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TRIAXIAL STUDIES OF GRAY CLAYS IN DIFFERENT LOADING MODES AS A FOUNDATION FOR UNDERGROUND CONSTRUCTION

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Abstract: Statement of the problem. The safety of underground structures depends on the reliability of the foundation. When designing foundations of buildings with a developed underground part and foundations of underground structures, the question of the mechanical characteristics of soils arises. The least studied at the moment are gray clays, since in their natural state they occur at significant depths and have not been studied before. The main objective of this study is to identify the features of deformation of gray clays of a damaged structure under triaxial loading at different values of moisture, holding time in a desiccator and loading conditions. To achieve this goal, the following tasks were solved: identical samples of clays of a damaged structure were created; triaxial experimental studies were carried out; the ultimate strength of the samples and deformation characteristics were determined; graphical dependencies of strength, deformation modulus and shear modulus on moisture and loading conditions were constructed. Results. Experimental triaxial studies were performed on samples made of soil with a disturbed structure. The main results of the studies are new data on the development of vertical deformations and general deformation moduli, as well as shear moduli under triaxial loading depending on different soil moisture values, the time of sample holding in a desiccator before testing, the magnitude of lateral pressure and the presence of the first loading stage. Conclusions. The established influence of the factors under consideration on the deformation of gray clay under triaxial compression should be taken into account when calculating the settlement of building foundations and underground structures.

Keywords: clay soil, triaxial compression, mechanical properties of soil, moisture, foundation

1. INTRODUCTION

Well-designed foundations are the guarantee of safety of underground structures. Being one of the weakest building materials, soil often plays a decisive role in the destruction of underground structures, uneven soil subsidence, landslides and slope instability, which leads to a number of infrastructure damages and to some extent to human casualties (Sadono, 2017; Houston Sandra L. et al, 2001). Clayey soils of semi-solid consistency, such as clay, are problematic soil types in construction (Mohamad et al, 2016; Ural, 2018), since such soils generally have low shear strength and high compressibility (Ural, 2018; Uge, 2017; Giao et al, 2023). The physical properties and deformability of clayey soils depend on their age and genesis (Sharafutdinov, 2023; Lunev and Katsarskii, 2022). Moisture and the presence of defects are some of the factors affecting the shear strength of the soil, and time affects the stress-strain state, where deformation and strength change depending on the load. In the design process, it is assumed that the physical and mechanical characteristics of the soil base are constant throughout the life cycle of the building. In reality, the mechanical characteristics of foundation soils are unstable (Elhassan A.A. et al, 2023; Malizia and Shakoor, 2018) and continuously change under the influence of man-made (Bian et al, 2016; Cabello-Suarez L.Y. et al, 2017; Chen H., 2018), technological (Mirsayapov and Aysin, 2019; Song et al, 2020) and external force effects (Mirsayapov and Sharaf, 2023; Mirsayapov and Aysin, 2023; Mirsayapov and Koroleva, 2023). The features of deformation of samples at the following values of specified moisture are considered: 38 %, 40 % and 42 %. Some researchers believe that moisture close to the plasticity index is optimal for clays (Musbah et al, 2024; O'Kelly, 2023; Haigh et al, 2013).

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The tests were carried out on a triaxial compression device, which better simulates the behavior of soil in the field (Leong et al, 2013).

The problem of changes in the strength and deformation characteristics of grey clay, arising as a result of the influence of such factors as changes in moisture and time, is practically not discussed in the existing literature.

The aim of this study is to analyze the influence of soil moisture, the presence of the first stage of loading and defects in the structure of the sample caused by this loading, the time of holding the sample in a desiccator before the beginning of the second stage of two-stage loading, the magnitude of lateral pressure at the second stage on the features of deformation of gray clays of a damaged structure under triaxial loading conditions.

Research objectives:

- creation of identical samples from clays with a damaged structure;
- conducting triaxial experimental studies;
- determination of the ultimate strength of samples and their deformation characteristics;
- construction of graphical dependencies of strength, deformation modulus and shear modulus on moisture and loading conditions.

2. MATERIAL AND METHODS

Experimental studies are laboratory tests of gray clay with a disturbed structure at different moisture values and loading histories. The soil was crushed, moistened and formed into a monolith by layer-by-layer compaction (Mirsayapov and Koroleva, 2011a, 2019). This technique allowed us to obtain identical twin samples without large pores and inclusions, the presence of which in soils with an undisturbed structure does not allow us to perceive the samples as identical.

