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Long-term stability of slopes

La stabilité de longue durée des pentes

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ABSTRACT
In this article are presented new rheological equations for clay soils, using dependence of speeds of soils' shear strains on a degree of approximation to a limiting condition. For tested versions of clay soils the above-stated dependence is represented as linear dependence of the natural logarithm of shear strains' speed on a degree of approximation to a limiting condition. On the basis of the offered dependence it is possible to carry out the forecast of long-term strains of soils' masses on known values of a degree of approximation to a limiting condition in various points of soils' mass.

RÉSUMÉ
Dans l'article presenter de nouveau reologic l'équation pour argileux sol, les vitesses, utilisant la dépendance, des déformations de cisaillement du sol du degré de l'approche vers l'état limite. Pour des investigat variétes argileux sol la dépendance ci-dessus indiquée semble la dépendance linéaire du logarithme naturel de la vitesse des déformations de cisaillement du degré de l'approche vers l'état limite. A la Base de la dépendance proposée il est possible de réaliser le pronostic des déformations de longue durée des massifs de sol selon les grandeurs connues du degré de l'approche vers l'état limite dans les points divers du massif de sol.

1 INTRODUCTION

Division of natural slopes on steady and unstable conditionally, if to take into account the factor of time. The slope or the declivity, steady in the given moment of time, can become unstable on the expiration of long time or to be in unsteady condition of ancient creep, not passing in a phase of catastrophic destruction, i.e. to failure.

2 MAIN PRINCIPLES

For a quantitative estimation of short-term stability of slopes and declivities, numerous methods, based on the requirements of SNiP 2.02.01-83 are developed. Criterion of slope short-term stability, in the given moment, is a factor of stability stock, which should be more than normative factor of stability stock. Such estimation of short-term stability is necessary for prevention of a slide catastrophic phase, as allows to define a degree of approximation to a limiting condition. Such accounts concern to I group of limiting conditions, and they answer a question (yes or not) about slope stability at present time (short-term stability).

However, results of such accounts are not enough informative. They are necessary, but are not sufficient to answer the important question about possible slide displacements even, if the factor of stability stock more then normative meaning. The loss of slope stability occurs, as a rule, on the certain surface of sliding close to circle-cylindrical or another one. The slope comes to such condition for a long time consequently of change of stress-strain condition and accumulation of viscous-plastic strains on all volume of soil mass, composing slide slope. The catastrophic phase can come in only case, when collecting strains of shear along some surface reach limiting meaning $\gamma_{(x,y)} = \gamma_{\max}$, owing to what the strains of shear are located, and there is a relative displacement of one (top) part of mass concerning another (bottom). All this was observed repeatedly on slides after catastrophic displacements.

The carried out numerous laboratory tests of clay soils on the torsion apparatus of hollow cylindrical patterns and on the shear apparatus confirm such mechanism of shear strains development down to localization them on the certain plane.

The soil pattern in the process of kinematical loading (given displacements) tests shear strains on all height, not breaking continuity so long as the shear strain will not reach limiting meanings for the given kind of soils and for the data of density - humidity. For the most of all clay soils these strains are within the limits of 7-10%. After achievement of shear (angular) strain of this value is observed the localization of shear strain in soil patterns, formation of a sliding surface and sharp fall of resistance to shear. Thus the strains in the top and bottom parts of a pattern further do not change, and their displacement occurs on the formed plane of sliding C-C (Fig. 1). Besides the stress of shear at $\gamma = \gamma_{\max}$, reach the maximum too, i.e. peak meaning (peak strength) and then quickly fall after formation of sliding surface up to the minimum, i.e. up to residual strength.

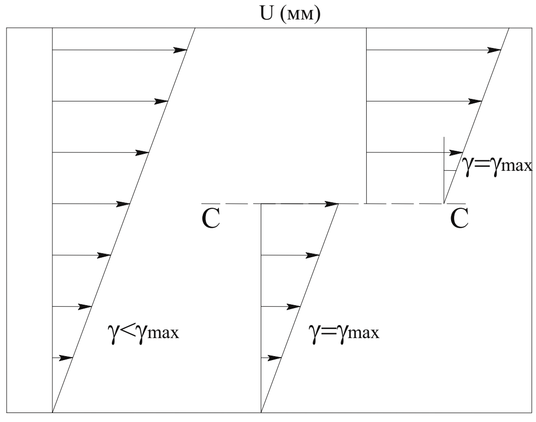

Fig.1 The basic scheme of development of soils' angular strains on apparatuses of ring torsion and of shear.

