Numerical simulation of the structures bases stress-strain state taking into account the time factor

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Abstract. The complexity of recent numerical calculations is steadily growing because of the desire to obtain more reliable forecast results taking into account the complex processes of deformation of the ground base in complicated ground conditions and considering the use of modern construction technologies. The phenomenon of creep refers to such complex processes. Its occurrence can be taken into account using a creep-based model, for example Soft Soil Creep, which is a part of the PLAXIS software package. The article provides verification calculations that allow determining the degree of comparability of the samples behaviour in the calculation model and real soil base samples, methods for correcting the results of laboratory tests. An example of a numerical simulation of the construction of an underground structure is given, which shows the significant effect of creep on the deformed state of the substrate after a long period of its operation. Using the example of a single barrette, it was shown that taking creep into account under the lower end leads to a redistribution of the external load along the lateral surface, additional mobilization of frictional forces, which leads to a change in the operation of such an element as a whole.

1. Introduction

At present, there is a constant complication of geotechnical tasks solved within the framework of ongoing projects for the construction of an underground cycle of civil and industrial buildings and structures, special purpose facilities and transport infrastructure. New and often not very simple areas from the point of view of the engineering and geology structure are developed including the overlapping specific soils, the complex arrangement of soil layers, the presence of several water horizons with complex hydrological links, and so on. Modern underground facilities are built with a lot of developed technologies, which made it possible to realize even the most complex and difficult space-planning solutions developed for large depths from the surface.

In general, the solution of the tasks of geotechnics taking into account the time became necessary with the requirements of modern regulatory documents on the calculation of the foundation of structures for deformations. It is necessary to distinguish between primary consolidation, which is a
process of simultaneous soil compaction and outflow of pore water under the influence of excessive pore pressure. Creep refers to secondary consolidation consisting in the appearance of a shear strain of any soil with an unchanged pressure on the base, and also in the absence of a quantitative ratio of the phases per unit volume of the soil. It is known that continuous body with the application of external loads, exhibit the property of deformation in time. The creep time interval can differ by orders of magnitude depending on the material.

Soils when applying loads to them also exhibit the properties of prolonged deformation even in those cases when the pore fluid is removed and the excess pore pressure is dissipated. The most prone to creep were dense clays, frozen and rocky soils [1].

Proceeding from the foregoing, a number of practical problems of geotechnics arise, so it is necessary to determine the parameters and use specialized models that take creep into account. Many components of underground structures and foundation based on solid clayey soils (tunnels, underground bottom chambers deep foundations). Given the high strength and deformation characteristics of soil at a great depth may get a false sense of security of the completed project, but the creep phenomenon may significantly worsen the situation over time, which can show itself in increasing the structure average settlement and the difference between the structure parts settlements.

The purpose of this article is to describe the main provisions on the application of the modern design model in numerical calculations, the methods of working with the parameters of this model. In connection with this, issues of optimization of model parameters and verification of numerical calculations performed with their use become topical.

2. Literature review
The development of shear strains without increment of tangential stress was first of all studied by specialists in the field of long-term stability of slopes, both in our country and abroad. The most fundamental scientific results in this field are in the works of S.R. Meschian [2-3]. However, the growth of volumetric deformations leading to the sediments of structures is more important (for the purposes of civil engineering). Studies of the creep of clay soils in Russia involved SS. Vyalov, Z.G. Ter-Martirosyan and other researchers. These studies made it possible to introduce into the normative technical documents a method for determining the parameter of secondary consolidation with α in the compression instrument by the log-time method (Appendix K of GOST 12248).

In recent years the themes of the work of soil foundation under load taking into account the time factor associated with the creep, has not lost its relevance [4 - 12]. Use as natural bases silty clayey soils having creep properties considerably complicates the design rationale of the expected structures precipitate. In the current regulatory documents there are no methods for calculating the precipitation due to secondary consolidation over time. At the same time, note 3 to paragraph 5.6.5 of SP 22.13330.2016 states: "Where necessary ... it is necessary to calculate the sediment in time taking into account primary and secondary consolidation". The only document that reflects the methodology for performing such calculations using the secondary consolidation parameter is PI AE 5.10-87 "Bases of reactor departments of nuclear power plants", in which the secondary consolidation coefficient mv2 is used, which differs from α and is determined by another method.

