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MODERN APPROACHES TO SLOPE STABILITY VALUATION WHILE SURFACE MINING

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СУЧАСНІ ПІДХОДИ ЩОДО ОЦІНКИ СТІЙКОСТІ УКОСІВ ПРИ ВІДКРИТІЙ РОЗРОБЦІ РОДОВИЩ КОРИСНИХ КОПАЛИН

Controlling rock massif conditions and forecasting stability of slopes and pit walls are among the most important engineering challenges for safety and efficiency of operations while surface mining. At present there are about 300 methods developed for studying geomechanical processes occurring in open pit slopes that allow predict their stability considering the impact of natural and anthropogenic factors.

Purpose. Elaboration of new methodological approach regarding integrated slope stability assessment of pit walls and overburden dumps.

Technique. The paper is based on the analysis of existing methods for estimation of slope stability well proven in practical applications. The general analytical solutions concerning slope stability based on hypotheses of flat and circular cylindrical sliding surface are considered. The application of slope stability nomograms based on an integrated approach to assessment of slopes with consideration of geological conditions and geometrical parameters are in detail discussed.

Findings. The slope stability nomograms with dimensionless quantities obtained via numerical simulation allow us to determine geometric parameters of the rock massif nearby the slope face considering geological, hydrogeological and technological factors.

Originality. As a result of multiple stages of numerical modeling of geomechanical processes in the landslide prone slopes, the values of the safety factor for the pit walls and dumps of the opencast colliery Maikubenskiy (Republic of Kazakhstan) have been calculated, which allowed us to develop the slope stability nomogram for changeable geological and mining conditions of the deposit.

Practical value. Development and application of the slope stability nomograms is a useful engineering tool for quick calculating geometric parameters of rational open pit edges with regard to specific geological conditions of the deposit and controlling the state of rock massif at the quarry.

Keywords: *stability of pit edges and overburden dumps, surface mining, slope, landslide, safety factor, Mohr-Coulomb failure criterion, slope stability nomogram*

Introduction. Failures of rock slopes, both man-made and natural, include rock falls, overall slope instability and landslides, as well as slope failures in open pit mines. The consequence of such failures can range from direct costs of removing the failed rock and stabilizing the slope to a wider variety of indirect costs.

Design methods for rock slopes fall into two groups – *limit equilibrium analysis* and *numerical analysis of stresses and strains*. Limit equilibrium analysis calculates the factor of safety of the slope and ensues different procedures used for plane, wedge, circular and toppling failures; the type of failure being defined by the geology of the slope. Numerical analysis involves analysis of stresses and strains occurring inside the slope, and stability is assessed by comparing the stresses in the slope with the rock strength.

In order to provide a guideline on stable angles of pit slopes, a number of studies have been carried out showing the relationship between slope angle, height and geology; the records also distinguished whether the slopes were stable or unstable.

Variable properties of overburden rocks and soils significantly affect results of slope stability assessment. Application of the random process models allows with a certain degree of probability to determine the geomechanical characteristics of soils as well as the slope stability parameters under the influence of external factors. Heterogeneity and variability of physical and mechanical properties of soils prone to subsidence, at different levels of the massif study are caused by synergetic changes of paleo-geomorphic conditions occurring during its formation and also by modern conditions. Stochastic modeling of the variability of soils geotechnical properties enables to im-

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prove the accuracy and validity of geotechnical predictions (Mokritskaya, 2013). An alternative approach to probabilistic models are the complex nomograms for evaluation of natural and man-made slopes stability that allow to control slope geometric parameters under changing physical and mechanical properties of overburden rocks or soils. By analyzing results of numerical simulation integrated into nomograms of slope stability it is possible to carry out geomechanical forecast for landslide emergence and control the state of the rock mass.

Main methodological approaches to assessment of slope stability. Analysis of modern engineering methods, based on different approaches to the evaluation of the slopes stability, is of practical interest for the analysis of physical and mechanical processes occurring in rocks or soils. The design methods and the design data are common to both mining and civil engineering. A basic feature of all slope design methods is that shear takes place along either a discrete sliding surface, or within a zone, behind the face. If the shear force (or displacing force) is greater in value than the shear strength of the rock (retaining force) along the surface, then the slope will be unstable. Instability could take the form of displacement that may or may not be tolerable, or the slope may collapse either suddenly or progressively. The definition of instability will depend on the application. For example, an open pit slope may undergo several meters of displacement without effecting operations, while a slope supporting a bridge abutment would have little tolerance for movement. Also, a single rock fall from a slope above a highway may be of little consequence if there is an adequate ditch to absorb the fall, but failure of a significant portion of the slope that reaches the traveled surface could have serious consequences.

