the equality of the main stresses \(\sigma_1 = \sigma_3\) \((\sigma_2 = \sigma_3)\), acting in the plane of the samples deformation. Before the start of the experiment, soil 9 was compacted by vibration, and soil 11 was compacted by manual tamping. Soils 10 and 12 (Table 1) were investigated under conditions of hydrostatic stress state of the samples, i.e. under the action of main stresses \(\sigma_1 = \sigma_3\) \((\sigma_2 = \sigma_3)\).
\( \sigma_2 = \sigma_3 \). In this case, the assessment of the degree of deformation anisotropy of soils was carried out by comparing the values of deformation in two mutually perpendicular horizontal directions. When analysing the obtained results, it became possible to estimate the degree of deformation anisotropy of soils by the anisotropy index \( \alpha = s_x/s_z = \varepsilon_x/\varepsilon_z \), where \( s_x \) and \( s_z \), \( \varepsilon_x \) and \( \varepsilon_z \), are absolute and relative deformations in the vertical and horizontal direction, respectively, and for soils 10, 12, this estimate was made with respect to \( s_x/s_y \) (along the mutually perpendicular horizontal directions \( y \) and \( x \)).

Indicators of anisotropy \( \alpha \) of the studied soil types are given in Table 2, with indicators \( \alpha \) varying from 0.5 to 2.1, i.e. are practically palpable. Conducted research of sands and clay soils expanded the area of soils with the established deformation anisotropy. Clay soils of Novosibirsk, previously investigated by V.P. Pisanenko [11-13] was characterized by the values \( \alpha = 1.43 \) (loams) and \( \alpha = 1.24 \) (sandy loams). From the analysis of the results obtained, we can conclude that the nature of the deformation anisotropy of the studied soil types is different - for plastic sandy loams 1–3, the indicator is \( \alpha \leq 1 \); for loessy sandy loams and loams 4-6, as a rule, \( \alpha > 1 \); for sands 7, 8 medium density and dense, tested under compression, \( \alpha < 1 \). As the compressive load increases, the values \( \alpha \) increase. Sand of average density in these conditions exceed one, and dense sand - less than one. With an increase in the level of acting stresses under conditions of plane deformation and hydrostatic compression of dense sand of average density, the character of anisotropy does not change. Under flat deformation conditions, the indicator \( \alpha \) is less than under hydrostatic compression conditions. Indicators \( \alpha \) of the sand of medium density in these conditions exceed 1, and of dense sand – lower than 1.

### Table 2. Indicators of anisotropy of the studied soils (1-12), calculated from the averaged values of sample deformations.

| № of soil (Table 1) | Values \( \alpha = s_x/s_z \) in stresses \( \sigma_z = \sigma_1 \), MPa | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | \( \alpha_{avg.} \) (0.05-0.30) |
|---------------------|-------------------------------------------------|------|------|------|------|------|------|------------------|
| 1                   | 1.04                                            | 1.07 | 1.06 | 1.05 | 1.02 | 0.98 | 1.04            |
| 2                   | 0.50                                            | 0.65 | 0.70 | 0.71 | 0.81 | 0.83 | 0.7             |
| 3                   | 0.57                                            | 0.69 | 0.74 | 0.69 | —    | —    | 0.67            |
| 4                   | 1.65                                            | 1.43 | 1.47 | 1.60 | 1.54 | 1.43 | 1.53            |
| 5                   | 2.15                                            | 2.27 | 2.35 | 2.34 | 1.92 | 1.82 | 2.1             |
| 6                   | 1.60                                            | 1.37 | 1.32 | 1.39 | 1.48 | 1.48 | 1.4             |
| 7                   | 0.58                                            | 0.65 | 0.71 | 0.78 | 0.86 | 0.88 | 0.74            |
| 8                   | 0.75                                            | 0.90 | 1.05 | 1.13 | 1.47 | 1.47 | 1.13            |
| 9                   | 0.10                                            | 0.20 | 0.30 | 0.40 | 0.50 | 0.60 | (0.10-0.60)     |
| 10                  | 1.30                                            | 1.36 | 1.43 | 1.50 | 1.42 | 1.41 | 1.36            |
| 11                  | 1.15                                            | 1.34 | 1.44 | 1.39 | 1.44 | 1.34 | 1.32            |
| 12                  | 0.49                                            | 0.57 | 0.66 | 0.62 | 0.67 | 0.69 | 0.58            |
|                     | 0.70                                            | 0.50 | 0.52 | 0.50 | 0.48 | 0.48 | 0.52            |

