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# Viscous resistance of clay soil under kinematic shear

## Résistance visqueuse des sols argileux sous cisaillement cinématique

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**ABSTRACT**: Based on the concept proposed by N.N. Maslov, the ultimate shear resistance of clay soil can be represented as the sum of Coulomb friction, structural cohesion and cohesion of water-colloidal bonds. However, this concept doesn’t take into account the influence of shear rate. Note that during kinematic shear in a soil medium that has viscosity, viscous resistance may appear. In this regard, within the framework of this work, it was proposed to present the general cohesion in clay soil as a sum of three components: structural cohesion, cohesion of water-colloidal bonds and viscous soil resistance. To take into account the influence of shear rate on the shear resistance of clay soil, experimental studies were carried out on samples of clay soil in a simple shear device in a kinematic loading mode. The tests were carried out at four different shear rates and at three different values of constant vertical load. The design of the simple shear device used during testing allows for the realization of a homogeneous stress-strain state inside the soil sample during testing, since each individual elementary layer of the sample moves by the same amount during shear. Based on the results of experimental and theoretical studies, a new rheological equation was obtained, which simultaneously takes into account the influence of Coulomb friction, structural cohesion, cohesion of water-colloidal bonds and viscous resistance of the soil. The resulting equation can be used for further improvement of methods for quantitative assessment of the stress-strain state of foundations composed of weak clay soils.

**RÉSUMÉ**: Basé sur le concept proposé par N.N. Maslov, la résistance ultime au cisaillement d'un sol argileux peut être représentée comme la somme du frottement coulombien, de la cohésion structurelle et de la cohésion des liaisons eau-colloïdales. Cependant, ce concept ne prend pas en compte l’influence du taux de cisaillement. Notez que lors d'un cisaillement cinématique dans un milieu de sol ayant une viscosité, une résistance visqueuse peut apparaître. A cet égard, dans le cadre de ce travail, il a été proposé de représenter la cohésion générale dans les sols argileux comme la somme de trois composantes : la cohésion structurelle, la cohésion des liaisons eau-colloïdales et la résistance visqueuse du sol. Pour prendre en compte l'influence du taux de cisaillement sur la résistance au cisaillement des sols argileux, des études expérimentales ont été réalisées sur des échantillons de sol argileux dans un dispositif de cisaillement simple en mode de chargement cinématique. Les tests ont été effectués à quatre taux de cisaillement différents et à trois charges verticales constantes différentes. La conception du dispositif de cisaillement simple utilisé lors des essais permet de réaliser un état de contrainte-déformation homogène à l'intérieur de l'échantillon de sol pendant les essais, puisque chaque couche élémentaire individuelle de l'échantillon se déplace de la même quantité pendant le cisaillement. Sur la base des résultats d'études expérimentales et théoriques, une nouvelle équation rhéologique a été obtenue, qui prend simultanément en compte l'influence du frottement coulombien, de l'adhésion structurelle, de l'adhésion des liaisons eau-colloïdale et de la résistance visqueuse du sol. L'équation résultante peut être utilisée pour améliorer encore les méthodes d'évaluation quantitative de l'état de contrainte-déformation des fondations composées de sols argileux faibles.

**Keywords:** Viscous resistance; kinematic shear; simple shear device; creep.

## 1 INTRODUCTION

Due to the high pace of development of housing, transport and hydraulic engineering over the past hundred years, the study of the phenomenon of creep in clay soils has become the subject of scientific research.

The process of creep of clay soils in nature manifests itself in the form of long-term settlements, displacements, tilts, horizontal movements of structures, as well as in the form of slow sliding of clay masses along the natural slopes and slopes of structures made from soil materials.

