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Possibilities of analytical estimation of clay slope stability

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1. Introduction

Soil slope stability estimation is an important problem. An unstable slope slide happens unexpectedly and may cause damage to buildings and loss of lives. To avoid a slope slide its stability computing is performed. The computing lies in comparison of the forces causing the slide and resisting it.

Slope stability depends on a complex system of slope geometry, soil mechanical characteristics and hydrogeological conditions. Up to now the stability has been verified by numerical computing, whose technology is based on a trial and error method supported by a number of assumptions and simplifications. To estimate stability this technology is not convenient as well as the ways to increase it. Besides, reliability of computing results is rather of law.

Stability of an artificial slope of a highway and railway excavation and the embankment, also that of a dam slope is computed and verified in all cases. Despite that fact the slopes slid of such man made structures are also common. Nowadays the constructed international highway Via Baltica suffers from this type of deformations. According to research data of some Lithuanian scientists [1] stability of road structures makes influence not to it's longevity only, but to traffic safety also. Significant expenses are required for repairing the slopes along the road.

We have many rivers in Lithuania - approximately 1 km of river for each km^2 of area. Most valleys are deep, slopes are steep. Sedimentary soils in Lithuania are of low resistance to scour caused by the river flow [2, 3], therefore river beds are not stable, their banks slide often, bed changes are usual. Changes in a river bed affect hydraulic structures, first at all embankments [4]. The slopes of river valleys slide even more often than the banks and artificial slopes [5, 6]. Thus slope stability problem in Lithuania is rather actual [7].

About 70% of the earth surface in Lithuanian territory is formed of clay and loam. These soils possess peculiar mechanical properties. When suddenly loaded they reduce internal friction, cohesion, even liquefy. They recover and return their initial properties only after a rather long lasting period of consolidation. Thus, in a spring snow melting period, or during the intensive lasting summer shower, when top soil pores are quickly filled by infiltrating water, compression of the soil in deeper layers increases, cohesion and also an internal friction angle of soil decrease. Then slope slide takes place frequently.

The phenomenon of slope slide was investigated by many authors [8, 9], but the above mentioned peculiarities of clay slopes up to now were left without any attention [7]. The other peculiarity is that slope slid mechanics is insufficiently investigated. All known solutions of soil slope stability are based on the assumptions and done by trial-error and numerical approximation methods, which do not guarantee their reliability.

Known methods and specialized computer programs [10] have some serious shortcomings. Such important peculiarities of clay as its liquefying under vibration or sudden increment in compression and forces of porous pressure are insufficiently taken into account neither in slope stability computation technologies nor in computer programs realizing the methods of these computations.

The aim of this work is analytical determination of the dependence of a slope stability coefficient and construction of the hierarchy rank of the main forces participating in a clay slope slid phenomenon.

2. Theoretical analysis of clay slope slide phenomenon

Slope stability depends on its dimensions, mechanical properties of soil and hydro-geological conditions. If these characteristics are presented in succession according their importance to the slope stability, the ways of increasing slope stability and its estimation in computing become more visible and reliable. Let us analyze this dependence in a general case.

Slope stability is usually estimated by stability coefficient k which is expressed by the following formula

$$k = \frac{M_f + M_c + M_l}{M_g + M_s + M_p} \tag{1}$$

here M_f , M_c, M_l, M_g , M_s and M_p are the moments of friction, cohesion, lateral, gravity, seepage and pores pressure forces, respectively. Numerator of (1) $M_f + M_c + M_l$ estimates the factors creating slope resistance to the slide, denominator $M_g + M_s + M_p$ estimates the factors causing the slide.

It is evident without proof that cohesion and shear strength of soil determining M_c and M_l, maintain the slope stability. Ground water seepage and pores pressure determining M_s and M_p reduce the slope stability. The remaining two terms of M_f and M_g (1) depend on gravity force whose increment leads to enlargement of both of them. Due to the difference in their location (M_f belongs to numerator, M_g – to denominator) the influence of gravity force in general is indefinite. To clarify it let us expand formula (1) and try to get the relation between stability coefficient k and primary characteristics of slope and soil.