It is obvious, that in soils' mass, composing sliding body, the formation of a sliding surface occurs more difficultly. It is caused by heterogeneity of a structure and stress-strain condition of slopes, influence of numerous slide-formed factors (hydro-geological conditions, processes of humidifying, hardening, human activity on slope etc.), which influence is difficult for simulating in laboratory conditions. Therefore not always creep process comes to the end by a catastrophic image, this process can occur many years with different intensity.

Thus, appear a necessity of quantitative forecasting sliding displacements in time. The account of slopes on strain (in time) is necessary not only for protection of environmental territory (ecological task), but especially is necessary when soils' masses on slopes and declivities serve the bases or environment of various structures, including buildings, roads and highways, pipelines, tunnels, supports of electrotransfers' lines etc. Many of listed structures are sensitive to strains of their bases and can not sustain non-uniform displacements and for them there can appear damaging situation.

Now for quantitative forecasting of sliding displacements in time and also horizontal displacements of hydrotechnical structures is widely used the equation of viscous-plastic flow of Bingham-Shvedov-Maslov. Due to the simplicity and limited quantity of parameters which are included in this equation (three), it allows to solve many applied tasks of geomechanics by an estimation of stress-strain condition of soil masses. The main lack of this equation consist that it excludes an opportunity of forecasting of shear strains at shear stress smaller $\tau_{\lim}$ and does not take into account the dependence of viscosity from tangential and normal stress. At the same time, observation for numerous sliding slopes and bases of hydrotechnical structures and for retaining walls show, that the shear strain in clay soils develop at any meanings shear stress and long time, not passing in a phase of fading creep. Thus, the more degree of approximation of the strain condition to limiting $\Omega = \tau / \tau_{\lim} \geq 1$, the above speed of shear strain, and at $\tau \geq \tau_{\lim}$ occurs qualitative jump in the dependence $\tau = f\left(\dot{\gamma}\right)$. The dependence for this (second) section is described by the equation of Bingham-Shvedov-Maslov, i. e.

$$\dot{\gamma}_{vp} = \frac{\tau - \tau_{\lim}}{\eta_{vp}} \ . \tag{1}$$

On this site of shear strain speed are great and reach (10^{-3}-10^{-5}) sec^{-1}, that has a place not always in natural conditions.

The greatest interest represents an initial (flat) site of the dependence $\tau = f\left(\dot{\gamma}\right)$, when the speeds of angular strains do not surpass 10^{-6} sec^{-1}.

Actually, the observations for sliding displacements of slopes and for displacements of retaining and hydrotechnical structures show, that the real speeds of displacements on a surface of clay soils' mass by capacity from several meters up to tens meters change in limits from one - two of centimeters up to ten-twenty centimeters per one year, that corresponds to speed of angular strains from 10^{-6} up to 10^{-10} sec^{-1}, and their viscosity varies depending on speed of strains. Such angular strains correspond to an initial site of dependence $\tau = f\left(\dot{\gamma}\right)$.

In this connection there is a necessity of the description of a viscous-plastic flow's curve (strains) clays, including initial (flat) and second (abrupt) sites of dependence $\tau = f\left(\dot{\gamma}\right)$. It is possible at use bilinear or nonlinear aforesaid dependence.

So, for example, at bilinear dependence we have:

At $\tau \leq \tau_{\lim}$ - $\dot{\gamma}_v = \dfrac{\tau}{\eta_v}$;at $\tau > \tau_{\lim}$ - $\dot{\gamma}_{vp} = \dfrac{\tau}{\eta_v} + \dfrac{\tau - \tau_{\lim}}{\eta_{vp}}$, (2)

where $\tau_{\lim} = \sigma \cdot tg\ \varphi_l + c_l$, (3)

φ_l and c_l - parameters of peak strength, determined by results of kinematical or relaxative tests on torsion or shear apparatuses, and σ - effective part of a normal stress (not account of pores pressure).

η_v and η_{vp} - parameters of viscous and viscous-plastic flow at shear (Pa $\cdot$ sec),

and $\dot{\gamma}_{vp}$ - speed of viscous-plastic shear strain.

The first member of the equation (2) describes strain speeds in an interval - $0 < \tau \leq \tau_{\lim}$ on a flat site, and the second member - at $\tau > \tau_{\lim}$ on an abrupt site of this dependence.

