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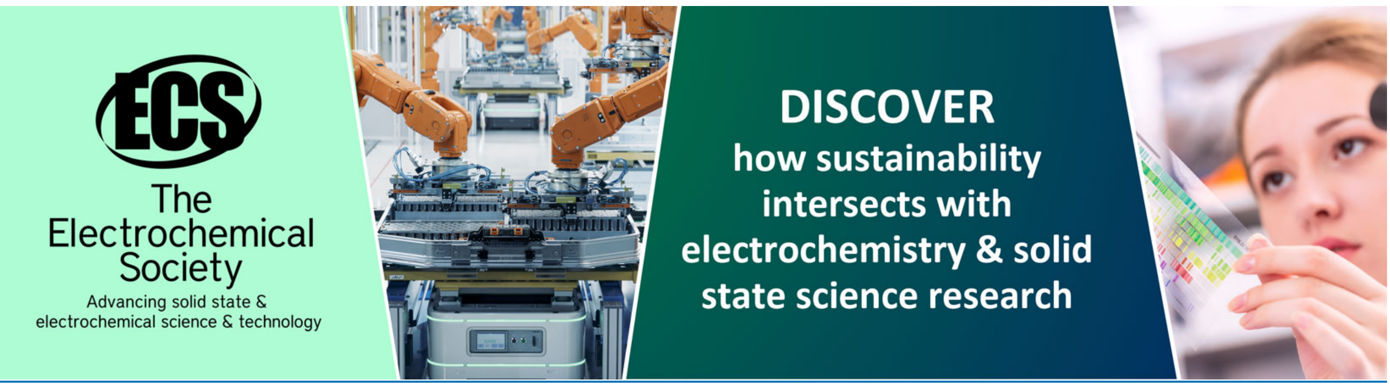

Stability of Artificial Urban Slopes to Mini-Landslides

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Abstract. The growth of cities causes changes in the natural landscape and is associated with the construction of structures on natural and artificial slopes. In this regard, large areas become susceptible to landslide danger. The paper considered slip microslides that appear on the slopes of urbanized areas. The functional dependence of the coefficient of friction in soil on moisture, density and type of soil was obtained on the basis of considering soil moisture as a phase that has interfaces with soil air and the solid phase of the soil. For gray forest and soddy podzolic soils, the values of moisture content (0.30±0.04 m^3/m^3 and 0.22±0.04 m^3/m^3, respectively) were revealed, at which the stickiness of the soil begins to affect the friction. Using the obtained dependence of the coefficient of friction in the soil on moisture, density and type of soil, an expression was proposed to estimate the ratio of the thickness and length of a landslide for various angles of slope inclination. The carried out numerical estimates of geometric landslide characteristics were consistent with real landslide processes on artificial slopes of urban planning objects.

1. Introduction

The process of growth of cities and urban population is continuously associated with the need to solve problems associated with the construction of structures on natural slopes or the construction of artificial slopes. Artificial change in the shape of the relief (the creation of artificial hills, reservoirs, depressions, ridges, etc.) is a promising direction in modern landscape architecture [1]. In this regard, large urban areas become susceptible to landslide hazards [2], protection from which requires significant financial costs [3]. Although it is believed that due to the measurement and control of soil properties, it is possible to accurately determine the stability of the constructed 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 profile deformation development are crucial in assessing slope stability. When setting 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]: forecasting the possibility of landslide formation, substantiating the steepness of slopes and the need to implement corresponding 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 the threat of landslide movements for existing structures and the safety of the terrain, as well as to establish the content and sequence of anti-landslide measures [7].

Slip landslides, that is, separation and sliding displacement of earth masses under the influence of gravity, arising in urbanized areas, are often caused by a decrease in the frictional properties of the soil when it is naturally moistened, washed away and undercut. Friction in the soil depends on the moisture content [8, 9] and particle size distribution [10, 11] of the soil. Within a certain range of moisture values, a significant change in the value of the friction forces occurs. In a number of works, in particular in [12, 13], it was experimentally shown that the coefficient of friction increases with increasing soil moisture and reaches a maximum, and then falls. However, the generalized coefficients of the influence of moisture, porosity and particle size distribution on friction in the soil are not presented in the literature, which does not allow for a numerical assessment of the frictional characteristics of the soil depending on the soil parameters. The problem of theoretical substantiation of the dependence of the friction force on moisture, porosity and specific surface area 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 based on 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 disturbance in 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 the landslide body along the sliding surface. A network of temporary micro-streams of melt water or natural precipitation is one of the causes of 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 μ.

