# Formation conditions and parameters of mini-landslides on agricultural slope landscapes

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**Abstract.** The paper investigated the stability of agricultural land slopes to mini-shear landslides on the basis of a numerical assessment of the influence of soil parameters in the Volga-Vyatka region of Russia on its frictional properties. It has been established that at a moisture content of $0.30 \pm 0.04$ $m^3/m^3$ of gray forest soil and $0.22 \pm 0.04$ $m^3/m^3$ of soddy-podzolic soil, the contribution of soil stickiness to the soil friction coefficient was the most significant, which was due both to the aggregation of soil particles and to the destruction of soil capillaries, and corresponded to the lower limit of soil plasticity. On the basis of the ratio proposed in the paper, a numerical assessment of the ratio of the power and length of the landslide along the slope for different slope angles was carried out, the results of which correspond to real landslide processes on natural and artificial slopes of agricultural land.

## 1 Introduction

The intensification of processes in the agro-industrial complex, with a shortage of territories, is directly related to the need to preserve areas both on natural and artificial slopes. Artificial change in the shape of the relief (creation of artificial hills, reservoirs, depressions, ridges, etc.) is often a necessary direction in modern land use [1]. However, growing crops on such sloping land often leads to landslides (Fig. 1), protection from which requires significant financial costs [2, 3]. Although it is believed that by measuring and controlling soil properties it is possible to accurately determine the stability of slopes [4, 5], practice shows the opposite: in some cases, neither artificial fibers nor geosynthetics can properly strengthen the slope.

The type and mechanism of development of profile deformations are of decisive importance in assessing slope stability. When formulating the problem of assessing the stability of a slope, when the sliding surface has not yet formed, the following points are taken into account [6]: predicting the possibility of landslide formation, justifying the steepness of slopes and the need to implement appropriate measures to ensure stability. The task of assessing the stability of an existing landslide, when there is already a sliding surface, is to determine the degree of stability, the degree of threat of landslide movements for existing structures and the safety of the area, as well as to establish the content and sequence of anti-landslide measures [7].

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**Fig. 1.** Harvesting on a potentially landslide-prone slope.

Slip landslides, that is, separation and sliding displacement of land masses under the action of gravity, occurring in agricultural areas, are often caused by a decrease in the frictional properties of the soil when it is naturally moistened, washed away and cut. Friction in soil depends on moisture [8, 9] and grain size distribution [10, 11] of the soil. Within a certain range of moisture values, a significant change in the magnitude of the friction forces occurs. In a number of works, in particular in [12, 13], it was experimentally shown that the friction coefficient increases with increasing soil moisture and reaches a maximum, and then decreases. However, the generalized coefficients of the influence of moisture, porosity, and particle size distribution on friction in the soil are not given in the literature, which does not allow a numerical assessment of the frictional characteristics of the soil depending on its parameters. The problem of theoretical substantiation of the dependence of the friction force on moisture, porosity and specific surface of soil particles remains relevant for assessing and predicting the stability of slopes. In this paper, the stability of a landslide formed on a slope is analyzed on the basis of a numerical assessment of the influence of soil parameters on its frictional properties.

## 2 Materials and methods

The occurrence of a landslide, associated with a violation of the balance of forces acting on the soil mass, begins with the appearance of a crack (fault) on the slope and develops as the movement of a landslide body along the sliding surface. A network of temporary micro-streams of melt water or natural precipitation is one of the reasons for the imbalance. Micro-streams "cut" the surface and increase soil moisture. An increase in moisture leads to an increase in soil density and a change in its properties such as stickiness $L$ and coefficient of friction $\mu$.

The equilibrium state of the landslide body on the flat sliding surface (Fig. 2) is determined by the equations:

$$mg\sin i = F_\mu + F_1 \quad (1)$$

$$N = mg\cos i + F_2 \quad (2)$$

where $mg\sin i$ is component of gravity, tending to move a landslide of mass $m$; $F_\mu$ is the friction force; $N$ is the reaction force of the support (sliding surface); $F_1$ и $F_2$ are the forces due to the stickiness of $L$.