At use of nonlinear dependence we have an opportunity of the curve description $\tau = f\left(\dot{\gamma}\right)$ on all a range from τ equal to zero up to $\tau_{\max} > \tau_{\lim}$ (from $\Omega = 0$ up to $\Omega = 1$), i.e

$$\dot{\gamma} = \dot{\gamma}_{\min} \cdot \exp \frac{\Omega\left(\dot{\gamma}\right) - \Omega_{\min}}{\lambda_\Omega} , \tag{4}$$

or $\Omega\left(\dot{\gamma}\right) = \Omega_{\min} + \ln\left(\dfrac{\dot{\gamma}}{\dot{\gamma}_{\min}}\right) \cdot \lambda_\Omega$, (5)

where $\lambda_\Omega = \dfrac{\Omega_{\max} - \Omega_{\min}}{\ln\left(\dot{\gamma}_{\max}\right) - \ln\left(\dot{\gamma}_{\min}\right)}$, and $\Omega_{\max}$ and $\Omega_{\min}$ maximal ($\Omega_{\max} = 1$) and minimal meanings of a degree of approximation to a limiting condition (peak durability) at the maximal and minimal values of speeds of angular strain accordingly, and $\dot{\gamma}_{\max} = 1$ sec^{-1}, $\dot{\gamma}_{\min} = 10^{-9}$ sec^{-1}.

For a speed account of shear strains on (4) it is necessary to define only one parameter λ_Ω for the given kind of clay soils at the given speed interval of angular strains $\dot{\gamma}_{\max}$ and $\dot{\gamma}_{\min}$. Value λ_Ω characterizes an incline of a straight line Ω - $\ln\left(\dot{\gamma}\right)$, and it is various for various soils. Parameter λ_Ω , shows which increment of an approximation degree to a limiting condition is necessary to realize for soil to increase the natural logarithm of speed of soils angular strains by unit. At Fig.2 are given dependences Ω - $\ln\left(\dot{\gamma}\right)$, approximated by straight lines for five soils varieties: 1)yurskaya clay of the Volga's layer from the basis of a high-rise building on Davydkovskaya street in Moscow (σ = 0,2; 0,4; 0,7 MPa); 2) yurskaya clay of the Oxford's layer (σ = 0,6 MPa) and 5) morenny loam (σ = 0,2 MPa) of a sliding slope on Vorobyevych mountains in Moscow - test on shear; 4) clays of a sliding slope from the district of Sarapul (σ = 0,2 MPa); 3) quaternary clay (σ = 0,2 MPa) of a sliding slope of Zagorskaya HAES from Sergiev Posad in Moscow region.

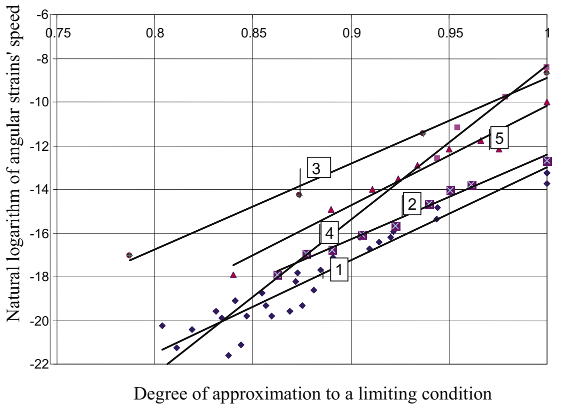

Fig.2 Dependence of angular strains' speed on degree of approximation to a limiting condition

In essence in the nonlinear dependence (4) parameter λ_Ω replaces two parameters η_v and η_{vp} - in the bilinear dependence (2) and allows to predict speeds of angular strain $\dot{\gamma}$ at any meanings of an approximation's degree to a limiting condition $\left(0 \div \Omega_{max}\right)$ and at difficult stress condition.

Moreover, in offered model the expression $\Omega = \tau \ / \ \tau_{max}$ can be calculated on a direction of realized trajectory of soil loading of the basis with parameter of a loading trajectory $K_\sigma = \Delta\sigma / \Delta\tau$, then the expression (4) can take into account trajectory of soil loading too.

It is necessary to note, that for achievement of limiting meanings of shear strain $\dot{\gamma}_{max}$, which is the characteristic for the given kind of soil and changes in limits from 7 up to 10 % in a kinematical mode of test with speed of angular strains

smaller then $\dot{\gamma}$ = 10^{-9} sec^{-1}, one test will make approximately 300 years.

Developed by us the kinematical-relaxing method of soils' test on the apparatus of ring shear allows to receive the minimal speeds of shear strains in a short interval of time.