To create a two-stage loading, tests were carried out in two triaxial compression devices. For the first stage, a cubic device with a rib height of 100 mm was used, and for the second – a cylindrical one. Cubic triaxial compression was carried out in a device developed in the laboratory of the Department of Foundations, Foundations, Dynamics of Structures and Engineering Geology of the Kazan State University of Architecture and Civil Engineering, which was used in previous studies (Mirsayapov and Koroleva, 2011a) and made it possible to establish the failure mode (Mirsayapov and Koroleva, 2011b) under static deviatoric loading ($\sigma_1>\sigma_2=\sigma_3$). This test made it possible to create a shear plane in the sample during deviatoric loading and subsequent failure according to the "crushing" scheme (Mirsayapov and Koroleva, 2011b, 2016). After failure, a cylindrical sample with a diameter of 38 mm and a height of 76 mm was cut out from the cubic soil sample, placed in a sealed desiccator for aging from 0 to 5 days, and then subjected to triaxial loading in a pneumatic stabilometer. Stabilometric tests were conducted at two values of lateral pressure $\sigma_2=\sigma_3$=100 kPa and $\sigma_2=\sigma_3$=300 kPa. It should be noted that the vertical stress deviator ($\sigma_1 - \sigma_3$) was applied in steps of 10 % from $\sigma_2=\sigma_3$ until the sample was destroyed. The destruction criterion was the achievement of a vertical deformation in the amount of 15 % of the initial height of the sample.

The research program planned 4 series of tests.

The samples of the first and second series were not tested in a cubic triaxial compression device, i.e. they did not have a "plane of failure", while in the first series the sample was subjected to triaxial compression ($\sigma_1>\sigma_2=\sigma_3$) in a stabilometer immediately after production, and in the second series it was kept in a desiccator for 5 days after production, and then placed in a cylindrical triaxial compression device for loading.

In the third and fourth series, soil samples with a disturbed structure were tested in a triaxial cubic device and acquired a defect in the form of a "destruction plane", then the cut samples of the third series were tested in a stabilometer, and in the fourth series, the samples were first kept in a desiccator for 5 days and then subjected to triaxial loading in a cylindrical device.

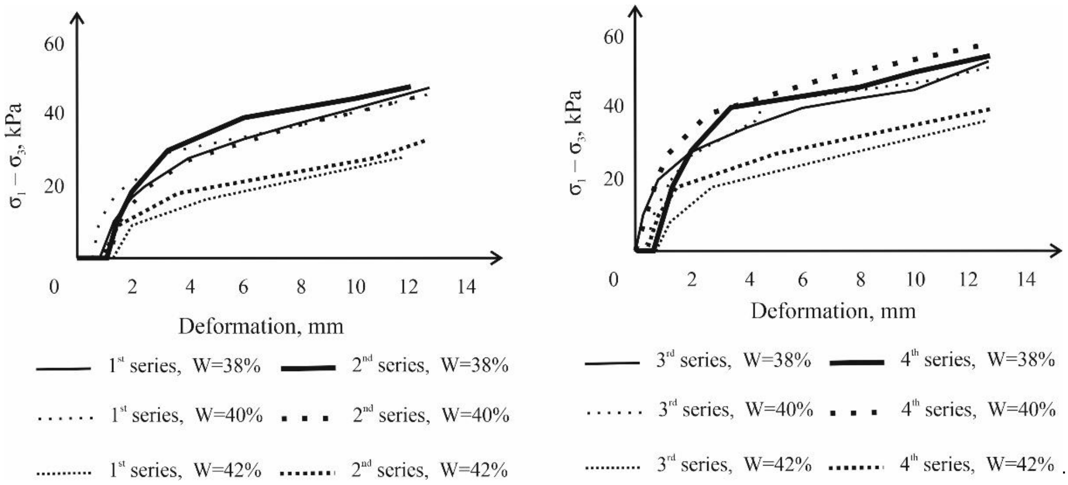
The experiments were carried out with artificially created soil samples of a disturbed structure with the following characteristics: plasticity index IP = 50,8; moisture content at the yield point WL = 0,924; moisture content at the rolling point WP = 0,416; fluidity index IL = - 0,07 at moisture content W = 38 %; IL = -0,03 at W = 40 % and IL = 0,007 at W = 42 % (the fluidity indices characterize natural soil according to GOST 25100 - 2020 "Soils. Classification" as hard and semi-hard clays).

The degree of soil water saturation $S_r \leq 0,8$. During the test, the samples were not additionally saturated with water, pore and effective pressures were not measured, and their influence was not assessed.

