Recommendations accounting for anisotropy in the calculation of soil bases

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Abstract. The article contains recommendations prepared for "SP 22.13330.2016" foundations of buildings and structures", where it is proposed to apply and take into account the deformation anisotropy in the calculations of ground bases. Consideration of deformation anisotropy is possible if there are reliable methods for predicting the stress-strain state (VAT) of soil bases. The existing calculation methods are based on the application of linear deformable medium theories. Over time, it becomes clear that the main provisions of the linear elasticity theory you can use it to describe underground areas, but with large adjustments, which leads to the development of new computational methods that take into account the deformation anisotropy.

1. Introduction
One of the main problems of modern construction is reliable and competent forecasting of the VAT of soil bases. This, in turn, will allow you to get the most economical and safe in operation foundations, which is directly related to the creation of reliable calculation models that fully reflect the real properties of the Foundation soil when exposed to various types of external loads.

The developed recommendations are intended for determining the calculated soil resistance R under the Foundation sole and determining the size of the Foundation sole, taking into account the anisotropy of the soil. The recommendations are developed for calculating the precipitation of inflexible foundations based on known methods for determining deformations. This approach provides a more reasonable way to assign Foundation dimensions and determine their precipitation. It is possible to get an economic effect.

2. The relevance of research
Highly important to take into incorporate all the factors that actually affect the soil mass in research. This issue is an example of discussion and discussion. This is evidenced by the work [1-8] and so on, which involve both theoretical and experimental results with studies of the anisotropy of the deformation of the base soil.

Solvability of this problem is to develop mechanisms for regulating the size of the sole and a method for calculating the Foundation precipitation based on the scheme of linear-deformable half-
space, according to SP 22.13330.2016. Creating a reliable method for calculating soil bases is especially important at the present time, if necessary, adjust known methods.

3. Formulation of the problem
The authors of the article suggest a step-by-step approach to account for deformation anisotropy. Make a preliminary sampling. Samples are taken from the monolith. Sampling is also possible at the construction site. There is a special sampling procedure. This procedure consists of sampling in mutually perpendicular directions. Direction 1 is perpendicular to the layering. Direction 2-parallel to the layering. In the second step (experimental), samples are tested in the laboratory using existing standard methods. At the third step (numerical experiment), numerical studies of the properties of anisotropic soil bases [9-10] are performed on a computer (different programs implemented using the finite element method) using methods planning of the experiment. At the fourth stage, the correction coefficients necessary to account for the deformation anisotropy in the calculation of Foundation precipitation are calculated.

4. Theoretical part
At the first stage (preparatory), the grunt samples are taken. Characteristics of the studied soils and their selection sites are shown in table 1.

At the second step (experimental), they are tested under laboratory conditions using existing standard methods. Deformation of samples 1-8 and 13-20 (see table. 1) was determined in the device of the "Hydroproject" system. Samples 9 and 11 (see table. 1) were tested in a three-axis compression device of the A. L. Kryzhanovsky system. The tests were performed when the main stresses $\sigma_1 = \sigma_3 (\sigma_z = \sigma_x)$ acting in the plane of deformation of the samples were equal. Sample 9 was compacted by vibration, and sample 11 was manually rammed. Samples 10 and 12 (see table.1) were studied under hydrostatic stress conditions.

The degree of deformation anisotropy of soils was estimated according to the experimental data. The values of deformations in two mutually perpendicular directions were compared. Thus, the index of soil deformation anisotropy was calculated. The anisotropy index $\alpha$ shows the level of soil anisotropy.

The anisotropy index is calculated by the ratio $\alpha = s_x/s_z = e_x/e_z$. The forecast $s_x$ and $s_z$, $e_x$ and $e_z$ are absolute and relative deformations in the vertical and horizontal directions respectively. For samples 10 and 12, the anisotropy index was estimated with respect to $s_x/s_z$.

The conducted research of sandy and clay soils allowed us to expand information about soils with defined deformation anisotropy. In previous studies (V. p. Pisanenko [7]), the values of the anisotropy index $= 1.43$ (loam) and $= 1.24$ (sandy loam) were obtained.

The accumulated database of experimental data allows us to assert that the indices of anisotropy deformation soil’s are different.