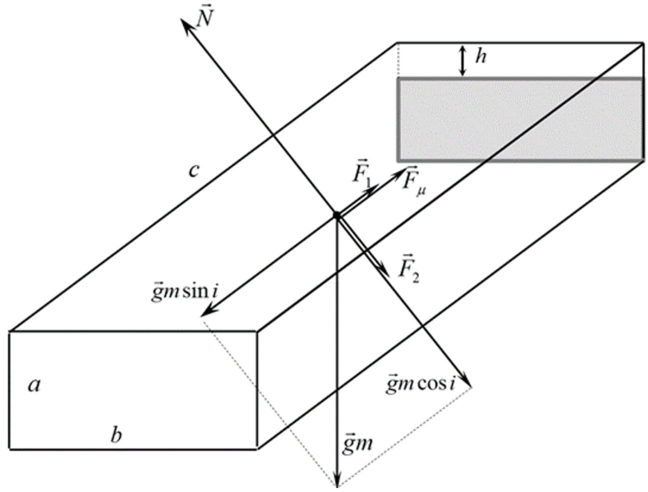



**Fig. 2.** Balance of forces.

Let *a, b* and *c* be the linear dimensions (thickness, width and length, respectively) of the landslide body, $A = bc$ is the contact area of the landslide body with the sliding surface, *h* is the depth of the crack, then the forces due to stickiness $L=F/A$ are equal to $F_1=L(a-h)b$ and $F_2=Lbc$.

Taking into account the fact that the friction force of $F_\mu=\mu N$, equations (1,2) are reduced to the form

$$mg\sin i = \mu\left(mg\cos i + Lbc\right) + L\left(a-h\right)b\,. \tag{3}$$

Representing the landslide mass *m* through its volume *V* and soil density *ρ* as $m=\rho V=\rho abc$ and denoting the ratio of the landslide thickness *a* to its length *c* and the crack depth *h* to the landslide thickness *a* as $\varepsilon=a/c$ and $\delta=h/a$, respectively, we get

$$\sin i = \mu\cos i + \frac{L}{\rho g}\left(\frac{\mu}{a} + \frac{1-h/a}{c}\right). \tag{4}$$

Usually when calculating not the entire volume of the landslide body is taken into account, but only a 1-meter-wide rock mass identified along the line of the calculated geological section. Since expression (4) does not contain such a parameter as width, its use allows you to do without this convention.

An extremum study of the second term on the right side of expression (4) gives

$$\begin{cases} \left.\left(\dfrac{\mu}{a} + \dfrac{1-h/a}{c}\right)\right|_a = 0, \\ \left.\left(\dfrac{\mu}{a} + \dfrac{1-h/a}{c}\right)\right|_c = 0 \end{cases} \tag{5}$$

and shows that in the interval $0<h<a$ there is a stationary point that is not an extremum point.

Let us determine the relationship between *a* and *c* for different values of the slope and satisfying (4):

$$\left(\sin i-\mu\cos i\right)\frac{\rho g c}{L}=\frac{\mu}{\varepsilon}+1-\delta\,. \tag{6}$$

Expressing $\varepsilon$ from the equation (6) we get

$$\varepsilon=\frac{\mu}{\left(\sin i \quad \mu\cos i\right)\frac{\rho g c}{L}+\delta \quad 1}\,. \tag{7}$$

In the obtained expression (7), $L$ and $\mu$ for each specific soil are functions of moisture $w$ and must be taken into account in the calculations.

Dependences of the coefficient of friction and stickiness on the type, density and soil moisture can be obtained by considering soil moisture as a phase in contact with the solid phase of the soil and soil air. The relationship between the soil moisture potential $\psi$ and surface energy $E$ at the interface between the phases is written as $\psi=E/m_{\mathrm{w}}$ (where $m_{\mathrm{w}}$ is the mass of moisture) [14], and, when considering the soil-water retention curve, is represented through the equivalent pressure $p=\rho\psi$ (where $\rho$ is the density of soil moisture) [15]. Taking into account the soil porosity $n_0$ ($\mathrm{m}^3/\mathrm{m}^3$), we express the density $\rho$ of the soil as follows

$$\rho=\rho_{\mathrm{s}}\left(1-n_0\right)+\rho_{\mathrm{w}}\,, \tag{8}$$

where $\rho_{\mathrm{s}}$ is the density of soil solid phase and $\rho_{\mathrm{w}}$ is the density of water.