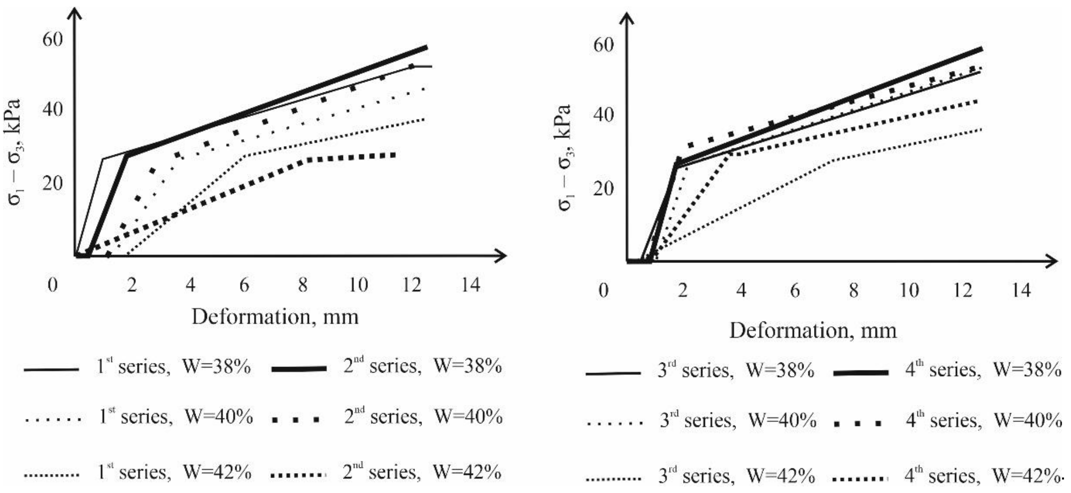
Thus, the main factors influencing the change in deformations, the modulus of total deformations and the shear modulus of samples under loading in a stabilometer are the magnitude of the lateral pressure, the moisture of the sample and the presence of a "plane of destruction" obtained as a result of the first stage of loading in a cubic device (3rd and 4th series).

3. RESULTS AND DISCUSSIONS

The samples of the first series of loading were taken as "standard" since they lacked the first stage of loading, and therefore the "plane of destruction", and they were not kept in a desiccator and were tested immediately after manufacture. The plotted graphs of deformation development (Fig. 1) allowed us to establish that the samples of second series have smaller deformations at the same value of the vertical stress deviator ($\sigma_1 - \sigma_3$) as the samples of first series. This indirectly confirms the restoration of colloidal bonds in the sample of the damaged structure during its holding in the desiccator.



a)



b)

Figure 1. *Development of soil sample deformations under different loading conditions: a) at $\sigma_2=\sigma_3=100$ kPa, b) at $\sigma_2=\sigma_3=300$ kPa.*

The presence of a destruction plane in the sample (Fig. 1, 3rd and 4th series) did not increase the rate of deformation development, but slowed it down at the first stages of loading by 1,4–1,8 times, and by 28 % with further loading. This is explained by the occurrence of zones of different density in the sample (Mirsayapov and Koroleva, 2011a, 2011b, 2019), which arose at the first stage of loading, and by the processes of reorientation of solid soil particles under loading. It is noted that in clays of semi-solid consistency, vertical deformations increase at a higher rate, since in this case the film water acts as a “lubricant” and helps to achieve the ultimate relative deformations that record the destruction of the sample. The data on the modulus of general deformations and the shear modulus, given in the article, were calculated automatically by the testing equipment program.

Based on the experimental studies results, the growth of vertical deformations graphs for each series of loading, changes in the modulus of general deformations E and the shear modulus G depending on the moisture of the sample and the presence of holding time in the desiccator were constructed; the strength of the sample was also graphically assessed at different values of lateral pressure.

It has been established that soil moisture plays an important role: the higher the moisture content, the lower the vertical stress that the specimen can withstand when tested until failure (Fig. 2). Upon closer examination, it is evident that moisture content close to the rolling limit resulted in an increase in strength for specimens of 4th series at $\sigma_2=\sigma_3=100$ kPa and does not have a significant effect at lower moisture content under conditions of $\sigma_2=\sigma_3=300$ kPa. A further increase in moisture content results in a decrease in strength by 20 % and 10 % for specimens of first and second series and by 15 % and 5 % for specimens tested at the first loading stage, respectively. It should be noted that the holding time in the desiccator resulted in the expected increase in strength compared to specimens without holding at a moisture content of 42%. The presence of a fracture plane and a loosening zone around it (Mirsayapov and Koroleva, 2011a, 2011b, 2019) did not result in the predicted decrease in specimen strength, but, on the contrary, contributed to its increase. This is caused by additional compaction of the soil when loaded into the stabilometer.