Actually, stability of slopes can be expressed in one or more of the following terms (Duncan C. Wyllie, 2005):

1. *Factor of safety, FS* – Stability quantified by limit equilibrium of the slope, which is stable if $FS > 1$.
2. *Strain – Failure* defined by onset strains great enough to prevent safe operation of the slope, or that the rate of movement exceeds the rate of mining in an open pit.
3. *Probability of failure* – Stability quantified by probability distribution of difference between resisting and displacing forces, each expressed as probability distributions.
4. *LRFD (load and resistance factor design)* – Stability defined by the factored resistance being greater than or equal to the sum of the factored loads.

In engineering practice the main criterion for assessment of both natural and man-made slopes remains the factor of safety *(FS)*. Usually, for assessment of open pit slopes stability, *FS* value can be represented as the ratio of retaining forces F_{ret} and shear forces F_{sh} along the hypothetic line (or slip surface) as $FS = F_{ret} / F_{sh}$. There are three possible states of the rock massif adjacent to the slope area: $FS > 1$, when the slope is stable; $FS = 1$ that corresponds to the maximum steady state at the time of the landslide initiation; and $FS < 1$which occurs at the state of slope failure. It is assumed that the area of the rock massif, wherein $FS = 1$ identifies a potential sliding surface along which a slope failure occurs. Therefore, the main problem of the slopes engineering design is to identify factors affecting the stability of rock or soil massif near the slope, and calculating *FS* taking into account geometrical parameters and physical properties (Shashenko, 2004).

Up to date, the factor of safety is the most common method of the slope design, and there is wide experience in its application to all types of geological conditions, both rock and soil. Furthermore, there is a generally accepted factor of safety values for slopes excavated for different purposes, which promotes the preparation of reasonably consistent designs. For open pit mines the factor of safety generally used is in the range of 1.2–1.4, using either limit equilibrium analysis to calculate directly the factor of safety, or numerical analysis to calculate the onset of excessive strains in the slope.

Setting objectives and tasks. The objective of this paper is to analyze modern methods for evaluation of stability of natural and man-made slopes. Within the framework of the paper, the following topics are considered: 1. Analysis of existing methods for slope stability evaluation based on the hypotheses of flat and circular cylindrical sliding surface. 2. Development of the slope stability nomograms based on the results of numerical simulations for the conditions of opencast colliery Maikubenskiy (Republic of Kazakhstan).

Methods of slope stability evaluation based on the hypothesis of plane sliding surface. The simplest assumption regarding the form of the potential slip surface is a flat surface. fig. 1 presents a typical layout of the slope failure with plane sliding surface.

P.M. Tsimbarevich justified one of the first solutions of the problem for the limit slope height (Shashenko, 2004). The calculation scheme is shown in fig. 1. It is assumed that homogeneous rock massif has a zero resistance to rupture strength. Sliding of ABC block with width equal to one occurs upon the certain plane, and AC being the trace of this plane. Shear force is the projection of the weight *T* of the prism ABC on the line AC, and confining forces are cohesion *C* and friction force $N\mathrm{tg}\rho$ along the line *AC*.

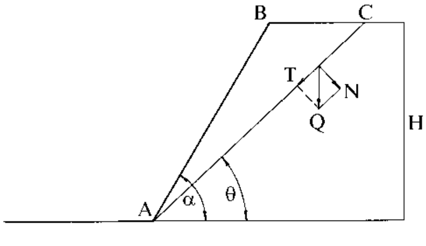

Fig. 1. Scheme of the slope failure with plane sliding surface by P.M. Tsimbarevich: ABC is the prism of the rock; AC – the line of plane sliding surface; H – height of the slope; N – normal forces; T – shearing forces; α – angle of the slope inclination; θ – angle of sliding surface inclination

In general case a condition of balance in the rock along the sliding surface *AC* looks like

$$Q\sin\theta = Qtg\rho\cos\theta + cl, \qquad (1)$$

where l – the length of sliding curve AC; θ – angle of inclination of the sliding surface; C – cohesion; ρ – angle of internal friction of sliding rocks.

The values presented in the equation (1) are defined as

$$Q=\frac{1}{2}\gamma H^2\left(ctg\theta-ctg\alpha\right); \tag{2}$$

$$l=\frac{H}{\sin\theta}, \tag{3}$$

where H – the height of the slope; α – angle of inclination of the slope surface; γ – volume weight.