The pressure of soil moisture is due to its interaction with both the solid phase of the soil and its interaction with soil gas. The contribution $p'$ and $p''$, respectively, of each of the specified interactions to the total pressure of soil moisture can be represented as [16]:

$$p'=A\Omega_0^3\left(w^{-3}-n_0^{-3}\right), \tag{9}$$

$$p''=\Omega_{\mathrm{c}}\sigma_{\mathrm{lg}}\,, \tag{10}$$

where $A$ is the Hamaker constant (J) divided by $6\pi$; $\Omega_0$ – volumetric specific surface of the solid phase of the soil ($\mathrm{m}^2/\mathrm{m}^3$); $n_0$ – soil porosity ($\mathrm{m}^3/\mathrm{m}^3$); $w$ – volumetric moisture ($\mathrm{m}^3/\mathrm{m}^3$); $\Omega_{\mathrm{c}}$ – is the volumetric specific surface area of the condensed soil phase ($\mathrm{m}^2/\mathrm{m}^3$) and $\sigma_{\mathrm{lg}}$ is the specific free surface energy at the water/air interface ($\mathrm{J}/\mathrm{m}^2$).

The relation between $\Omega_0$ and $\Omega_{\mathrm{c}}$ is realized through the function $D(w,n_0)$ [17] which depends on the specific number of soil pores, their orientation and structure:

$$\Omega_{\mathrm{c}}=\Omega_0 D\left(w,n_0\right)=\Omega_0\left[1-\left(\frac{w}{1-n_0+w}\right)\right]-\left(1-\frac{w}{n_0}\right)^{2.5}. \tag{11}$$

Stickiness, in turn, is due to the interaction of the solid phase of the soil with the surrounding bodies through the liquid phase of the soil and depends on the average size and specific number of capillary menisci in the soil, as well as the degree of their filling with water, which, like the coefficient of friction in the soil, is determined by the grain size, chemical and mineralogical composition, structure and soil moisture. Stickiness, in particular, is characterized by three parameters: maximum stickiness value $L_{\max}$, maximum sticking moisture $w_{\max}$ and initial sticking moisture $w_0$ [18]. Stickiness does not appear when the moisture is below $w_0$, at which the water pressures are equal in the form of a "film" ($p'$) and a "cuff" ($p''$) [19, 20]. Sticking occurs at moisture values $w > w_0$ as a result of the pressure difference $\Delta p = p'' - p'$ which taking into account (8), (9) and (10), is obtained in the form

$$\Delta p = p'' - p' = \sigma_{\mathrm{lg}} \Omega_0 D\left(w, n_0\right) - A\Omega_0^3\left(w^{-3} - n_0^{-3}\right). \tag{12}$$

The dependence of the friction coefficient on moisture, density and type of soil can be obtained from the following considerations. With an increase in porosity, the area of actual contact between soil particles decreases. Dry friction manifests itself at low values of moisture, stickiness begins to play a significant role at moisture above $w_0$. It follows that the coefficient of friction $\mu$ has two parts. One part is directly proportional to the fraction of the solid phase of the soil ($1-n_0$), the surface area of its contact with the liquid $w^{2/3}$ and ($1-\beta w$) [21]. The other part is directly proportional to the stickiness $L$, which depends on the mechanical composition of the soil and is determined through the specific surface area $\Omega_0$ and the function $D(w,n_0)$, which depends on the particle size distribution. It should be noted that the content of clay in the soil (particles smaller than 0.01 mm) has a significant effect on the coefficient of friction $\mu$. The coefficient of friction is directly proportional to the content of clay $\Omega_0$, i.e. physical clay content, since stickiness, in its turn, is directly proportional to the specific surface area of the solid phase of the soil $\Omega_0$. As a result, for the coefficient of friction we have:

$$\mu = \alpha\Omega_0 w^{2/3}\left(1-\beta w\right)\left(1-n_0\right) + \gamma L\,, \tag{13}$$

where $\alpha$, $\beta$ and $\gamma$ – coefficients.