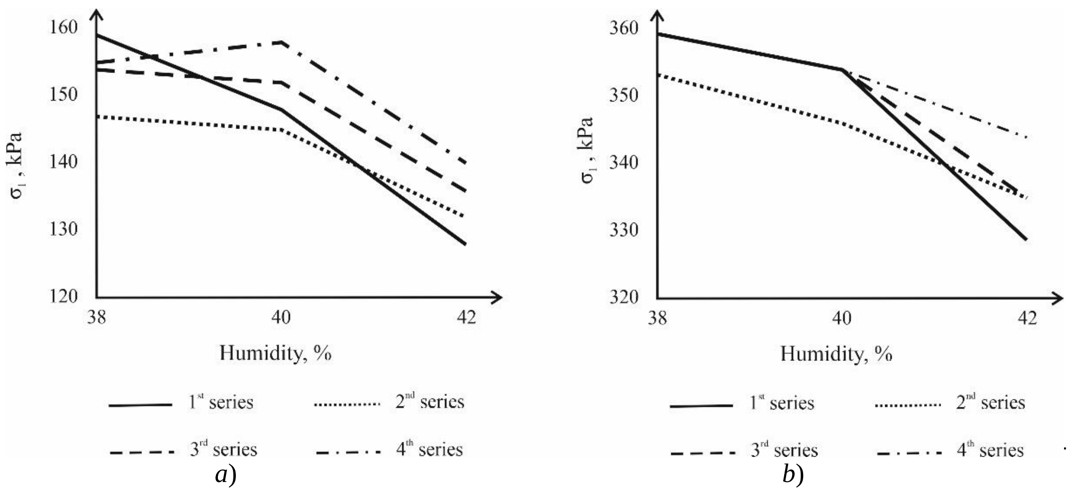


Figure 2. *Change in the strength of a soil sample depending on moisture under different loading conditions: a) at $\sigma_2=\sigma_3=100$ kPa, b) at $\sigma_2=\sigma_3=300$ kPa.*

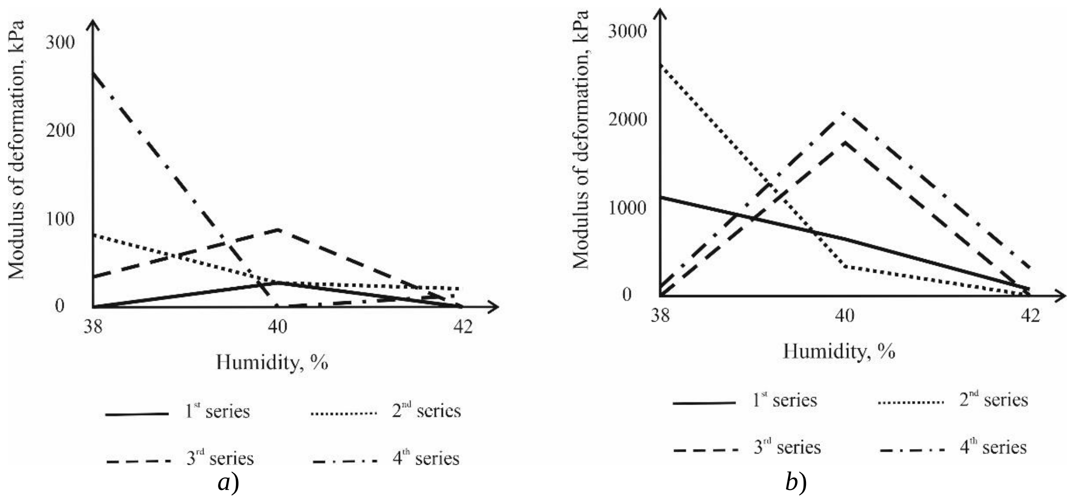


Figure 3. *Change in the value of the modulus of general soil deformations from moisture under different loading conditions: a) at $\sigma_2=\sigma_3=100$ kPa, b) at $\sigma_2=\sigma_3=300$ kPa.*

The graph of deformation modulus change under different lateral loads (Fig. 3) shows that deformation modulus increases with moisture increase to 40 % under lateral load of 100 kPa 1st and 3rd series (Fig. 3a) and under $\sigma_2=\sigma_3=300$ kPa 3rd and 4th series (Fig. 3b), but its value decreases significantly with moisture increase to the rolling limit (41,6 %) for all samples except 4th series under $\sigma_2=\sigma_3=100$ kPa. The holding time in a desiccator under 38 % moisture allows to reduce soil deformability for all tested samples, which is associated with restoration of structural bonds in soil with damaged structure. It should be noted that under lateral load of 300 kPa (Fig. 3b), deformation modulus in “without destruction” samples decreases with moisture increase from 38 % to 42 %. In another case, for samples "with destruction", the deformation modulus increases at 40 % moisture, with a further increase in moisture, the deformation modulus decreases. These results allow us to conclude that moisture has a significant effect on the deformation properties of clay soil with a damaged structure.