For plastic loam 1-3 the anisotropy index $\alpha=1$. for loess-like loams and loams 4-6 the anisotropy index $\alpha>1$. For Sands 7, 8 of medium density and dense, tested under compression conditions, the anisotropy index $\alpha<1$. As the compressive load increases, the anisotropy indexes $\alpha$ the score increases. For the specified conditions, the index $\alpha >1$, for the medium-density sands. Under these circumstances, the index $\alpha<1$, for dense sands.

The degree of anisotropy is estimated by the formula $\alpha = E_z/E_x$ [9], taking into account different Poisson’s coefficients. Ez and Ex are the modulus of deformations in mutually perpendicular directions.

The indicator of deformational anisotropy $\alpha = E_z/E_x = e_x/e_z$ is established based on the results of compression check of standard soil samples.

The ECI forecast of $e_z$ can be determined by testing samples in a stabilometer. The forecast of the Poisson coefficient $e_{xz}$ are taken from the tables. These values are equal to: for sand-0.25; sandy loam-0.30; loam-0.35 and clay-0.40.
### Table 1. Kinds of the studied soil.

| №  | Name ground                        | $\gamma$, kH/M$^3$ | $W$, % | $I_p$, % | $I_l$, th. | The sampling site                  |
|----|------------------------------------|-------------------|--------|----------|------------|-----------------------------------|
| 1  | Flowing powdery sandy loam         | 18,7              | 31     | 4        | 1,2        | Kemerovo                          |
| 2  | Lamellar powdery sandy loam        | 17,2              | 38     | 6        | 1,0        | Kemerovo                          |
| 3  | Lamellar powdery sandy loam (plane strain $\sigma_1 = \sigma_3$) | 17,7              | 18     | 6        | 0,6        | Novosibirsk, Leninsky district    |
| 4  | Plate sand sandy loam              | 19,2              | 18     | 3        | 0,4        | Novosibirsk                       |
| 5  | Hard sand sandy loams              | 17,4              | 18     | 1        | 0          | Novosibirsk Opera and Ballet Theatre |
| 6  | Semi-hard silty light clay         | 17,5              | 20     | 13       | 0,1        | Kemerovo                          |
| 7  | Sands dense                        | 17,20             | 3,0    | —        | —          | Novosibirsk, construction pit     |
| 8  | Medium density Sand                | 18,20             | 9,0    | —        | —          | Novosibirsk                       |
| 9  | Medium density Sand ($\sigma_1 = \sigma_3$) | 15,60             | 3,0    | —        | —          | Sites in the Novosibirsk          |
| 10 | Medium density Sands ($\sigma_1 = \sigma_2 = \sigma_3$) | 15,60             | 3,0    | —        | —          | Novosibirsk                       |
| 11 | The sands is dense ($\sigma_1 = \sigma_3$) | 18,00             | 3,0    | —        | —          | Sites in the Novosibirsk, region  |
| 12 | Sand is air-dry, Dense             | 18,01             | 3,0    | —        | —          | Sites in the Novosibirsk          |
| 13 | The loam is hard, compacted with a heavy rammer (9-11 t) light, dusty solid loess-like, subsidence Loams | 19,01             | 16     | 10       | < 0        | Barnaul, 2001 quarter            |
| 14 | Solid loams, subsidence            | 15,5              | 6      | 10       | < 0        | Barnaul, 2001 quarter            |
| 15 | Sandy loams Solid, subsidence      | 21,4              | 10     | 2,50     | < 0        | Barnaul, fashion Studio           |
| 16 | Sandy loam Solid, subsidence       | 20,3              | 15     | 6,0      | < 0        | Barnaul                           |
| 17 | Solid loam, subsidence             | 17,4              | 19     | 11,0     | < 0        | Barnaul, the site of river station |
| 18 | Solid loams, subsidence            | 17,20             | 18     | 7,50     | < 0        | Sites in the Novosibirsk region   |
| 19 | Solid loam, subsidence             | 17,10             | 15     | 13,0     | < 0        | Novosibirsk, region               |
| 20 | Solid loam                         | 17,00             | 18     | 11,0     | < 0        | Novosibirsk, region               |

At the third stage (numerical experiment), numerical studies of the properties of anisotropic soil bases are performed [10].

Research is carried out on a computer (on various software systems based on the ideas of the finite element method) play the methods of planning of the experiment. The model of anisotropic soil base is presented by the parameter notation $E_x$, $E_z$, $\nu_{zx}$, $\nu_{xz}$, $G_{xz}$.