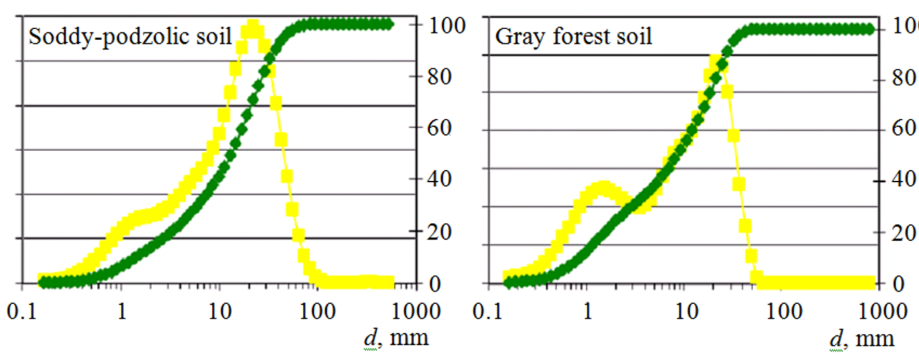



**Fig. 3.** Granulometric composition of the investigated soils: differential and cumulative particle curves (content of fractions in percent depending on particle size $d$).

The objects of study were the slopes covered with gray forest and soddy-podzolic soils of the Chuvash Republic (Russia). The granulometric composition of the particles of the studied soils is presented in Fig. 3. The porosity $n_0$ and the specific (per mass unit) surface of $A_\mathrm{m}$ particles were 0.56 and 66.5 $\mathrm{m}^2$/g for dark gray forest soil and for soddy-podzolic soil 0.53 and 31.4 $\mathrm{m}^2$/g respectively.

## 3 Results

The dependences of the friction coefficient on moisture for gray forest and soddy-podzolic soils obtained numerically on the basis of relation (13) are shown in Fig. 4. When the moisture value is less than a certain critical value $w_0$ stickiness does not appear, that is $L$=0 and formula (4) returns to its classical form.

Substitution of the known functional dependences $\rho=\rho(w)$, $\mu=\mu(w)$, $L=L(w)$ into equation (7) allows to obtain relations between $\varepsilon$ and $c$ (or between $a$ *and* $c$) for any values of the angle of inclination $i$ and slope length $c$.

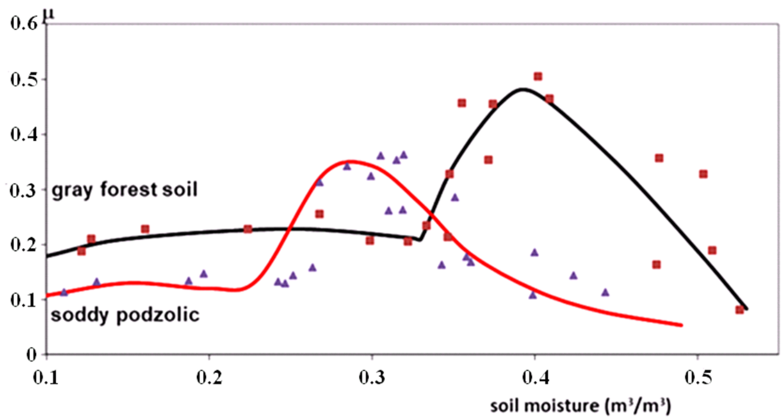
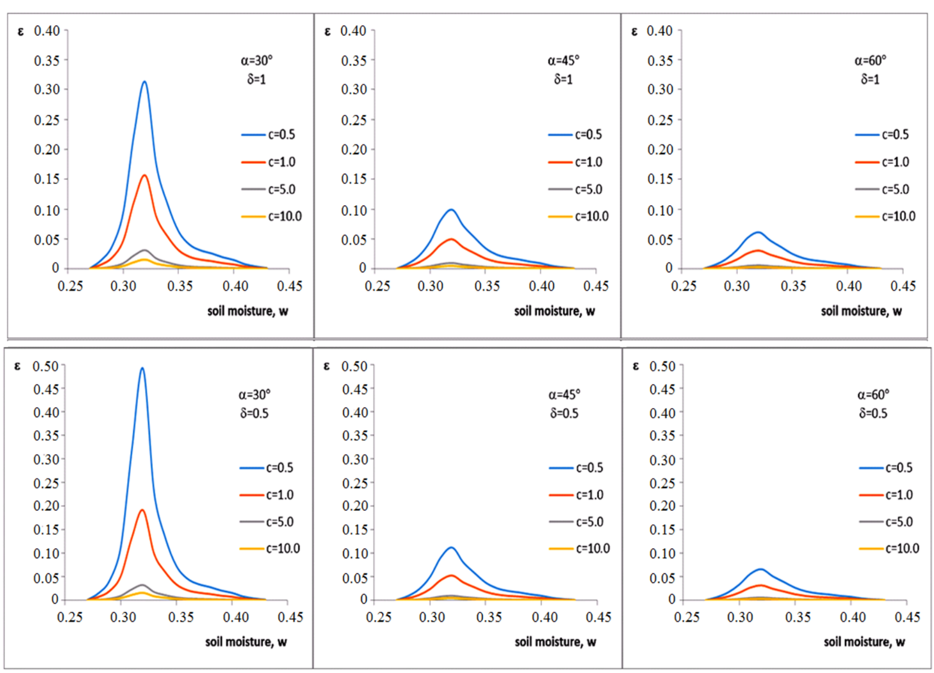