In order to describe the rheological properties (creep) of clayey soils, various techniques are currently widely used (Meschyan, 2005; Shirinkulov and Zareckij, 1986; Ter-Martirosyan, 1990; Ter-Martirosyan and Ter-Martirosyan, 2020), which are based on the use of mechanical models, the theory of plastic flow and hereditary creep, etc., on the basis of which various equations of state are derived (Bodas Freitas, Potts and Zdravkovic, 2011; Chen, Weiqiang, Chen and Yin, 2023; Gu, Zou, Fang, and Hu 2018; Li and Yue 2014; Santa Maria and Santa Maria, 2018), containing several parameters that can be determined during experimental studies of soil in various instruments (Roman and Kotov, 2016; Yuan, Wang, Chen and Huang , 2023).

## 2 MATERIALS AND METHODS

Based on the concept proposed by N.N. Maslov, the ultimate shear resistance of clay soil can be represented as the sum of Coulomb friction ($\sigma tg\varphi$), structural cohesion ($c_c$) and cohesion of water-colloidal bonds ($c_w$):

$$\tau^* = \sigma tg\varphi + c_c + c_w \tag{1}$$

However, the presented concept (1) doesn't take into account the influence of shear rate ($\dot{\gamma}$).

Note that during kinematic shear ($\dot{\gamma} = const$) in a soil medium that has viscosity, viscous resistance may appear $\left(c_{\dot{\gamma}}\right)$.

If we assume that viscous resistance is due to the viscosity of the soil as a whole, then during kinematic shear viscous resistance will arise $\left(c_{\dot{\gamma}} = \dot{\gamma}\eta\right)$. Therefore, we represent the general cohesion in clay soil as a sum of three components:

$$c = c_c + c_w + c_{\dot{\gamma}} \tag{2}$$

In order to take into account the effect of the shear rate ($\dot{\gamma}$) on the shear resistance of clay soil in the laboratory of the REC "Geotechnics" named after Z.G. Ter-Martirosyan (National Research University MGSU), experimental studies were carried out in a simple shear device in a kinematic loading mode ($\dot{\gamma} = const$) at four different shear rates ($\dot{\gamma}_1 > \dot{\gamma}_2 > \dot{\gamma}_3 > \dot{\gamma}_4$) and at three different values of constant compaction load ($\sigma_1 < \sigma_2 < \sigma_3$) acting on the soil sample during testing.

Pre-compacted samples of fluid-plastic loam ($I_P$ = 10,60, $I_L$ = 0,80) with a diameter $d$ = 71,4 mm and a height $h$ = 22 mm were tested in a simple shear device in the kinematic loading mode ($\dot{\gamma} = const$) (at a constant shear displacement rate equal to $\dot{u} = \dot{\gamma}h$), under the action of a constant vertical compaction load ($\sigma = const$), as well as with constant measurement of the shear force.

## 3 RESULTS

Figures 1-4 show the results of testing fluid-plastic loam in a simple shear device in a kinematic loading mode ($\dot{\gamma} = const$).

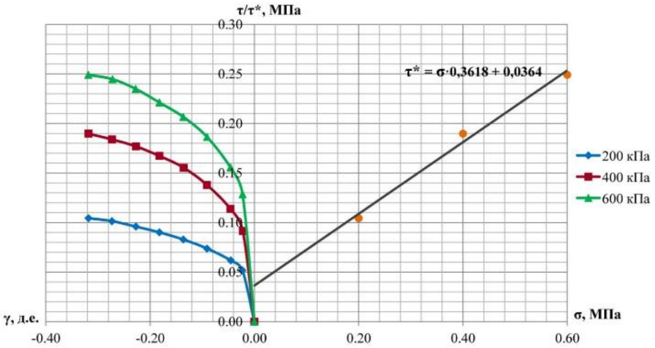

*Figure 1. A graph of the dependence of the acting shear stresses on shear strains $(\tau - \gamma)$ and a graph of the dependence of the ultimate shear stresses on normal stresses $(\tau^* - \sigma)$ at a constant shear displacement rate equal to $\dot{u}$ = 5 mm/min.*