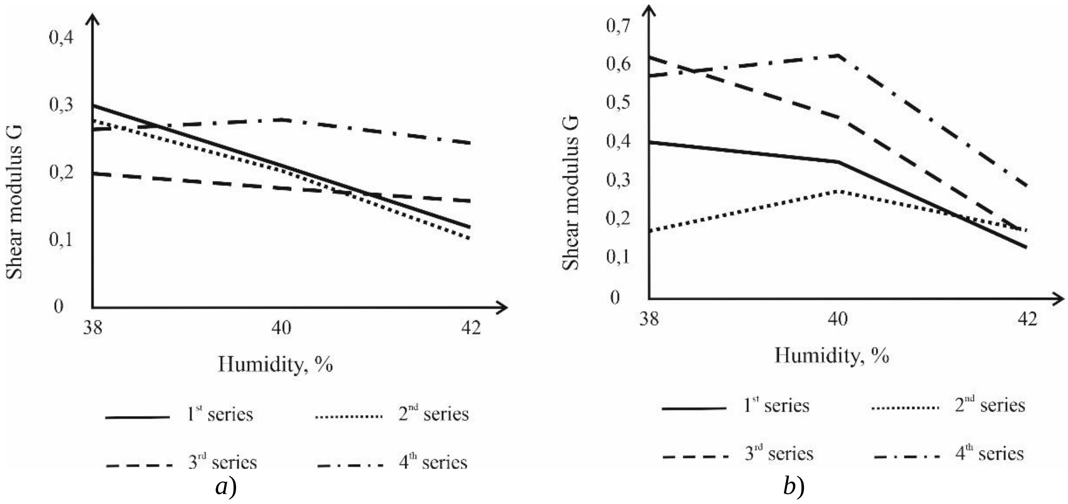


Figure 4. *Change in the value of the modulus of general soil deformations from moisture under different loading conditions: a) at $\sigma_2=\sigma_3=100$ kPa, b) at $\sigma_2=\sigma_3=300$ kPa.*

The shear modulus G characterizes the ability of the soil to resist shear deformation and is determined based on the results of standard triaxial tests. The value of the shear modulus of the disturbed structure soil depends on the moisture, the presence of the first of the two loading stages and the holding time after it. Analyzing the obtained graphical dependencies (Fig. 4), it can be noted that the value of the shear modulus G decreases with an increase in moisture from 40 % to 42 % for all tests, which is explained by the formation of a water film that reduces the friction force between clay particles. The shear resistance of the samples is higher in the case of $\sigma_2=\sigma_3=300$ kPa after two-stage tests. "Rest" in a desiccator made it possible to improve the shear resistance to 35 % (series 4^{th}, Fig. 4) due to strengthening caused by the restoration of water-colloidal bonds in the decompaction zone. The samples of the second series did not have a loosening zone acquired during the first stage of loading, so free water played the role of a lubricant and reduced the shear strength.

The issues of clays structural strength were studied in the works (Meng et al, 2020; Aiwu et al, 2023), the results obtained by the authors do not contradict these studies.

4. CONCLUSION

1. The deformation characteristics of clays with a damaged structure were studied under two-stage triaxial loading. Graphic dependences of the change in the deformation modulus E, shear modulus G and the magnitude of the destructive load were obtained depending on the soil moisture, the presence of the loading first stage and defects in the sample structure caused by this loading, the time of the sample holding in a desiccator before the beginning of the second stage of two-stage loading, the lateral pressure magnitude at the second stage. The deformation development graphs for each series of loading were analyzed.

2. It has been established that moisture is the main factor influencing the deformation characteristics of soil. An increase in the moisture of the disturbed structure soil to 42% almost always leads to a decrease in the deformation modulus E and the shear modulus G, as well as to an increase in the rate of increase in vertical deformations.

3. Under two-stage loading conditions, especially in the case of exposure in a desiccator (4^{th} series), the soil exhibits higher deformation characteristics.

4. Water in soil with a disturbed structure plays a dual role: in the loosened zone it promotes the restoration of water-colloidal bonds and increases the deformation modulus E and the shear modulus G, and in soil without loosening it acts as a “lubricant” and accelerates deformation processes.

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