Let us estimate the moments in (1) in such a general form

$$M = \int_0^{\alpha_o} R dF$$

where R is an arm of elementary force dF acting on a small element of the sliding mass of the slope. Let us accept the shape of the element as a slice limited from the top side by the slope soil free surface, from the bottom – by the slide surface, from two sides – by the vertical planes perpendicular to the slope axis and located at distance *b* between them, from the two other sides – by the vertical planes parallel to the slope axis and located at distance *dl* between them (Fig. 1). Let us express the distance through the radius of the slide surface at the bottom of element *R* and the angle between the radius and horizontal direction from the slope in the following way

$$dl = R\,cos\alpha\,d\alpha \tag{2}$$

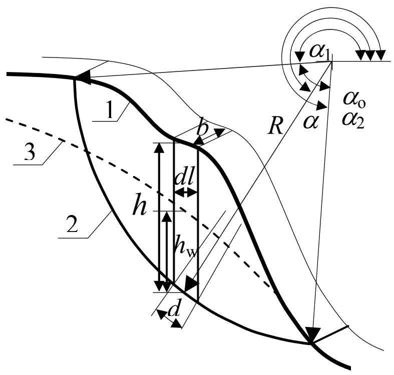

Fig. 1 Scheme of vertical cross section of the slope

Friction force dF_f increasing slope stability may be expressed through a normal (to the slide surface) component of gravity force dF_g (Fig. 2) and a tangent of internal friction angle φ of the soil at the bottom of the slice.

Friction force

$$dF_g = gdm \tag{3}$$

where *g* is gravity acceleration and mass *dm* of the slice which may be recorded as

$$dm = \rho hbdl \tag{4}$$

here ρ is average density of the soil in the slice

$$\rho = \rho_d + (\rho_w - \rho_d)\frac{h_w}{h}$$

where ρ_d and ρ_w are densities of dry and wet (saturated by water) soil, h_w and h are heights of total and saturated part of slice, respectively (Fig. 2).

The normal component of gravity force now may be expressed as

$$dF_{gn} = cos\,\alpha \cdot dF_g$$

and, according to (2), (3) and (4), friction force is

$$dF_f = tg\varphi\,cos\alpha\,g\rho hbR\,cos\alpha\,d\alpha$$

The arm of the force corresponds to the radius of the slide surface at the bottom of slice *R*. Thus the moment of friction force may be recorded now in the following form

$$M_f = gb\int_{\alpha_1}^{\alpha_2} R^2 h\,tg\varphi\,cos^2\alpha\,d\alpha \tag{5}$$

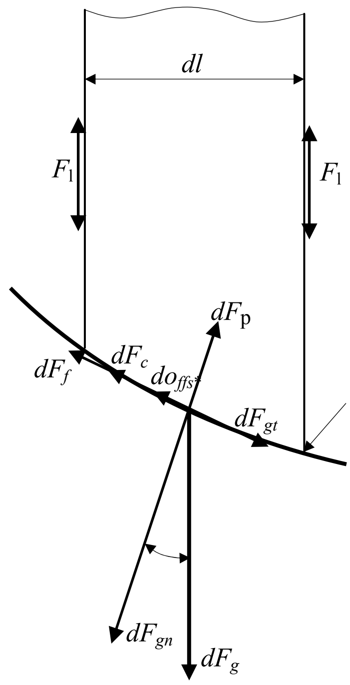

Fig. 2 Scheme of forces acting slice

Cohesion force dF_c (Fig. 2) may be expressed as a product of cohesion *C* and the area of the bottom of slice $bRd\alpha$, i. e.