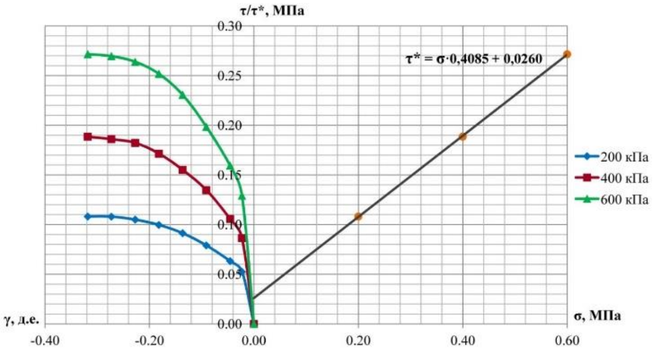

*Figure 2. A graph of the dependence of the acting shear stresses on shear strains $(\tau - \gamma)$ and a graph of the dependence of the ultimate shear stresses on normal stresses $(\tau^* - \sigma)$ at a constant shear displacement rate equal to $\dot{u}$ = 0,5 mm/min.*

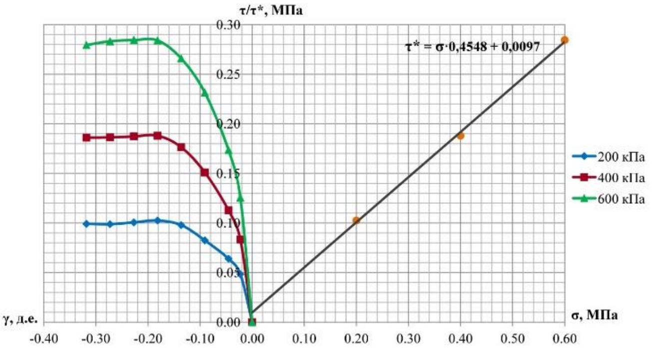

*Figure 3. A graph of the dependence of the acting shear stresses on shear strains $(\tau - \gamma)$ and a graph of the dependence of the ultimate shear stresses on normal stresses $(\tau^* - \sigma)$ at a constant shear displacement rate equal to $\dot{u}$ = 0,05 mm/min.*

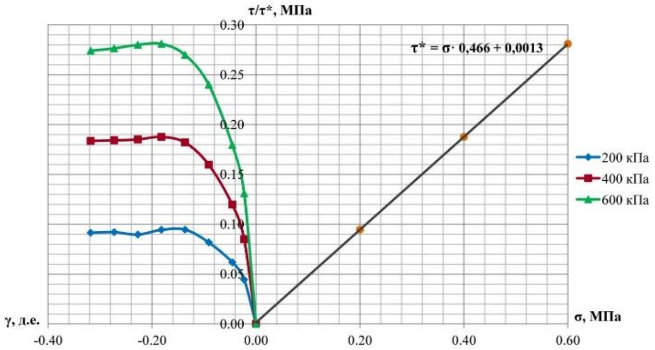

*Figure 4. A graph of the dependence of the acting shear stresses on shear strains ($\tau - \gamma$) and a graph of the dependence of the ultimate shear stresses on normal stresses ($\tau^* - \sigma$) at a constant shear displacement rate equal to $\dot{u}$ = 0,005 mm/min.*

Numerous experimental tests of quaternary clay samples of disturbed and undisturbed structure, carried out in the kinematic loading mode ($\dot{\gamma} = const$) and at different values of vertical stress $\sigma$ (100, 200, 300 and 500 kPa), described in the work of M.B. Kornouhov, showed (Figure 5) that the limit lines at different shear rates ($\dot{\gamma}_1 > \dot{\gamma}_2 > \dot{\gamma}_3 > \dot{\gamma}_4$) have the same slope equal to $\varphi = const$, and this angle doesn't depend on the shear rate ($\dot{\gamma}$).