The degree of deformation anisotropy can be estimated not only by the ratio of the deformations of the soil samples in orthogonal directions. Also by comparing the values of the deformation modules in two mutually perpendicular directions \( \alpha = E_z/E_x \) taking into account the different values of Poisson's coefficients (coefficients of lateral expansion of the soil); where \( E_z \) and \( E_x \) - deformation modules in vertical and horizontal directions (\( \alpha \) - further on the indicators of anisotropy).

At the third stage (numerical experiment), numerical studies of SSS of the anisotropic soil foundations [14], are carried out on a computer (on various software packages based on the ideas of the finite element method) using the mathematical planning of the experiment. In this case, a model of a continuous, linearly deformable, homogeneous, anisotropic substance with a transversely isotropic anisotropy [15] is considered. In the calculations, a model of an anisotropic soil foundation was used, described by parameters \( E_x, E_z, \nu_{xz}, \nu_{yx}, G_{xz} \). When applying the methodology of mathematical
planning [16], [17] of an experiment, the influence of each of the anisotropy parameters on the response (stress) functions was evaluated [18]. The factors varying at three levels were $E_x$, $E_z$, $v_{xz}$, $v_{yx}$, $G_{xz}$. The levels and range of variation are shown in Table 3.

**Table 3. Variation of parameters of the deformation anisotropy of the substance.**

| Variation factors | $x_i$ | Variation levels | Variation interval |
|-------------------|------|------------------|--------------------|
| $E_x$, MPa        | $x_1$| lower -1 0 upper 1| 17.5               |
| $E_z$, MPa        | $x_2$| 5 22.5 40         | 17.5               |
| $v_{xz}$          | $x_3$| 0.25 0.30 0.35    | 0.05               |
| $v_{yx}$          | $x_4$| 0.25 0.30 0.35    | 0.05               |

As a result of numerical studies, arrays of values were obtained $\sigma_{xz}$, $\sigma_{x}$, and $\tau_{xz}$ stresses for anisotropic substance and the corresponding values of stresses $\sigma_{z}$, $\sigma_{x}$, and $\tau_{xz}$ isotropic variant ($\alpha = 1.0$). At the fourth stage (calculation of correction coefficients), when comparing the results of calculating the stress-strain state of uniformly anisotropic and isotropic bases in the form of different power and half-plane layers, a method was developed that takes into account the deformation anisotropy of the base soils with the help of soil anisotropy coefficients [19]. These coefficients show what proportion of the stress in an isotropic substance is the corresponding stress in the anisotropic one. The values of the coefficients are calculated by the formula:

$$K_{\alpha} = \frac{\sigma_{a}}{\sigma_{z}}$$

$K_{\alpha}$ - soil anisotropy correction coefficients; $\sigma_{a}$ - vertical and horizontal stresses for anisotropic substance; $\sigma_{z}$ - the same thing for isotropic one.

The stresses $\sigma_{xz}$ and $\sigma_{x}$ are calculated for characteristic points of the soil mass located on the central and angular verticals of the loaded surface area, in accordance with the requirements of [1]. Correction factors of the soil anisotropy can be used to adjust the sediment values of the foundations, calculated by any of the currently existing methods [1]. The obtained data are sufficient for calculating the sediment of foundations located on the surface of a half-plane or layers of different thickness. The coefficients $K_{\alpha}$ and $K_{\alpha'}$ are calculated for the midpoints of the horizontal layers assigned under the basement footing according to [1] through $0.4b$ ($b$ is the width of the loaded base portion equal to the width of the basement footing). An improved practical method of accounting for deformation anisotropy can be recommended for the introduction into practice of designing foundations for buildings under construction, reconstruction and rehabilitation, as well as for the construction of high-rise and large-span buildings and structures in difficult ground conditions. The coefficients determined for the angular vertical points are necessary for calculating the sediment taking into account the influence of loads from the neighboring foundations. The values of the correction factors for the stresses $\sigma_{z}$ (central and angular verticals) are given in Tables 4-5.