The condition of equilibrium of the landslide body on a flat inclined sliding surface (figure 1) is determined by the equations:

$$\begin{aligned} mg\sin\beta &= F_\mu + F_1, \\ N &= mg\cos\beta + F_2, \end{aligned} \tag{1}$$

where $mg\sin\beta$ is the gravity component tending to shift a landslide with mass m; F_μ is the friction force; N is the reaction force of the support (sliding surface); $F_1 = Lab$ and $F_2 = Lbc$ are the forces, due to stickiness $L = F/A$; A is the contact area of the landslide body with the sliding surface; a, b, and c are the linear sizes (thickness, width and length, respectively) of the landslide body.

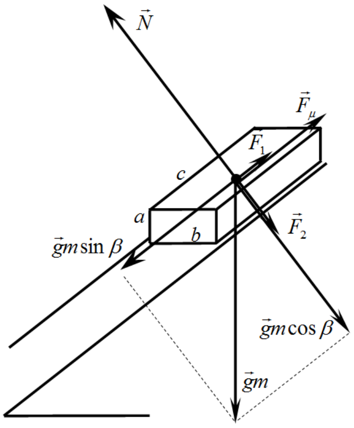

Figure 1. Balance of forces.

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

$$mg\sin\beta = \mu\left(mg\cos\beta + Lbc\right) + Lab. \tag{2}$$

Denoting the ratio of the landslide body thickness a to its length c as $\varepsilon = a/c$ and expressing the landslide body mass $m = \rho abc$ in terms of its volume $V = abc$ and soil density ρ, we obtain

$$\sin\beta = \mu\cos\beta + \frac{L}{\rho gc}\left(\frac{\mu}{\varepsilon} + 1\right). \tag{3}$$

Usually, when calculating, not the entire volume of the landslide body is taken into account, but only a meter-wide soil mass, allocated along the line of the calculated geological section. Since expression (3) does not contain such a parameter as width, its use allows us to do without this practice.

Obtaining the dependences of stickiness and friction coefficient on moisture, density and type of soil is possible when considering soil moisture as a phase that has interfaces with soil air and with the solid phase of the soil. The surface energy E of the phase boundaries is associated with the potential of soil moisture $\psi = E/m_w$ (where m_w is the mass of moisture), which, when considering the soil water retention curve, is replaced by equivalent pressure $p = \rho\psi$ (where ρ is the density of soil moisture) [14]. Soil density ρ can be expressed in terms of porosity Π_0, density of the solid phase ρ_s and water density ρ_w by the formula:

$$\rho = \rho_s(1-\Pi_0) + \rho_w . \tag{4}$$

The pressure of soil moisture p', due to the interaction of moisture with the solid phase of the soil, and the pressure p'', due to the interaction of moisture with soil gas, can be represented as [15]:

$$p' = A\Omega_0^3\left(\frac{1}{w^3} - \frac{1}{\Pi_0^3}\right), \tag{5}$$

$$p'' = \Omega_c \sigma_{lg}, \tag{6}$$

where A is the Hamaker constant (J) divided by 6π; Ω_0 is the volumetric specific surface area of the solid phase of the soil (m^2/m^3); Π_0 is the soil porosity (m^3/m^3); w is the volumetric moisture (m^3/m^3); Ω_c is the volumetric specific surface area of the condensed soil phase (m^2/m^3) and σ_{lg} is the specific free surface energy at the water/air interface (J/m^2).