When applying the method planning of the experiment [3], the influence of each parameters on the response (stress) functions was estimated [10]. Encompassing of changes in the parameters of the deformation anisotropy of the medium are given in work [11-13].

In the course studies were obtained arrays of forecast of voltages $\sigma_{zx}$, $\sigma_{xz}$ and $\tau_{zx}$ for anisotropic media. The stress values $\sigma_x$, $\sigma_z$, and $\tau_{zx}$ of the isotropic variant ($\alpha = 1,0$) were also obtained.

The stress and strain state of a transversally isotropic half-plane (layer) is recommended to be founded on the results of calculations done by the finite element method. For the calculation, set the assessment of the soil medium deformation modules $E_z$ and $E_x$ in mutually perpendicular directions. For the computation, the Poisson coefficients $\nu_{zx}$ and $\nu_{xz}$ are set, assuming $\nu_{zx} = \nu_{xz}$, where the first sign
characterizes the lateral expansion of the soil in the isotropy plane and the second sign characterizes the growth in the vertical direction from normal horizontal stresses. Set the shear modulus $G_{xz}$ in the vertical plane of deformation and the value $\nu_{zx} = \nu_{xz} \left( \frac{E_z}{E_x} \right)$.

It is recommended to determine the deformation modulus $E_z$ using known methods (SP 22.13330.2016). The values of the shift modulus $G_{xz}$, it is recommended to calculate by dependence:

$$G_{xz} = \frac{E_{zp}}{2(1 + \nu_{zp})}$$  \hspace{1cm} (1)

The finite element method calculates all the stress components of the elements forming the zone of the ground base located under the face of the loaded section of the half-plane surface. The load is uniform, the spreading depth is equal to a quarter of the width of the loaded section. The values of the main stresses $\sigma_1$ and $\sigma_3$ and the value of the angle of greatest deviation $\theta_{\text{max}}$ are found. Calculated average values for the zone.

The calculations are made under the assumption $\nu_{yx} = \nu_{xz} = \text{const} \ (0.3)$. The value of $\theta_{\text{max}}$ is set according to the known dependence of the stress theory:

$$\sin \theta_{\text{max}} = \frac{(\sigma_1 - \sigma_3)}{\sigma_1 + \sigma_3 + 2c \cdot \tan \varphi}$$  \hspace{1cm} (2)

Here $\varphi$ and $c$ are the angle of internal friction and the specific force of soil adhesion, respectively; for non-connected soil, $c = 0$.

The limit (for the strength of the soil in the zone under consideration) state will be reached when the condition is met:

$$\sin \theta_{\text{max}} = \sin \varphi (\sin \psi),$$  \hspace{1cm} (3)

where $\psi$ is the shift angle;

$$\tan \psi = \frac{\tan \varphi + c}{\sigma},$$  \hspace{1cm} (4)

where $\sigma$ is the normal direction on the shift pad.

A fixed value of $\varphi$ ($\psi$) for a certain type of ground corresponds to different values of external loads (pressure $p = R$), depending on the anisotropy index $\alpha = E_z/E_x$. The graphs show the change in the pressure value $p_a = R_{\alpha a}$ in the case of an anisotropic base compared to an isotropic one ($p = R, \alpha = 1$), where:

$$E_{zp} = \frac{E_z + E_x}{2},$$  \hspace{1cm} (5)

$$\nu_{zp} = \frac{\nu_{yx} + \nu_{xz}}{2}.$$  \hspace{1cm} (6)

The evaluation of the design resistance of the base $R$ are calculated according to SP 22.13330.2016. At a known value of the external load $N$ at the level of the Foundation sole, the width $b$ of the Foundation the Foundation is installed by dependencies:

$$b = \frac{N}{R},$$  \hspace{1cm} (7)

a for an anisotropic half plane:

$$b_a = \frac{N}{R_a},$$  \hspace{1cm} (8)

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$$b_a = b \frac{R}{R_a}.$$  \hspace{1cm} (9)

The size of the Foundation sole $b$ is set by the usual method and the ratio $R/R_a = p/p_a$ according to the graph, we have corrected determine the value $b_a$. The $R/R_a$ or $b_a/b$ ratios it is estimated as the
effect of accounting for anisotropy. At the fourth stage, a method was proposed that takes into account the deformation anisotropy of the base soil. Accounting is carried out using coefficients of influence of soil anisotropy [11]. The capture of soil deformability in mutually perpendicular directions under the action of vertical $\sigma_{zp,\alpha}$ and horizontal $\sigma_{xp,\alpha}$, taking into account additional stresses, determines the essence of the considered technique.

