Experience in determining viscosity of soil on the basis of experimental studies

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Abstract. Modern construction is developing at enormous speed, which leads to the need for more in-depth study of the physical and mechanical properties of soils in general, and clay soils in particular, in order to make rational use of their natural properties in the construction and design of foundations, foundations and soil structures. In this regard, recently, special attention has been paid to the study of the rheological properties of soils. One of the main rheological parameters of the soil is its viscosity. To determine the coefficient of viscosity of the soil in this study, a simple shear device was used. An artificially created sandy loam consisting of fine quartz sand (60% by weight) and clay particles (40% by weight) was adopted as the test soil. In the course of the study, characteristic graphs of the dependence of tangential stresses on shear deformation at different test speeds were obtained. Also, taking the Newton equation as a basis, the average value of the soil viscosity coefficient was determined for each shear rate.

1. Introduction

Currently, in order to study the dependence of stresses on the deformations that occur in soils when different types of forces are applied, the tests of the soils are carried out in various devices. One of these devices is a simple shift device. Studies of the rheological properties of soils in general, clayey in particular, under simple shear conditions, are extremely important for taking into account the processes occurring over time in the soil mass when designing buildings and structures.

The test in a simple shear device can be characterized as follows - the process by which the slip (displacement) of planes parallel to the plane of the stationary stamp (upper or lower, depending on the device design) occurs by an amount close to their distance from this plane. In other words, with a simple shift of the cubic sample, at the end of the test it takes the form of an inclined parallelepiped (Figure 1). When testing for a simple shift, the volume of the soil sample does not change and remains constant, but only its shape changes. Figure 2 shows a schematic diagram of a simple shear test.

![Figure 1. Simple shear test of a cubic sample: a) sample prior to testing; b) the sample after the test.](image-url)
Figure 2. Schematic diagram of the test for simple shear: a) the application of the vertical load on the sample; b) application of shear load on the sample.

Experiments on a simple shift most fully allow you to recreate the conditions of the shift of the soil structure or under it. The advantages and limitations inherent in tests under simple shear conditions are described in a number of papers [1-16].

2. Review of literature

The rheological properties of soils, such as creep, stress relaxation, long-term strength, are closely related to the viscosity of the soil itself. The concept of viscosity in soil mechanics is inextricably linked with the fact that any rheological model includes the simplest model of Newton - $\dot{\gamma} = \tau / \eta$ [17-20]. Currently, various methods are used to describe the rheological properties of clay soils, which are based on the use of mechanical models, on the theory of hereditary creep and theory of plastic flow. On the basis of these theories, various equations of state are derived, containing several parameters that are subject to experimental investigation. There is a fairly large number of mechanical models that describe the rheological properties of the skeleton of the soil. This is achieved with a combination of elastic, viscous and plastic elements. The main mechanical models that describe the rheological properties of the skeleton of the soil include models: Kelvin-Voigt - $\dot{\gamma} = \frac{\tau - \dot{\gamma} \cdot G}{\eta}$, Maxwell - $\dot{\gamma} = \frac{\tau}{G} + \frac{\tau}{\eta}$, Shvedova - $\dot{\gamma} = \frac{\tau - \dot{\gamma}^*}{\eta} + \frac{\tau^*}{G}$, a modified model of Timoshenko - $\dot{\gamma} = \frac{\tau}{\eta} \cdot \frac{\tau^*}{\tau - \tau}$ [17-20].

In the thesis [21], a new equation for the creep of soil under shear was proposed, which is based on the Bingham-Shvedov-Maslov model - $\dot{\gamma} = \frac{\tau - \tau^*}{\eta_0} \left( e^{\alpha \tau} + e^{\beta \tau} \right)$. From this equation it follows that the creep rate depends on the accumulated tangential deformation. However, despite the large number of rheological models that contain a viscosity parameter, at the moment there is no specific methodology for determining this parameter. And now this is quite an urgent task, since the correct determination of the soil viscosity parameter is important for calculations and engineering design of base deformations in time.