$$dF_c = CbRd\alpha \tag{6}$$

The arm of the moment of force is the same as for friction force, i. e. - *R*, therefore the moment obtains the following expression

$$M_c = b\int_{\alpha_1}^{\alpha_2} R^2 C d\alpha \tag{7}$$

Lateral force (Fig. 2) dF_l may appear only in the case *R* = *var*. A change in slide surface radius *R* causes vertical shift of soil masses, also it cuts and scrubs soil at the zone of the slice wall and bottom. Resistance to vertical shift may be estimated as a product of shear stress σ_s [11] and the area of slice walls 2*hb*. Resistance to soil cut and scrub at the slice bottom may be evaluated multiplying soil shear strength σ_{s*} [12] by bottom area $bRd\alpha$. This area contains $d\alpha$, therefore it is definitely smaller than 2*hb*. Therefore only soil cut and scrub at the bottom of the slice is possible. Thus, lateral force should be expressed as

$$F_l = \sigma_{s*} bRd\alpha$$

The arm of this force in the expression of the moment corresponds to the radius of the slid surface, surface, therefore the moment acquires the following expression

$$M_1 = b\int_{\alpha_1}^{\alpha_2} R^2 \sigma_s\,d\alpha \tag{8}$$

The slope slide causing moment M_g of gravity force may be expressed from the product of tangential (to the slid surface) component of total gravity force (4) as

$$dF_{gt} = sin\alpha\, dF_g$$

According to (3) and (4), knowing that the arm of the force is R, we may have the moment as

$$M_g = gb\int_{\alpha_1}^{\alpha_2} \rho R^2 h\, sin\alpha\, cos\alpha\, d\alpha \qquad (9)$$

Seepage force [13, 14] dF_s may be understood as a drop potential energy of ground water flow which may be expressed by gravity force of water volume, equal to the lower part of the slice volume saturated by water

$$dV = h_w bdl$$

multiplied by water density ρ_w, gravity acceleration g, also hydraulic gradient I, i.e.

$$dF_s = \rho_w g h_w bIR\, cos\alpha\, d\alpha$$

The expression of the moment of seepage force obtains the following form

$$M_s = gb\int_{\alpha_1}^{\alpha_2} \rho_w R_s R h_w I\, cos\alpha\, d\alpha \qquad (10)$$

here R_s is an arm of seepage force, the approximate magnitude of which may be computed by the following formula

$$R_s = \left(R\, cos\,\alpha - \frac{h_w}{2} \right) / (1 - I)$$

Here it should be mentioned, that special hydrodynamic investigation of the ground water flow parameters should be performed to obtain ground water flow surface line, which is necessary to determine h_w and I. To avoid a complex study the simplifications are usually introduced into this computing. For example, in computing the earth dam slope stability, when there is impervious screen or clay core, hydraulic gradient I is usually so small, that moment M_s in (1) is rather small compared to the rest of the terms and may be neglected. In the case of steep ground water flow surface such simplifications should be neglected.

For convenience of practical computings moment arm R_s may be substituted by product $k_w R$, where coefficient k_w expresses the ratio

$$k_w = \frac{cos\,\alpha - \dfrac{h_w}{2r}}{1 - I}$$

Then (10) may be rewritten in a more convenient for further treatment form

$$M = gb\int_{\alpha_1}^{\alpha_2} \rho_w k_w R^2 h_w I\, cos\alpha\, d\alpha \qquad (11)$$