**Table 4. Values of correction coefficients for stresses $\sigma_{z}$, central vertical (band load).**

| Relative digging-in | correction coefficients $\alpha = 0.222$ | SIGMA 1 | Vertical 1 |
|---------------------|-----------------------------------------|---------|-------------|
|                     | Calculated values of correction coefficients for: |         |             |
| 0.2b                | 0.6b                                    | 1.0b    | 1.4b        |
| 1.8b 2.2b 2.6b 3.0b | 3.4b 3.8b 4.2b 4.6b 5.0b 5.4b 5.8b 6.2b |         |             |
| 1-250               | 0.9 0.75 0.66 0 0 0 0 0 0 0 0 0 0 0 0 |         |             |
| 2-500               | 0.9 0.76 0.66 0.6 0.57 0.55 0 0 0 0 0 0 0 0 0 |         |             |
| 3-750               | 0.9 0.77 0.67 0.62 0.58 0.56 0.55 0.53 0.52 0 0 0 0 0 0 |         |             |
| 4-700               | 0.9 0.78 0.68 0.62 0.6 0.58 0.58 0.58 0.58 0.58 0.58 0.58 0 0 0 0 |         |             |
| 6-560               | 0.9 0.78 0.68 0.62 0.6 0.61 0.61 0.62 0.64 0.66 0.68 0.7 0.72 0.75 0.77 0.77 | | |
Correction coefficients \( \alpha = 0.562 \)  

| Relative digging-in | Sigma 1 | Vertical 1 |
|---------------------|---------|------------|
| 0.2b 0.6b 1.0b 1.4b 1.8b 2.2b 2.6b 3.0b 3.4b 3.8b 4.2b 4.6b 5.0b 5.4b 5.8b 6.2b |
| 0.97 0.93 0.89 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.97 0.93 0.89 | 0.86 | 0.85 | 0.84 | 0.82 | 0.82 | 0.81 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.97 0.93 0.89 | 0.86 | 0.85 | 0.84 | 0.84 | 0.83 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 | 0 | 0 | 0 | 0 | 0 |
| 0.97 0.93 0.89 | 0.87 | 0.86 | 0.85 | 0.85 | 0.85 | 0.85 | 0.86 | 0.86 | 0.86 | 0.86 | 0.87 | 0.88 | 0.88 | 0.88 |

Correction coefficients \( \alpha = 1.778 \)  

| Relative digging-in | Sigma 1 | Vertical 1 | Central vertical \( \sigma_z \) |
|---------------------|---------|------------|-----------------------------|
| 0.2b 0.6b 1.0b 1.4b 1.8b 2.2b 2.6b 3.0b 3.4b 3.8b 4.2b 4.6b 5.0b 5.4b 5.8b 6.2b |
| 1.02 1.06 1.09 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.02 1.05 1.09 | 1.11 | 1.13 | 1.14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.02 1.05 1.09 | 1.11 | 1.13 | 1.14 | 1.15 | 1.16 | 1.16 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.02 1.06 1.09 | 1.11 | 1.13 | 1.14 | 1.15 | 1.16 | 1.17 | 1.17 | 1.17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Correction coefficients \( \alpha = 4.500 \)  