In numerical modeling in PLAXIS software, additional sediment due to the creep of the skeleton can be taken into account by indirect methods, for example, by setting the previously known creep strain of individual layers calculated analytically or directly using the Soft Soil Creep (SSC). This model is based on the famous Cam-Clay model [13].

The basic idea of the SSC model is the use of the logarithmic relationship between the volumetric strain $\varepsilon_v$ and the average effective stress $p'$:

$$\varepsilon_v = -\lambda^* \cdot \ln \left(\frac{p'_0}{p'}\right),$$

where $\varepsilon_v$ is volumetric deformation due to primary loading; $p'$ is current average effective stress value; $p'_0$ is mean effective stress at the start of stress interval; $\lambda^*$ is coefficient of SSC model.

For unloading and secondary loading processes only the coefficient changes:
where $\varepsilon^B_T$ is volumetric strain due to re-loading; $k^*$ is coefficient of SSC model.

In addition to the modified coefficient of unloading (swelling) $k^*$ and the coefficient of compression $\lambda^*$, the set of initial parameters also include: cohesion $c$ [kN/m$^2$]; friction angle $\varphi$ [º]; dilatancy angle $\psi$ [º]; modified creep coefficient $\mu^*$ [unit fraction]; Poisson’s coefficient at unloading and reloading $\nu_{ur}$ [unit fraction]; coefficient of lateral pressure in normal consolidation conditions $K^N_C$ [unit fraction]; slope parameter of critical state line $M$ [unit fraction].

All these parameters are determined based on the results of laboratory tests. However, direct use of results in programs for geotechnical calculations is not always possible. This is due to the technical features inherent in the algorithm of software systems, for example, the limits of the ratio of certain parameters of the model. Therefore, the programs give to the user recommendations for correcting the input set of parameters. In addition, many users of calculating software complexes, software developers and scientists identify the problems of convergence of the graphs of the behavior of laboratory and model samples (in the design scheme of the program) under load.

In connection with these problems, the question arose of the necessity of carrying out the optimization of the model parameters obtained in the laboratory for comparison and adjustment of these parameters, based on the degree of approximation of model tests with laboratory ones. At present, such an algorithm is embedded in some software systems that implement the models under consideration, for example in PLAXIS (the Soil test subroutine). Using the Soil test, the triaxial and oedometer tests are simulated on the basis of the input parameters of the soil and the initial test data (the points of the test curves for constructing the laboratory curves, the loading parameters).

To verify the correctness of the results obtained, modeling of laboratory tests by the finite element method was carried out and stress-strain curves for the oedometer test regime were constructed. Verification finite element calculations were also carried out separately in the mode of long-term consolidation.

![Figure 1. Comparison of the curves obtained from the results of laboratory tests (indicated the depth of sampling), numerical modeling using the initial soil parameters (Plaxis (laboratory parameters)) and optimized parameters (Plaxis (optimized parameters))](image-url)
As can be seen in Figure 1, the curve obtained from the results of numerical modeling with a set of input parameters obtained as a result of processing laboratory curves showed poor convergence with the curves of laboratory tests themselves (the depths of sampling were noted). After carrying out the optimization process in the Soil test subroutine, a set of initial optimized parameters was obtained, which provided material behavior much closer to the real one in the oedometer device (PLAXIS (optimized parameters)). The parameters of the Soft Soil Creep model, obtained from direct laboratory tests and optimized soil parameters, are presented in Table 1.

Figure 2. Comparison of the curves obtained from the results of laboratory tests (indicated the depth of sampling), numerical modeling using the initial soil parameters (Plaxis (laboratory parameters)) and optimized parameters (Plaxis (optimized parameters)) in the consolidation regime