Pores pressure force dF_p and its moment M_p may be expressed similarly to cohesion force (6) and moment (7)

$$dF_p = p_p bRd\alpha$$

Let us express here pores pressure p_p through piezometric head

$$h_p = \frac{p_p}{\rho_w g}$$

Then the moment of pores pressure force obtains the expression

$$M_p = bg\rho_w \int_{\alpha_1}^{\alpha_2} R^2 h_p d\alpha \qquad (12)$$

Expressions (5), (7) - (9), (11) and (12) allow to rewrite equation (1) in such shape

$$k = \frac{gb\int_{\alpha_1}^{\alpha_2} \rho R^2 h\; tg\varphi\, cos^2\alpha\, d\alpha + b\int_{\alpha_1}^{\alpha_2} R^2 C d\alpha + \int_{\alpha_1}^{\alpha_2} R^2 \sigma_s d\alpha}{gb\int_{\alpha_1}^{\alpha_2} \rho R^2 h\, sin\alpha\; cos\alpha\, d\alpha + gb\int_{\alpha_1}^{\alpha_2} \rho_w k_w R^2 h_w I\, cos\alpha\, d\alpha + gb\rho_w \int_{\alpha_1}^{\alpha_2} R^2 \sigma_s d\alpha}. \qquad (13)$$

Let us divide numerator and denominator of by $gb\int_{\alpha_1}^{\alpha_2} \rho R^2 h\, sin\alpha\, cos\alpha$ and rearrange the equation. The result will be the following

$$k = \frac{\int_{\alpha_1}^{\alpha_2} tg\varphi ctg\alpha d\alpha + \int_{\alpha_1}^{\alpha_2} \frac{C + \sigma_{s*}}{\rho gh\, sin\,\alpha\, cos\,\alpha} d\alpha}{\int_{\alpha_1}^{\alpha_2} d\alpha + \rho_w \int_{\alpha_1}^{\alpha_2} \left(k_w h_w I + \frac{h_p}{cos\,\alpha} \right) \frac{d\alpha}{\rho h\, sin\,\alpha}} \qquad (14)$$

Obtained Eq. (14) is called by us differential equation of soil slope stability. All variables: φ, C, σ_{s*}, ρ, h, h_w, I, h_p should be expressed through angle α first at all to solve the equation. The first term of denominator of (14) may be integrated. Taking into account that $\alpha_2 - \alpha_1 = \alpha_o$ (Fig. 1) the term will have such shape

$$\int_{\alpha_1}^{\alpha_2} tg\varphi\, ctg\alpha\, d\alpha = tg\varphi\, ln\frac{sin\alpha_2}{sin\alpha_1}$$

Using this form of the term in the most simple computation case of slope stability, when $\varphi = const$, $C = const$ and $\sigma_{s*} = const$, (14) may be transformed further obtaining the following formula

$$k = \frac{1}{\alpha_o} \frac{tg\varphi \ln \frac{\sin\alpha_2}{\sin\alpha_1} + \frac{C+\sigma_{s*}}{g} \int_{\alpha_1}^{\alpha_2} \frac{2d\alpha}{\rho h \sin 2\alpha}}{1 + \frac{\rho_w}{\alpha_o} \int_{\alpha_1}^{\alpha_2} \left(k_w h_w I + \frac{h_p}{\cos\alpha} \right) \frac{d\alpha}{\rho h \sin\alpha}} \qquad (15)$$

In the case of weak seepage and horizontal ground water flow free surface, say in downside side of the earth dam ($I \cong 0$), and in the absence of pores pressure, for example, when consolidation process is complete ($h_p \cong 0$) formula (15) accepts the following form

$$k = \frac{1}{\alpha_o} \left(tg\varphi \ln \frac{\sin\alpha_2}{\sin\alpha_1} + \frac{C+\sigma_{s*}}{g} \int_{\alpha_1}^{\alpha_2} \frac{2d\alpha}{\rho h \sin 2\alpha} \right) \qquad (16)$$

For non-cohesive soil ($C = 0$) and cylindrical slide surface case (R = const and $\rho_s^* = 0$) formula (16) accepts this simple form

$$k = \frac{1}{\alpha_o} tg\varphi \ln \frac{\sin\alpha_2}{\sin\alpha_1} \qquad (17)$$

It is evident from the structure of (15), (16) and (17) that in the case $\alpha_1 = 0°$ and $\alpha_1 = 180°$ the formulas yield indefinite results. Therefore, angle α should be measured from horizontal direction to the right (Fig. 1). Besides, an indefinite result is obtained when $\alpha_o = 0°$ ($R = \infty$), i. e. in a case of the flat slide surface. In other cases the formulas yield interesting results which may be useful to scientific research.