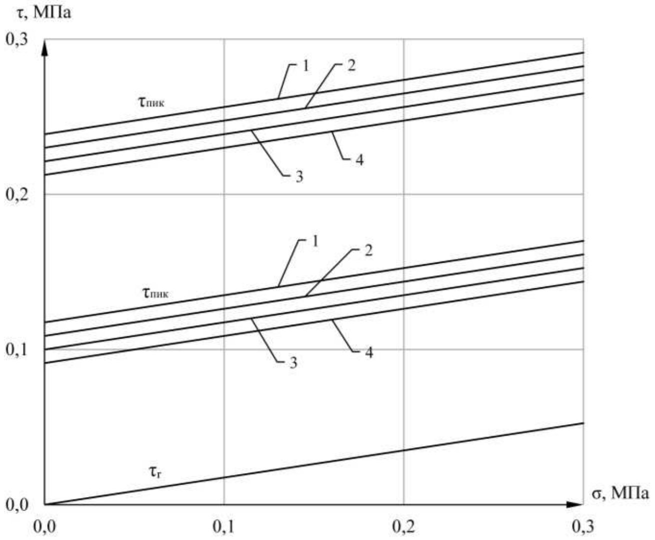

*Figure 5. Graph of the dependence of the peak and residual strength of quaternary clay of an undisturbed structure (a) and a disturbed structure (b) on vertical stress ($\sigma_{n_1}$ = 0,1 MPa; $\sigma_{n_2}$ = 0,2 MPa and $\sigma_{n_3}$ = 0,3 MPa), acting on the sample at different shear rates: 1 - $\dot{\gamma}_1$ = 0,066 min$^{-1}$; 2 - $\dot{\gamma}_2$ = 0,0041 min$^{-1}$; 3 - $\dot{\gamma}_3$ = 0,00026 min$^{-1}$; 4 - $\dot{\gamma}_4$ = 0,00002 min$^{-1}$.*

The ultimate value of shear resistance ($\tau^*$) largely depends on the angle of internal friction ($\varphi$) and the general cohesion ($c$). And the general cohesion ($c$) significantly depends on the shear rate ($\dot{\gamma}$), and as the shear rate increases, the ultimate shear resistance also increases in direct proportion $ln\dot{\gamma}$ (Figure 6).

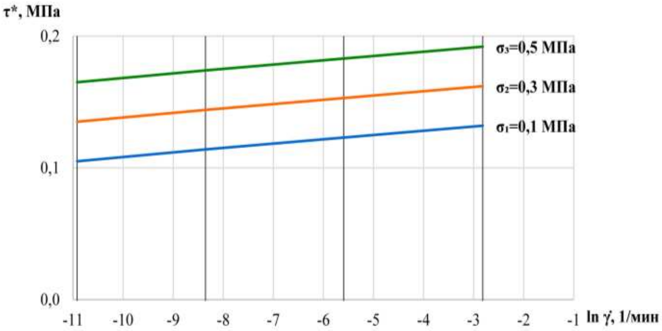

*Figure 6. Graph of the dependence of the peak strength of quaternary clay of a disturbed structure on the deformation rate.*

Since, according to the results of experimental studies, it was found that the structural cohesion ($c_c$) and the angle of internal friction ($\varphi$) don't depend on the shear rate ($\dot{\gamma}$), the viscous resistance was presented in the following form:

$$c_{\dot{\gamma}} = c_{\dot{\gamma}_0} + \alpha\, ln(\dot{\gamma}/\dot{\gamma}_1) \qquad (3)$$

where $\alpha$ is a parameter determined on the basis of experimental data.

Based on the Maxwell elastic-viscous body model, we present the rheological equation for kinematic shear in the following form:

$$\dot{\gamma} = \frac{\tau - \tau^*}{\eta} + \frac{\dot{\tau}}{G} \qquad (4)$$

where $\tau^* = \sigma tg\varphi + c_0$ (and $c_0 = c_c + c_w$); $\eta$ is the viscosity of the soil as a whole; $\dot{\tau}$ - rate of change of shear stress; $G$ - soil shear modulus.