The relationship between Ω_0 and Ω_c is realized through the function $D(w, \Pi_0)$ [16], which depends on the specific number of soil pores, their orientation and structure:

$$\Omega_c = \Omega_0 D(w, \Pi_0) = \Omega_0\left(1 - \frac{w}{1-\Pi_0+w}\right)\cdot\left(1-\frac{w}{\Pi_0}\right)^{2.5}. \tag{7}$$

In turn, the stickiness due to the interaction of the soil solid phase 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, and the degree of their filling with water that, as the coefficient of friction in the soil, is determined by particle 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 [17]. Stickiness does not manifest itself when the moisture is below w_0, at which there is an equality of water pressures in the form of a "film" (p') and a "cuff" (p'') [18, 19]. Sticking occurs at moisture values $w > w_0$ as a result of the pressure difference $\Delta p = p' - p''$, which, taking into account (5), (6) and (7), is obtained in the form:

$$\Delta p = p'' - p' = \sigma_{lg}\Omega_0 \cdot D(w, \Pi_0) - A\Omega_0^3\left(\frac{1}{w^3} - \frac{1}{\Pi_0^3}\right). \tag{8}$$

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. Accordingly, dry friction takes place at low moisture, and stickiness begins to appear with an increase in moisture above w_0. Consequently, the coefficient of friction μ must include two components. One of them is proportional to the stickiness L associated with the mechanical composition of the soil through the specific surface area Ω_0 and the function $D(w,\Pi_0)$, which depends on the particle size distribution. Another component is proportional to the proportion of the solid phase of the soil ($1-\Pi_0$), the surface area of its contact with the liquid $w^{2/3}$ and ($1-\beta w$) [20]. This takes into account the significant effect on the friction coefficient μ of the content of physical clay (particles smaller than 0.01 mm). Since friction is associated with stickiness, which is directly proportional to the specific surface area of the solid phase Ω_0, then, therefore, the friction coefficient should be directly proportional to Ω_0, that is physical clay content. As a result, the coefficient of friction is expressed as follows:

$$\mu = \alpha\Omega_0 w^{2/3}(1-\beta w)(1-\Pi_0)+\lambda L\,, \tag{9}$$

where α, β and γ are dimensionless coefficients.

The objects of this study were slopes covered with gray forest and soddy podzolic soils of the Chuvash Republic (Russia). The particle size distribution of the studied soils is shown in Table 1. The porosity Π_0 and the specific (per mass unit) surface A_m of particles were 0.56 and 66.5 m^2/g for the gray forest soil, and 0.53 and 31.4 m^2/g for soddy podzolic soil, respectively.

Table 1. The granulometric composition of investigated soils.

Particle size, mm	The content of fractions, %	
	Gray forest soil	Soddy podzolic soil
0.001	28.2	18.7
0.005	16.4	10.3
0.01	12.1	7.6
0.05	36.2	52.5
0.25	5.8	8.8
1	1.3	2.1

3. Results and discussion

The dependences of the friction coefficient on moisture content for gray forest and soddy-podzolic soils, obtained numerically on the basis of relation (9), are shown in figure 2. When the moisture value is less than a certain critical value w_0, stickiness does not appear, that is, L = 0 and formula (3) returns to its classical form.

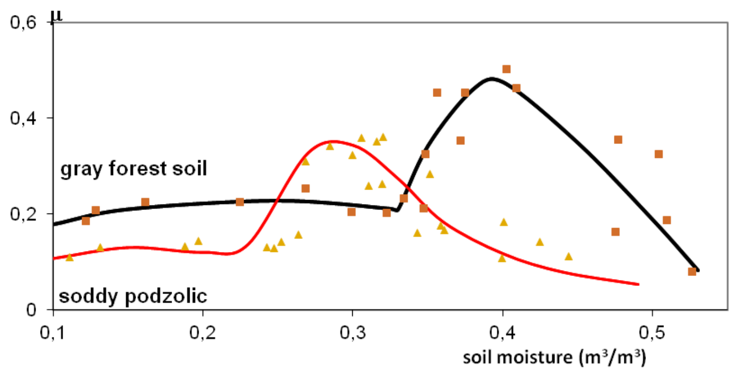

Figure 2. Dependence of the coefficient of friction on soil moisture.

From expression (3) it follows that

$$\varepsilon = a/c = \mu\left(\frac{(\sin\beta-\mu\cos\beta)\rho gc}{L}-1\right)^{-1}. \tag{10}$$

Substitution of the known functional dependences $\rho = \rho(w)$, $\mu = \mu(w)$ and $L = L(w)$ into equation (10) allows one to obtain relations between ε and c (or a and c) for any values of the inclination angle β and slope length c.