In the case of nominal magnitudes of slope and soil parameters, used in the numerical analysis described below, $h_o = 30$ m; $\alpha_o = 45°$; $\beta = 20°$; $\varphi_o = 26°$ and $C = 31$ kPa GEOSLOPE [15] gives $k = 0.87$. To apply formula (17) h_o, α_o and φ_o are required. To get α_o, α and α_2 graphical method [10] has been applied, which allows to get radius of slide surface R, the indicated angles and then the stability coefficient can be computed. The result $k = 0.79$ was rather close to that computed by means of software GEOSLOPE confirming the possibility to use our derived formulas (15), (16) and (17).

Formula (15) estimates slope stability in a more evident form than (14) and much clearer than (1). The simplicity of evaluation of the gravity force influence on slope stability in formula (17) by angles α_1, α_2 and φ may only be considered as a new approach to the problem.

Hierarchy of the factors determining stability of a slope is not visible from derived formulas, but to study it under definite conditions is easy and convenient. To increase clay slope stability computation results reliability via improvement accuracy of rated parameters, rank of their importance should be determined first at all. Multiple-criteria assessment method [16] is the most suitable for such analysis, although complexity of inter-parameter links indicate great difficulties, therefore we selected simpler numerical analysis method.

3. Numerical analysis of the rank of the factors influencing clay slope stability

According to the structure of (17) only angles α_1, α_2, α_o and φ define slope stability. Gravity forces and geometric parameters h, θ and R are hidden in the indicated above angles, therefore their influence is not visible. The influence of cohesion C is not clear (Eq. (16)) and depends on the same angles. Thus, to find out the influence of primary soil and slope characteristics φ, C, β, h, θ, (Fig. 3) on slope stability the computation of stability coefficients for great number of different cases has been performed. Diapasons variation of the parameters $\varphi = 0\text{-}60°$, $h = 10\text{-}60$ m, $\theta = 15\text{-}75°$, $\beta = 0\text{-}45°$, $C = 0\text{-}60$ kPa cover all possible in Lithuania natural and artificial slope cases.

Slope stability coefficient k we computed from 10 different magnitudes of soil internal friction angle φ and constant magnitudes of slope height $h_o = 30$ m, slope angle $\theta_o = 45°$, ground water flow free surface angle $\beta_o = 20°$, soil cohesion $C_o = 31$ kPa. Similar computations we performed with 9 magnitudes of slope height h, 7 magnitudes of slope angle θ, 9 magnitudes of water surface angle β, and 10 magnitudes of soil cohesion c, keeping constant indicated above magnitudes of the remaining parameters and internal friction angle $\varphi_o = 26°$.

Computer program for the application of our formulas (15), (16) and (17) has not been prepared jet. Therefore the computations we performed by means of popular software GEOSLOPE.

Table

Influence of different factors on slope stability numerical analysis results

Factor	φ/φ_o	h/h_o	θ/θ_o	β/β_o	C/C_o
Factor change	1.25	0.85	1.30	0.23	0.40
Rank No	2	3	1	5	4

Results of these computations in relative magnitudes k/k_o, φ/φ_o, h/h_o, θ/θ_o, β/β_o and C/C_o are given in Table and shown in Fig. 4. It is evident, that stability coefficient k is the most sensitive to the slope angle θ and to soil internal friction angle φ. Much less is the influence of ground water flow surface inclination angle β, also cohesion C. The influence of the slope height h on the coefficient is of intermediate significance.