**Fig. 4.** Dependence of the coefficient of friction on soil moisture.

The results of calculations of the dependence of the ratio of the landslide body thickness to its length on moisture content for various slopes for gray forest and soddy-podzolic soils are presented in Fig. 5 for the following parameter values: the length of the landslide body $c$ = 0.5÷10 m, the density of the solid phase of the soil $\rho_s$ = 2430 kg/m$^3$, soil porosity $n_0$=0.48. The results obtained show that stickiness does not manifest itself up to a certain moisture content $w_0$, namely for gray forest soil – 0.30 ± 0.04 m$^3$/m$^3$, soddy-podzolic soil – 0.22 ± 0.04 m$^3$/m$^3$. These moisture values correspond to the optimal aggregation of soil particles, the rupture of soil capillaries, and the lower limit of soil plasticity.



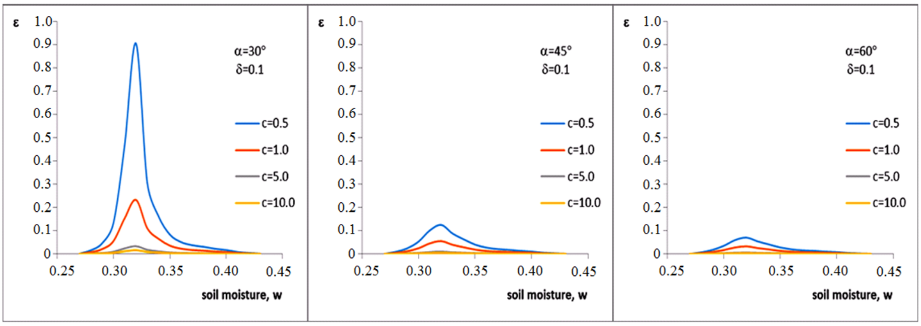



**Fig. 5.** Dependence of the ratio of the landslide body thickness to its length on soil moisture for various slopes and values $\delta = h/a$.

The method described above has been tested on natural and artificial slopes of agroobjects in Chuvash republic (Russia). In particular, for a landslide (soddy-podzolic soil, slope 33°) located on Cheboksary district of Chuvash Republic (Fig. 6), with landslide length $c$ = 14 ÷ 18 m, its average height $a$ is 0.25 ÷ 0.45 m, that is corresponds to $\varepsilon$ = 0.021÷0.038 which is consistent with the calculation results presented above.

a b c

**Fig. 6.** Mini-slides on slopes (a: from 7 to 12 m; b, c: from 0.5 to 1 m).

## 4 Conclusions

The dependence of the soil friction coefficient on the soil type, density, and soil moisture was obtained when considering soil moisture as a phase in contact with the solid phase of the soil and soil air. Soil stickiness makes a significant contribution to the soil friction coefficient at soil moisture values in the range of 0.30 ± 0.04 $m^3/m^3$ for gray forest soil and 0.22 ± 0.04 $m^3/m^3$ for soddy-podzolic soil.

An expression was proposed, according to which a numerical assessment of the ratio of the power and length of a landslide along the slope for different slope angles was carried out, based on the obtained dependence of the soil friction coefficient on the type, density and moisture of the soil. The numerical estimates carried out correspond to real landslide processes on natural and artificial slopes of agricultural lands.

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