3. Materials and methods

Laboratory tests of soils were carried out on certified equipment manufactured by OOO "NPP Geotek", which includes a shearing device, a measuring system and software. A general view of the installation on which samples of dispersed soils were tested using the simple shear method is presented in Figure 3. ASTM D6528-2007 [22] was adopted as a regulatory document that regulates the implementation of simple shear tests. Currently there are no Russian regulatory documents for this type of test. ASTM D6528 provides formulas for calculating consolidation characteristics: axial strain - $\epsilon_n$; normal effective stress - $\sigma_n^*$; shear characteristics: shear strain - $\gamma$; shear stress - $\tau$; axial strain - $\epsilon_a$. 
Artificial sandy loam was adopted as a test soil, containing as a percentage by weight 60% fine quartz sand and 40% clay particles. The tests were carried out at a soil density of 1.5 g/cm$^3$. The dimensions of the test sample of soil: diameter - 71.4 mm, height - 28 mm. The tests were carried out with the kinematic loading mode ($\dot{\gamma} = \text{const}$) and at a constant vertical load of 100 kPa. The precompression time was 30 minutes. In total, 16 tests were performed on twin samples of soil: 3 tests at a shear deformation rate of $\dot{u} = 0.05$ mm/min; 6 tests at a shear deformation rate of $\dot{u} = 0.5$ mm/min and 7 tests at a shear deformation rate of $\dot{u} = 5$ mm/min. The tests were carried out to achieve the maximum relative shear strain $\varepsilon = 20\%$.

![Figure 3. General view of the installation of a simple shear.](image)

4. Results of the study

As a result of simple shear tests, a series of curves was obtained. Typical graphs of the dependence of tangential stresses on shear deformation ($\tau - \gamma$) at various test speeds are presented in Figure 4.

On the basis of the obtained results, it can be concluded that at the shear deformation rate of $\dot{u} = 0.05$ mm/min there is a good convergence of the graphs, while at the shear deformation rate of $\dot{u} = 0.5$ mm/min and $\dot{u} = 5$ mm/min some variation of the graphs in a certain range of values is observed.

In order to determine the viscosity of the soil, the obtained data were processed on the basis of the Newton equation. The graphs were previously divided into two straight-line characteristic areas. For each shear rate, the average value of the soil viscosity coefficient was determined (Table 1) in both parts of the graph. Figure 4(a) shows a characteristic graph of the dependence of tangential stresses on shear deformation ($\tau - \gamma$), divided into two separate sections.

Analysis of the results showed that the coefficient of viscosity of the soil in the first section of the graphs grows in direct proportion to the growth rate of angular deformation, namely, with an increase in the rate of angular deformation by 10 times, the coefficient of soil viscosity also increases. In the second section of the graph, the soil viscosity coefficient also increases with an increase in the soil deformation rate, but this relationship is not linear. It can also be noted that the ratio of the viscosity of the soil in the first and second sections of the respective speeds was from 3 to 7.
Figure 4. A graph of the dependence of tangential stresses on shear deformation: a) with the division into sections, b) at shear deformation rate \( \dot{u} = 5 \) mm/min, c) at shear deformation rate \( \dot{u} = 0.5 \) mm/min, d) at shear deformation rate \( \dot{u} = 0.05 \) mm/min.

Table 1. The dependence of the viscosity of the soil on the shear rate.

| Shear deformation rate, \( \dot{u} \) (mm/min) | Viscosity, \( \eta \) (kPa*s) – section 1 | Viscosity, \( \eta \) (kPa*s) – section 2 |
|-----------------------------------------------|------------------------------------------|------------------------------------------|
| 0.05                                         | 487.8                                    | 71.6                                     |
| 0.5                                          | 49.3                                     | 13.5                                     |
| 5                                            | 4.6                                      | 1.4                                      |

5. Conclusion
Based on the results obtained, the following main conclusions can be drawn:

1. In the course of the study, the viscosity of artificially created sandy loam was determined at various shear rates. It was found that the shear rate greatly affects the coefficient of soil viscosity; the higher the shear rate, the lower the viscosity of the soil. It was also noted that at low shear rates there is a good convergence of the graphs.

2. The soil viscosity coefficient was determined on a simple shear device produced by OOO "NPP Geotek" using the simplest Newton model, which describes the straight-line relationship between tangential stresses and shear rate. (\( \tau - \dot{\gamma} \)).

3. The obtained graphs of the dependence of tangential stresses on shear deformation have a pronounced bilinear character. On this basis, the coefficient of viscosity of the soil was determined at each site separately. Moreover, as shown by the results of experiments, the soil viscosity coefficient in the first section of the graph is greater than in the second, which is associated with structural changes in the soil sample (transition to a new state of viscous-plastic flow).
4. It is important to note that a turning-point of the graph is observed when a relative shear strain of $\varepsilon = 7\%$ is reached at different shear rates, which, in almost all tests, corresponds to a shear stress of $\tau = 50$ kPa.

5. In order to more accurately describe the creep of the soil mass over time, complex rheological soil models should be used, which allow describing the entire curve within one equation. The applied approach makes it possible to determine a qualitative picture of the change in the coefficient of soil viscosity.

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