The computation is delivered for the points of the half-plane that are placed on the Central vertical in the middle of the layers $h_i$:

$$s = \sum E_{z,i} \cdot h_i$$

where:

$$E_{z,i} = \left( \frac{\sigma_{zp,\alpha} - \sigma_{zp}}{E_z} \right) (1 - v_{xy} \cdot v_{xy}) - \frac{\sigma_{zp,\alpha}}{E_z} (1 + v_{xy})$$

The effect of anisotropy can be taken into account most simply by correcting only the stresses $\sigma_{zp,i}$, i.e. by the formula: SP 22.13330.2016: [11].

$$s = \beta \sum (\sigma_{zp,i,\alpha} - \sigma_{zp}) \cdot \frac{h_i}{E_z}$$

It should be remembered that the accuracy of calculating the Foundation precipitation is somewhat reduced.

The thickness (denotation - $h_i$) and the number $n$ of layers are taken in accordance with the updated SP 22.13330.2016.

To calculate additional stresses, select the formula:

$$\sigma_{zp,i,\alpha} = \sigma_{zp,i} \cdot K_{\alpha}$$

$$\sigma_{zp,i,\alpha} = \sigma_{zp,i} \cdot K'_{\alpha}$$

$$\sigma_{xp,i,\alpha} = \sigma_{xp,i} \cdot K^{\alpha}_{xy}$$

$$\sigma_{xy,i,\alpha} = \sigma_{xy,i} \cdot K^{\alpha}_{xy}$$

where $\sigma_{zp}$ ($\sigma_{zp}$) and $\sigma_{xp}$ ($\sigma_{xp}$) at the corresponding points $i$ of the isotropic half-plane. $K_{\alpha}(K_{\alpha})$ and $K'_{\alpha}(K'_{xy})$ - the influence’s coefficients of soil anisotropy [11].

The forecast $K_{\alpha}(K_{\alpha})$ and $K'_{\alpha}(K'_{xy})$ are gained by connecting the stresses calculated by the finite element method at $\alpha = 1$ and $\alpha \neq 1$ and show what part of the stress in the isotropic medium is the respond stress in the anisotropic medium. Similar tables of correction coefficients have been compiled for horizontal stresses $\sigma_{z}$ (Central vertical) and vertical stresses $\sigma_{z}$ (angular vertical) and horizontal stresses $\sigma_{y}$ (angular vertical).

5. Results

The application of the described method for calculating the Foundation sediment is appropriate when taking into account the influence of neighboring foundations, as well as for calculating the precipitation of the final power layer. Consideration of anisotropy is also necessary when solving the problem of utilization and storage of various types of waste. In these cases, it is natural to expect a significant manifestation of anisotropy. It is established that if the index of deformation anisotropy $\alpha < 1$, the values of the calculated resistance of the base soil $R$ increase. This reduces the size of the Foundation sole and to a well-known economic effect. It was found that at $\alpha > 1$, an increase in the size of the sole is required in comparison with those set for SP 22.13330.2016. It is established that for ordinary soils, the effect of deformation anisotropy is estimated within 10-40 % of the calculated precipitation of the Foundation located on an isotropic base. When reconstructing buildings, installing superstructures, and performing additional calculations, the proposed methodology will be used effectively [12]. For anisotropic soils, the anisotropy index $\alpha < 1$ is calculated according to the SP 22.13330.2016 methodology, which does not take into account anisotropy, which leads to lot more
deformation’s values. The traditional calculation gives a decrease in the sediment value, if soils characterized by anisotropy index $\alpha > 1$.

When designing works on reconstruction and renovation of foundations, it is also necessary to perform corrective calculations. Deformation anisotropy can be taken into account when transferring foundations to piles, when building a new building near an existing one.

6. Conclusions

Following the Russian regulatory documents regulating the creation of new, more reliable and high-quality sets of rules for designers and builders, we have found a solution to one of the important problems in the field of calculating soil precipitation. These proposals should be reflected and occupy a corresponding niche in our domestic science. The proposed solution is the most accessible for any user and is designed to help eliminate the current gap. Having a sufficiently large experimental and theoretical base, based on a scientific approach, the results obtained can be considered technically feasible and economically profitable.

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