The results of calculations of the ratio dependence of the landslide body thickness to its length on moisture content for various slope inclination for gray forest and soddy podzolic soils are presented in figure 3 for the following parameter values: length of the landslide body c = 5 m, density of the soil solid phase ρ_s = 2430 kg/m^3, soil porosity Π_0 = 0.48. The results obtained show that stickiness does not appear until 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 rupture of soil capillaries, the lower limit of soil plasticity and optimal aggregation of soil particles.

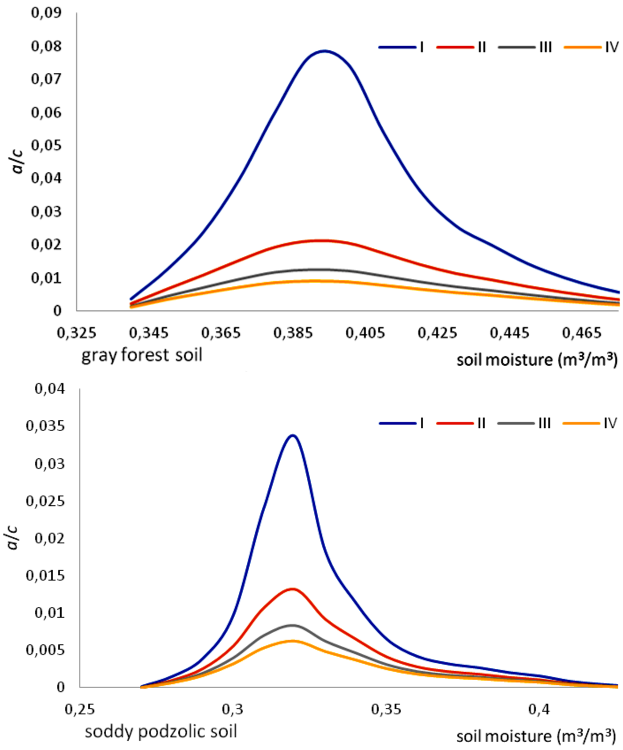

Figure 3. Dependence of the ratio of the landslide body thickness to its length on soil moisture for various slopes: I – 30°, II – 40°, III – 50°, IV – 60°.

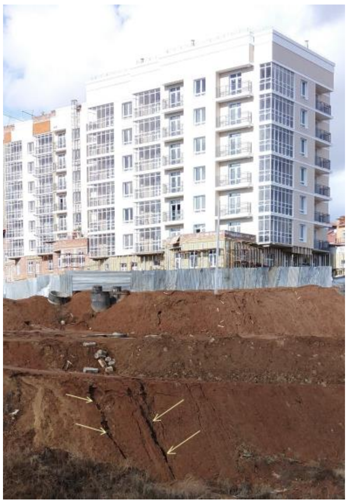

Figure 4. Landslide on an artificial slope.

The method described above has been tested on artificial slopes of urban development objects in Cheboksary (Russia). In particular, for a landslide (soddy podzolic soil, slope 43°) located on Prem'erskij proezd Street in Cheboksary (figure 4), with a landslide length c = 11÷12 m, its average height a is 0.25÷0.45 m, that is corresponds ε = 0.021÷0.038, which is consistent with the results of calculations presented in figure 3.

4. Conclusions

The functional dependence of the coefficient of friction in soil on moisture, density and type of soil was obtained on the basis of considering soil moisture as a phase that has interfaces with soil air and the solid phase of the soil. For gray forest and soddy podzolic soils, the values of moisture content (0.30 ± 0.04 m^3/m^3 and 0.22 ± 0.04 m^3/m^3, respectively) were revealed, at which the stickiness of the soil begins to affect the friction.

Using the obtained dependence of the coefficient of friction in the soil on moisture, density and type of soil, an expression is proposed to estimate the ratio of the thickness and length of a landslide for various slope angles. The carried out numerical estimates of geometric landslide characteristics are consistent with real landslide processes on artificial slopes of urban planning objects.

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