Having performed a certain grouping in equation (4), we obtain a differential equation of the following form:

$$\dot{\tau} + \tau \cdot \frac{G}{\eta} = \frac{G}{\eta} \cdot \left(c_{\dot{\gamma}} + \tau^*\right) \qquad (5)$$

The solution to equation (5) at a constant shear rate ($\dot{\gamma} = const$) has the form:

$$\tau(t) = (\sigma tg\varphi + c_c + c_w + c_{\dot{\gamma}}) \cdot (1 - e^{-\frac{G \cdot t}{\eta}}) (6)$$

At $t \to \infty$ $\tau(\infty) = \sigma tg\varphi + c_c + c_w + c_{\dot{\gamma}}$, and $c_{\dot{\gamma}} = \dot{\gamma}\eta$.

The obtained result corresponds to our ideas about the ultimate shear resistance (2). However, it should be noted that in this case, the viscous resistance $c_{\dot{\gamma}}$

increases in direct proportion to the shear rate $(\dot{\gamma})$, and this doesn't correspond to the results obtained during experimental studies (3). However, if we take dependence of the form (7) as a rheological model, we obtain a result corresponding to the experimental data:

$$(\dot{\gamma}/\dot{\gamma}_1)^{\alpha/\eta} = e^{\left(\frac{\tau-\tau^*}{\eta}+\frac{\dot{\tau}}{G}\right)} \tag{7}$$

where $\tau^* = \sigma tg\varphi + c_c + c_w$.

Equation (4) can also be represented as follows:

$$\frac{\alpha}{\eta} ln(\dot{\gamma}/\dot{\gamma}_1) = \frac{\tau-\tau^*}{\eta} + \frac{\dot{\tau}}{G} \tag{8}$$

The solution to equation (8) has the following form:

$$\tau(t) = (\sigma tg\varphi + c_c + c_w + \alpha\, ln(\dot{\gamma}/\dot{\gamma}_1)) \cdot (1 - e^{-\frac{G\cdot t}{\eta}}) \tag{9}$$

For $t \to \infty$ $\tau(\infty) = \sigma tg\varphi + c_c + c_w + \alpha\, ln(\dot{\gamma}/\dot{\gamma}_1)$.

From equation (9) it follows that $c_{\dot{\gamma}} = \alpha\, ln(\dot{\gamma}/\dot{\gamma}_1)$.

The obtained result concurs with the result of experiment (3), and using equation (9) it is possible to construct a diagram $(\tau^* - ln\dot{\gamma})$ (Figure 6).

By replacing time $t$ with the value $\gamma/\dot{\gamma}$ in equation (9), we obtain the dependence $(\tau - \gamma)$:

$$\tau(\gamma/\dot{\gamma}) = (\sigma tg\varphi + c_c + c_w + \alpha\, ln(\dot{\gamma}/\dot{\gamma}_1)) \cdot (1 - e^{-\frac{G}{\eta}\cdot(\gamma/\dot{\gamma})}) \tag{10}$$

## 4 CONCLUSION

The results of experimental studies carried out in a simple shear device in a kinematic loading mode showed that the shear rate has a significant effect on the cohesion of clay soil.

However, due to the limited scope of tests performed, additional research is required on clay soil samples with different plasticity numbers $I_P$ and fluidity index $I_L$ in order to identify and determine correlation dependencies.

Earlier in the works of many authors, it has been noted that total adhesion can be decomposed into two components: structural cohesion $(c_c)$ and cohesion of water-colloidal bonds $(c_w)$. Based on the results of experimental studies presented in Figures 5 and 6, and their analysis, it is explicitly shown that general cohesion also depends on the shear rate $\dot{\gamma}$.

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