Relative stability coefficient k/k_o changes corresponding unit of relative variables φ/φ_o, h/h_o, θ/θ_o, β/β_o and C/C_o are given in Table. It follows, that in computations of slope stability the most attention to be paid to the most important factors according to hierarchy rank No: to slope inclination angle θ, then to internal friction angle of the soil φ, height of the slope, cohesion C, ground water flow parameters.

The importance of definite slope and soil parameters for slope stability does not mean, that the factor of a lover rank is insignificant and may be neglected. It should be understood that an error in determining soil internal friction angle influences the reliability of slope stability computing results much more, than, say, the parameters of the ground water flow or cohesion. Thus, here it may be stated, that the internal friction angle should be studied with great responsibility and care.

4. Peculiarities of clay mechanical properties

It is known [17, 18] that mechanical properties of clay vary and depend greatly on its saturation degree, compression change speed, vibrations, state of consolidation, time. Thus, under the same conditions tough clay may liquefy and loose most of its internal friction and cohesion [13, 19].

Our investigations [20] and experience show that permeability of clay changes within a great range. When a hydraulic gradient decreases, permeability of clay reduces and, at a definite threshold gradient, the clay becomes practically impermeable. Thus, only at definite greater than that threshold gradient increment in compression may cause displacement of water from clay pores and its consolidation [20, 21]. Smaller changes in compression of weak vibrations may cause long lasting liquefying [22] of clay, but not its consolidation and strengthening which may end with clay slope slide.

To avoid errors, which may occur due to indicated above clay peculiarities, it should be tested in situ under nondrained nonconsolidated conditions with definite dimensions of zone under test [23].

According to the statement declared above a sudden increment in soil compression reduces the slope stability. It may happen due to sudden loading of the top of the slope because of a quick construction of a building here or storage of dense material, say soil, or mechanisms in large quantities (Fig. 3).

Compression stress in the slope ground may be changed due to infiltration of water into a top layer of soil during the intensive storm [24, 25] or snow melting. Dynamic factors, vibrations first at all, may initiate it also. Highway traffic, working mechanisms nearby the slope