For this purpose pattern in a given kinematical mode of shear strains' speeds $\dot{\gamma} \le \dot{\gamma}_{max}$ is brought to the peak strength $\tau < \tau_{max}$ and is translated in a relaxing mode of test by fixing the accumulating shear strain consequently of successive connection with dynamometer of final rigidity. In this system occurs relaxation of stress and additional development of shear strains with speeds varied (decreasing) in a wide range in time. In such tests it is possible to receive at one soil pattern the dependence $\Omega = f\left(\dot{\gamma}\right)$ in a wide range of change of angular strains speeds that is urgent for soil patterns with the not broken structure, when frequently it is difficult to pick up patterns - twins.

As an example of use of the offered equations of viscous-plastic behaviour of clay soils and is considered the forecast of sliding displacement speed of a slope on Vorobyevych mountains in Moscow at construction of a cable-chair road. The numerical modeling of stress-strain condition was carried out in conditions of flat strain through the finite elements' program «UniWAY», developed by A.N.Vlasov and M.G.Mnushkin. The task about stress-strain condition of a sliding slope was solved by the appendix of gravitation to the sliding slope of modern geometry.

The authors of this program together with Z.G.Ter-Martirosian and M.V.Proshyn after the decision of a task about stress-strain condition of a sliding slope in elastic-plastic putting-up (at soil model of Drukker-Prager) for calculating area of a sliding slope calculated degrees of approximation to a limiting condition $\Omega = \tau \ / \ \tau_{max}$, on which in various points of the basis and slope the speeds of angular strains were determined by numerical integration.

The afore-said numerical accounts have allowed further to receive speeds of horizontal displacements of a sliding body, by numerical integration on meanings of angular strains. The received meanings of horizontal displacements' speeds (up to 1,5 cm per one year - Fig. 3) will be well coordinated to results of natural measurements of horizontal displacements' speeds of a sliding body on a slope of Vorobyevych mountains in Moscow.

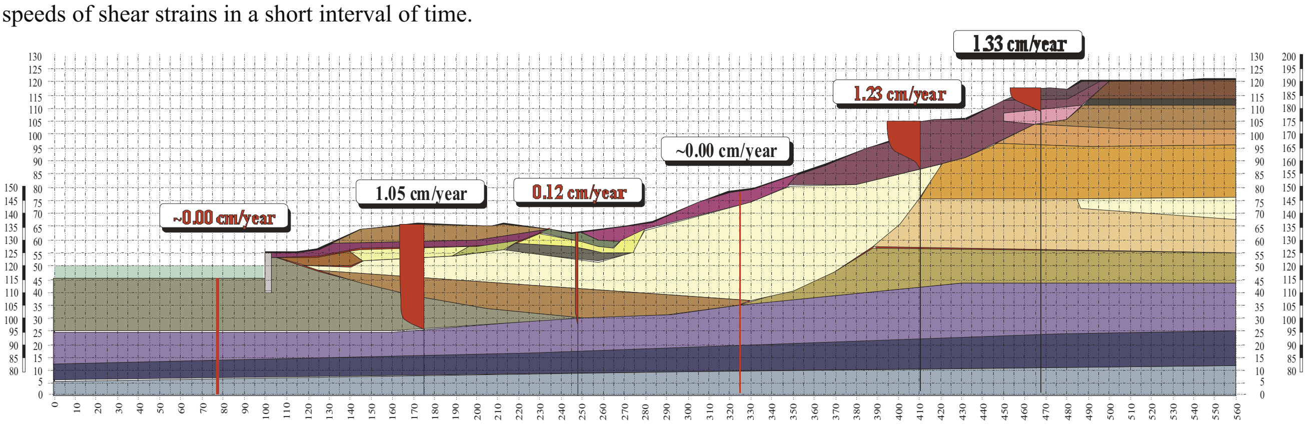

Fig.3 Absolute speeds of horizontal displacements by results of numerical accounts of a sliding slope's basis of cable-chair road on Vorobyevych mountains.

3 THE BASIC CONCLUSIONS

1. The quantitative estimation of slopes and declivities should include as accounts by I group of limiting condition, and by II group of limiting condition, especially when they serve the bases or environment of engineering structures and communications sensitive to non-uniform strains.

2. For the forecast of speeds of soil angular strains, it is expedient to use nonlinear dependence (4), allowing to describe speeds of shear strains in a wide range of stress-strain conditions' change, that has essential importance for practice.

3. The kinematical-relaxing mode of clay soils' tests in apparatuses of ring shear and of torsion allows to define rheological parameters by the above-stated dependences, and also meanings of peak and residual strengths at one pattern.

4. The quantitative forecasting of sliding displacements with use of rheological dependence (4) considerably becomes sim-

pler in the assumption of an invariance of the stress condition of a slope in the given interval of time.

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