Table 1. Summary table of normative values of the parameters for Soft Soil Creep model for the considered soil layer obtained from the results of direct laboratory tests and optimized parameters of it

| Parameter                      | Laboratory | Optimization |
|--------------------------------|------------|--------------|
| Modified coefficient of compressibility | 0.0174     | 0.0150       |
| Modified discharge factor       | 0.0189     | 0.0189       |
| Modified creep index           | 0.000687   | 0.000843     |
| Poisson number at unloading     | 0.383      | 0.352        |
| Coefficient of earth pressure   | 0.587      | 0.732        |
| The parameter of the critical state line | 2.04 | 1,795       |
| Overconsolidation ratio         | 1          | 1            |
| Angle of internal friction, °   | 36         | 36           |
| Specific cohesion, kPa          | 5          | 5            |
| Angle of dilatancy, °           | 0          | 0            |

3. Materials and methods
After obtaining optimized parameters, they are used directly for solving geotechnical problems, where an important factor is the consideration of long-term deformation in time. In this paper, two examples of predicting the change in the stress-strain state using the SSC model are given.

The first task describes the process of modeling the stress-strain state change in the basement of an underground metro camera mated with the tunnels that are a part of it. The calculation consists of several stages describing the sequence of construction - excavation of a deep pit, the construction
process of the chamber, tunneling, backfilling and long-term prediction of the growth of deformations. The main feature of the problem was the consideration of long-term creep strains of solid and semi-solid clay soils under the bottom of the chamber. It was necessary to check the time deposits for all parts of the underground structure, to estimate their relative difference and the risk of discontinuities from uneven displacements.

The second task describes the change in the stress-strain state of a soil massif interacting with a single barrette. The purpose of the calculation using the SSC model was to obtain a change in the distribution of the external load between the side surface of the deep foundation element and its bottom end when the barrette is buried in clay layers of the base with creep.

4. Results of investigations

Graphical results of numerical calculations are shown in Figure 3. The use of the model with allowance for creep makes it possible to predict the difference in settlement between different parts of a complex underground structure even at the time of the planned end of operation. At the time of the completion of the chamber construction its settlement was about 13-18 mm, but after the passage of the processes of long-term creep for 100 years, it became equal to 60-75 mm. The tunnels entering the chamber at the stage of construction completion received displacements of 12-15 mm, but after 100 years they received vertical displacements of 60-71 mm (at the interfaces with the chamber). The results obtained indicate the need to take into account the long-term creep strains in numerical modelling using modern models that take creep into account, since such deformations can be comparable with deformations during the construction phase and even exceed them.

![Figure 3. Isopoles of vertical displacements of the exit chamber and surrounding structures at the time of passing 100 years after the completion of construction, mm](image)

Figure 4 shows the variation of the axial force diagram of a single barrette, under load 40 MN, in 100 years. After the end of the loading process, the maximum force value on the diagram was 133100 kN, the minimum value was 40090 kN. After 10 years, these values dropped to 107400/29770, after
50 years - 103800/24450, in 100 years - 102200/21560. That is, the maximum and minimum values of the axial force along the barrette length have changed by 23-46%. This indicates a significant redistribution of the external load on the element. The reduced axial force indicates that the mobilized shear stress on the lateral surfaces of the barrette increases. If there is no reserve for tangent stresses along the lateral surfaces, then a sharp increase in pressure under the lower end of the element could be expected, which did not happen in this example. The results of the solution of the problem have shown the importance of predicting the change in the stress-strain state of creep-type soil massifs over time. It is necessary to check the working conditions of the deep foundations, predicting the conditions of its operation for a period not less than the operational lifetime of the structure. The absence of such forecasting can lead to a gradual increase in the deformations of the foundations.

![Figure 4](image.png)

**Figure 4.** Transformation of the axial force diagram during the time from the end of loading of the barrette up to 100 years after operation

**Conclusions**

1. The phenomenon of long-term creep of clay soils requires consideration in the process of numerical modeling, using modern models that take creep into account. To determine them, it is needed to perform direct laboratory or field tests.
2. When processing laboratory tests, it is recommended to verify or optimize the resulting model parameters, since there may be a significant difference in the behavior of the material being modeled and the soil base caused by various factors.
3. The SSC model can be widely used to calculate long-term deformations of clay soils at the base of critical structures with a long service life. In this case, the creep strains can be comparable with the deformations obtained during the construction of the object, and in some cases exceed them.
4. Consideration of long-term creep for calculating deep foundations can show a significant redistribution of the external load on the elements of the foundation in time, which can lead to a significant increase in settlements and change the conditions of their operation as a whole.

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