Substituting the values of Q and l from the equations (2) and (3) into the equation (1) we obtain

$$\frac{1}{2}\gamma H\left(ctg\theta-ctg\alpha\right)\left(\sin\theta-\cos\theta tg\rho\right)=\frac{C}{\sin\theta}. \tag{4}$$

Let us fulfill the following transformations

$$ctg\theta-ctg\alpha=\frac{\sin\left(\alpha-\theta\right)}{\sin\alpha\sin\theta};$$

$$\sin\theta-\cos\theta tg\rho=\cos\theta\frac{\sin\left(\theta-\rho\right)}{\cos\theta\cos\rho}.$$

Taking into consideration these relationships, we obtain the balance equation

$$\frac{1}{2}\gamma H\frac{\sin\left(\alpha-\theta\right)}{\sin\alpha\sin\theta}\times\frac{\sin\left(\theta-\rho\right)}{\cos\rho}=\frac{C}{\sin\theta}. \tag{5}$$

Solving the equation (5) relative to H, we obtain

$$H=\frac{2C}{\gamma}\times\frac{\sin\alpha\cos\rho}{\sin^2\left(\alpha-\rho\right)}.$$

For the vertical slope with α =90°, the following equation is fulfilled

$$H_{90}=\frac{2C}{\gamma}\times\frac{\cos\rho}{\sin^2\left(\frac{90^{\circ}-\rho}{2}\right)}.$$

Similar expression for the height of vertical slope is proposed by the formula of V.V. Sokolovskiy–I.A. Simvulidi (Shashenko, 2004) deduced on the assumption of limit equilibrium with linear Mohr-Coulomb envelope

$$H_{90}=\frac{2c}{\gamma}ctg\left(\frac{90^0-\rho}{2}\right).$$

Methods of slope stability evaluation based on the hypothesis of circular cylindrical sliding surface. Methods of circular cylindrical sliding surfaces are widely described in the technical literature. They are often applied both in surface mining and building practice. There are numerous versions of this method, such as: the Swedish method of compartments, W. Fellenius method, the Swedish method of circular cylindrical sliding surfaces, Terzaghi method, Terzaghi–Krey method, Petterson method, method of vertical elements, method of Ivanov–Taylor, Sven–Gulten method, method of weight pressure etc.

Methods for slope calculations based on the curved failure surface can be divided into two groups. The first group includes the methods in which the shape of the failure surface displacement is determined in the course of solving the problem. There are well–known analytical and graphic-analytical solutions developed by G.L. Fisenko, Yu.I. Maslov, V.V. Sokolovsky, I.S. Mukhin, A.I. Sragovich, N.N. Maslov, W. Fellenius etc. In the methods of the second group the curved shape of the failure surface is taken in advance, and the method booils down to the algorithm of this surface construction.

Yu.M. Solovyov proposed a method based on the hypothetical model of soil massif divided into vertical blocks. It is assumed that the vertical planes of the massif have no normal stresses and, consequently, there is no friction forces between vertical blocks, which conditionally split the prism of possible failure. The problem is reduced to the calculation of the extreme failure surface along which the shear strength has the smallest values. The calculation scheme is presented in fig. 2.

It is considered that the state of equilibrium is in the hypothetical point m, which is located on the extremal failure surface

$$dT_i-dF_i=a, \tag{6}$$

where a is very small quantity. Let us determine the values incoming into equation (6) as follows

$$dT_i=\gamma Z_i\sin\theta dx;$$

$$dF_i=\gamma Z_i tg\rho\cos\theta dx+C\frac{dx}{\cos\theta}.$$

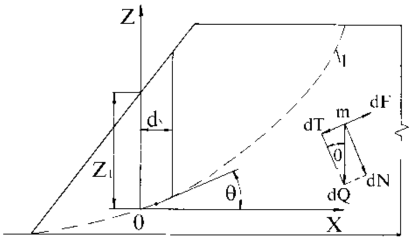

Fig. 2. Calculation scheme for determination of the extreme failure surface location: X, Z – axes in a plane; Z_l and d_x are the height and width of the hypothetical block; 1 – failure surface; θ – angle of inclination between sliding surface and horizontal axe X; dT, dN, dQ, dF are the tangent, normal, vertical and friction forces influencing the point m inside the elementary block of the massif

Then the general equation of equilibrium goes over

$$\gamma Z_i(tg\rho\cos\theta-\sin\theta)dx+C\frac{dx}{\cos\theta}=a. \tag{7}$$

The angle of inclination between sliding surface and horizontal axe is determined in such way that α value was minimal ($\alpha \rightarrow \min$). For this purpose the equation (7) is differentiated with respect to θ and the resulting expression equated to zero

$$\frac{da}{d\theta} = -\gamma Z_i (tg\rho \sin\theta + \cos\theta)dx + \frac{\sin\theta}{\cos^2\theta}dx = 0. \quad (8)$$

The expression (8) gives the following equation of the extreme failure surface

$$\frac{C}{\gamma Z_i} = (tg\rho + ctg\theta)\cos^2\theta.$$

To obtain the sliding surfaces by this method, which is often called the "method of sections", it is necessary to know the initial value of Z_i and then determine the position of the sliding surface from point to point. The idea of the slope stability design by Y.I. Solovyov comes to determination of the safety factor as the ratio between retaining and shearing forces in each section.