| Relative digging-in | Sigma 1 | Vertical 1 | Central vertical \( \sigma_z \) |
|---------------------|---------|------------|-----------------------------|
| 0.2b 0.6b 1.0b 1.4b 1.8b 2.2b 2.6b 3.0b 3.4b 3.8b 4.2b 4.6b 5.0b 5.4b 5.8b 6.2b |
| 1.04 1.12 1.21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.04 1.12 1.21 | 1.28 | 1.32 | 1.35 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.04 1.12 1.21 | 1.28 | 1.32 | 1.35 | 1.37 | 1.38 | 1.39 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.04 1.12 1.21 | 1.27 | 1.31 | 1.34 | 1.36 | 1.37 | 1.38 | 1.38 | 1.38 | 1.37 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 5. Values of correction coefficients for stresses \( \sigma_z \), angular vertical (band load).
Correction coefficients $\alpha = 4.500$  

| Relative digging-in | SIGMA 1 | Vertical 2 |
|---------------------|---------|------------|
| 1-250               | 1,02    | 1,09       |
| 2-500               | 1,02    | 1,09       |
| 3-750               | 1,02    | 1,09       |
| 4-700               | 1,02    | 1,09       |
| 6-560               | 1,02    | 1,09       |

5. Results

The application of the stated method of calculating the sediment basement is appropriate when taking into account the influence of neighboring foundations, as well as for the calculation of the sediment layer of final thickness. Accounting for the anisotropy of soils further aggravates the negative effects caused by imbalance in the modes of nature. Accounting for anisotropy is also needed when solving the problem of disposal and storage of various types of waste, since a characteristic feature of all its forms (landfills, dumps, storages, etc.) is their heterogeneity in density, composition and, as a result, in strength and deformability.

In these cases, a significant manifestation of anisotropy should be expected.

It was also established that in those cases when the base has an indicator of deformation anisotropy $\alpha < 1$, the values of the design resistance of the base soil $R$ increase, which leads to a decrease in the size of the bottom of the foundations and to obtain a known economic effect. When $\alpha > 1$, an increase in the size of the sole is required compared with that established in accordance with SP 22.13330.2016 [1]. Studies have shown that the use of an isotropic model for the calculation of soil bases leads to a distortion of the actual picture of the stress-deformable base.

The effect of the deformation anisotropy on the value of the predicted sediment, even with poorly pronounced anisotropy of conventional soils, is estimated to be $10-40\%$ of the calculated settlement of the foundation, located on an isotropic base. The data obtained can be used in the calculation of bases for the deformations in the superstructure of buildings and structures, taking into account that for anisotropic soils an indicator of deformation anisotropy $\alpha = 1$ calculation by the method of SP 22.13330.2016 [1] leads to an overestimated sediment value. Also with such methods of strengthening the foundations, such as the broadening of the bottom of the foundation, the device clips, shirts, extensions, etc.

For soils characterized by indicator of deformation anisotropy $\alpha > 1$, the traditional calculation gives a decrease in the sediment value, and if we consider that the influence of deformation anisotropy is especially great for such soils, since these are usually soils having a layered or columnar texture, then neglect this fact during the reconstruction is unacceptable. Deformation anisotropy must be taken into account when converting columnar foundations into strip foundations, as well as when transferring foundations to piles, since all of the above is also true for calculating pile foundations and their foundations by deformations. It is also necessary to take into account the deformation anisotropy when calculating the settlement of the foundations during the construction of a new building near the existing one. For weak soils of the base, an increase in the calculated precipitation due to the consideration of the deformation anisotropy may be unacceptably large, especially from the point of view of the non-uniformity of the sediment of neighboring foundations.

The research results were implemented when calculating the sediment foundations of the “House of Models” in Barnaul, the “Khimvolokno” enterprise in Kemerovo, several industrial and administrative buildings in Novosibirsk, in LLC “STROYDOR 2015” in Novosibirsk, in LLC “IID” in Novosibirsk and others.
6. Conclusions

Thus, the proposed improved practical method for calculating soil bases for deformations makes it possible to more accurately and reasonably calculate the settlement of foundations, taking into account their real properties [20,21]. The developed tables of correction factors for the effect of soil anisotropy can be recommended for calculating the sediment of foundations taking into account the deformation anisotropy according to [1].

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