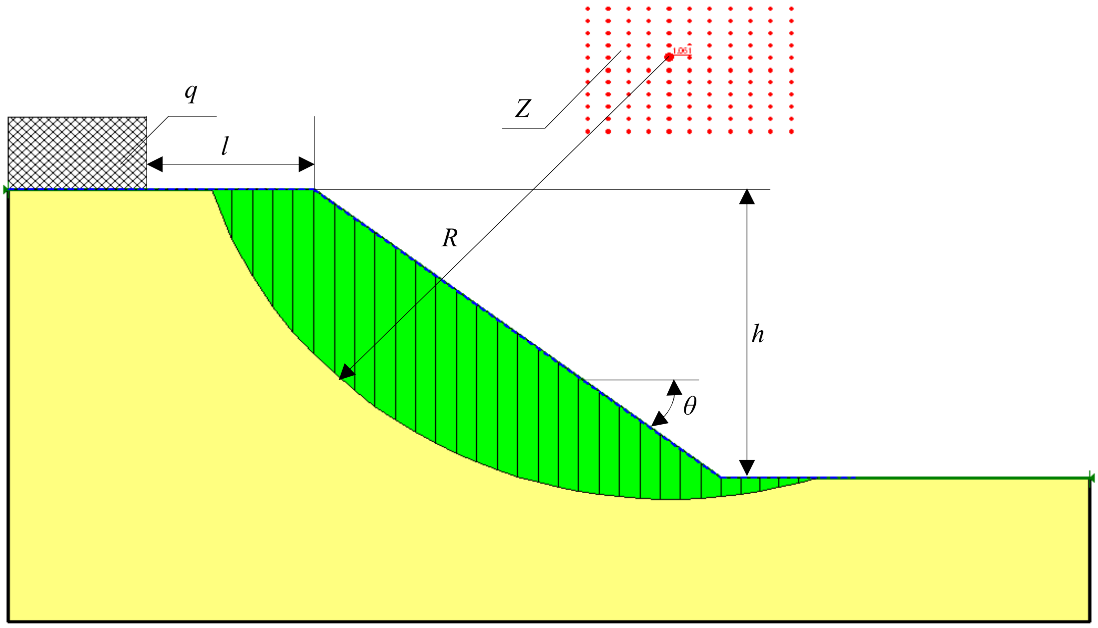

Fig. 3 Slope slid model with a loaded top

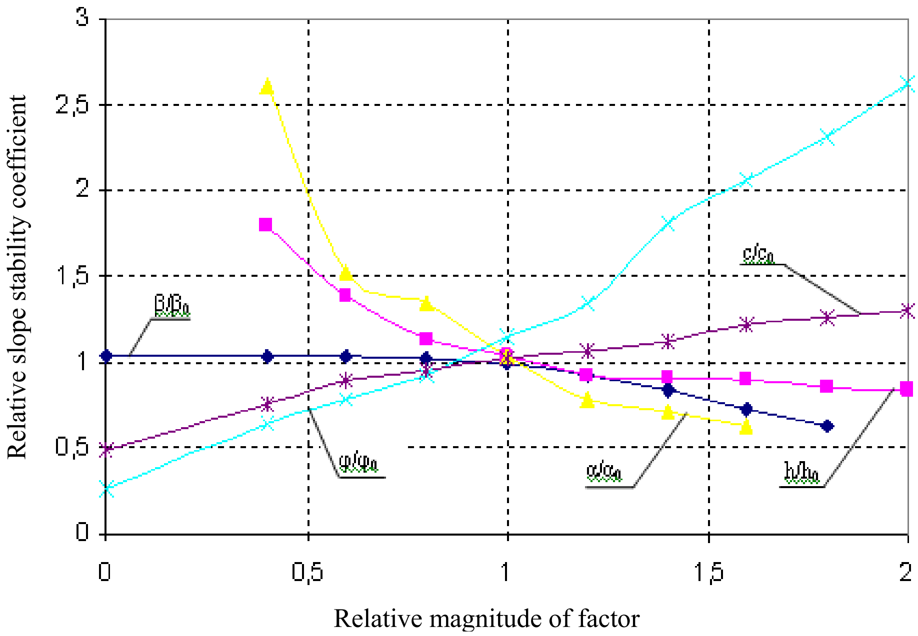

Fig. 4 Graph of multifactorial analysis

may be a source of periodical changes of compression and reduction in internal friction.

Drainage of the slope bottom may increase a ground water flow gradient, discharge and forces M_s and M_p in (1) reducing stability coefficient. It should be mentioned, that clay drainage is hardly possible, therefore increased pores pressure [26] may remain for long time [27].

5. Possibilities to prevent slope slide

There are some rather simple measures whose suitable application makes it possible to increase stability of the slope and to prevent its slide. Eliminating the factors causing slide and creating conditions at which stability of the slope increases - these are the principles of slide prevention. Loading the slope top by buildings or storage, approaching the slope with road or heavy mechanisms causing soil vibration are not acceptable. These measures are known and successfully applied.

To avoid soil saturation the slope should be protected with surface runoff collection and a quick bypass system. Drainage of the slope bottom reduces slope stability, although drainage of suppositional slide surface zone may increase the stability significantly due to double effects. First at all this measure eliminates seepage and porous pressure forces. Next, this measure increases soil internal friction.

To get a maximal effect of slope drainage the suppositional slide surface should be computed in advance and drainage should be arranged very carefully, without damaging and weakening soil there.

A measure of slope reinforcement by grouting, anchoring, insertion of geotextile requires intrusion into a very sensitive zone of the slid surface and its weakening, therefore this measure is doubtful and rather dangerous.

6. Conclusions

1. Direct solution of the differential equation of soil slope stability (14) is possible only for the simplest case: the slid surface is of cylindrical shape, cohesion and shear strength magnitudes equal to zero.

2. In the hierarchy of the importance to slope stability the angle of its inclination θ holds the first, the internal friction angle of the soil - the second and the height of the slope - the third ranks.

3. Set by us differential equation of soil slope stability is a universal tool applicable to any slope under different conditions including noncylindrical of variable radius slid surface, clayey soils and dynamic loading of the slope.

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MOLIO ŠLAITO STABILUMO ANALITINIO ĮVERTINIMO GALIMYBĖS

R e z i u m ė

Straipsnyje nagrinėjamos galimybės analitiškai įvertinti žemės šlaito stabilumą. Šlaito pastovumas priklauso nuo daugelio salygų ir tarpusavyje susijusių grunto charakteristikų, šlaito matmenų ir formos. Dėl šlaito šliaužimo reiškinio sudėtingumo šlaito stabilumo skaičiavimai atliekami grafiniais ir skaitiniais metodais. Savo tyrimuose pabandėme šlaito stabilumą išreikšti analitine formule, kurią gavome nagrinėdami jėgas, veikiančias be galo mažą šlaito elementą, ir integruodami šių jėgų sudaromų momentų sumą. Gautos šlaito stabilumo koeficiento formulės skaičiavimo rezultatai artimi pagal GEOSLOPE programą gautiems koeficiento dydžiams, kas patvirtina, kad formulė tinka moksliniams tyrimams ir projektavimo darbams, projektuojamų šlaitų parametrų variantams palyginti ir įvertinti. Ji ypač naudinga skaičiuoti molio šlaitų pastovumui, kuris, be įprastinių gruntų charakteristikų priklauso dar ir nuo jo dinaminių apkrovų, konsolidacijos ir vandens prisotinimo sąlygų.

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POSSIBILITIES OF ANALYTICAL ESTIMATION OF CLAY SLOPE STABILITY

S u m m a r y

Possibilities to estimate clay slope stability analytically are analyzed in this article. The slope stability depends on a number of conditions, also on intermediately related characteristics of the soil, slope shape and dimensions. Due to complexity of slope slip phenomenon the stability computations are performed by graphical – numerical methods. In our investigations we estimated slope stability by analytical formula, which we derived analyzing forces, acting infinite small slice of the slope and integrating moments of the forces equation. The received formula gives slope stability coefficients of similar to those of GEOSLOPE programme, what confirms the reliability of our formula and suitability of it to the application in scientific investigations, also in design works for comparison of a slope under design variants. The formula is especially useful for the estimation of stability of a slope, consisting of clay, which beside of usual soil characteristics has peculiar properties, depending on dynamic loads, consolidation, also saturation by water conditions.

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ВОЗМОЖНОСТИ АНАЛИТИЧЕСКОЙ ОЦЕНКИ СТАБИЛЬНОСТИ ГЛИНЯНОГО ОТКОСА

Р е з ю м е

В настоящей статье рассматриваются возможности привлечения аналитических методов для решения проблемы устойчивости земляных откосов. Известно, что стабильность откоса зависит от ряда взаимосвязанных характеристик грунта и откоса. Из-за сложности явления скольжения откоса расчет стабильности откоса до сих пор проводится графочисленными способами. В наших исследованиях мы попробовали оценить устойчивость откоса, аналитической зависимостью, которую получили, анализируя силы, действующие на элемент гипотетического массива скользящего грунта и интегрируя полученное дифференциальное уравнение. Полученная зависимость дает значения коэффициента стабильности откоса близкие к полученным с применением программы GEOSLOPE, что подтверждает ее надежность. Зависимость может быть полезна при оценке стабильности откоса из глинистых грунтов, характеристики которых являются переменными и зависящими от динамических нагрузок, степени консолидации, также от водонасыщенности.

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