K. Terzaghi proposed graphic-analytical method which is based on the assumption that the slope failure occurs on the circular cylindrical surface. Its calculation is fulfilled by approximation, which consists in repeating the calculations for several possible sliding surfaces. The most dangerous or extreme sliding surface will be the one with minimal FS value.

The essence of the method is described in fig. 3, *a*. On the layout of the slope, which is drawn in certain scale, a set of possible cylindrical sliding surfaces is plotted. And each surface provides a certain, as yet unknown, the safety factor K_i. Each of the outlined prisms of sliding is divided into vertical sections of the same width *b* (fig. 3, *b*). The weight of each section Q_i is parted into following components

$$T_i = Q_i \sin\alpha \text{ and } N_i = Q_i \cos\alpha.$$

To determine the slope stability parameter FS, the ratio of moments of retaining and shearing forces is parted according to formula

$$FS = \frac{F_{ret}}{F_{sh}},$$

where F_{ret} and F_{sh} are the moments of retaining and shearing forces influencing the slope stability.
These forces affect the rock parameters in certain section b relative to the point *O* as the center of cylindrical arc.

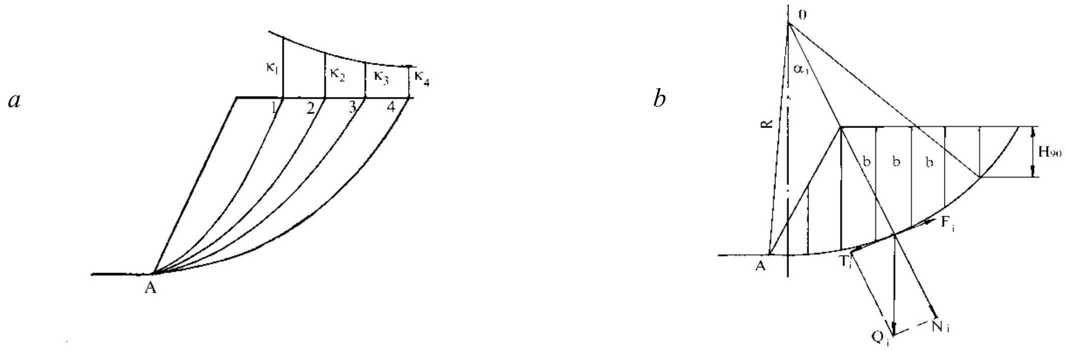

Fig. 3. Schemes of slope stability design by W. Terzaghi: a – hypothetic cylindrical sliding surfaces; b – method of segments; 1–4 are potential sliding surfaces and k_1–k_4 – safety factor values; O – center of cylindrical arc; R – radius of the sliding surface; α – angle between vectors of vertical and normal loads at certain segment b; H_{90} – height of vertical slope failure

The moment of forces retaining the slope equals to

$$F_{ret} = ClR + \sum_i^n N_i tg\rho R,$$

where C – cohesion; ρ – angle of internal friction; l – arc length; R – radius of the sliding surface.

The moment of forces shearing the slope equals to

$$F_{sh} = \sum_i^n T_i R.$$

Taking into account these relations, we obtain the formula for determining the slope *FS* value

$$FS = \frac{Cl + tg\rho \sum_i^n Q_i \cos\alpha_i}{\sum_i^n Q_i \sin\alpha_i}.$$

Terzaghi graphical and analytical method gives satisfactory results for relatively homogeneous and unsaturated rock massif.

Up to date, in slope stability analysis are widely used computational methods and designs developed by G.L. Fisenko and his scientific school (VNIMI methods). For example, the method of shear stresses is based on the theory of limit equilibrium of granular medium and enables to determine the sliding surface in a homogenious massif.

Despite the considerable variety of methods developed for slope stability design with the assumption of circular cylindrical sliding surface, their main disadvantage lies in their applicability to the cases when the slope area consists of homogeneous soft rocks. In actual geological conditions of the open pit mining, the pit edge massif is exposed to the combined impact of natural and anthropogenic factors, which requires development and application of advanced approaches and methodologies for assessment of slopes stability.

Application of circular failure charts for slope stability evaluation. Integrated assessment of the factors determining the geomechanical stability of slopes allowed to develop a specific chart to calculate *FS* and rational geometrical parameters for overburden rock massif made up of loams in application to the opencast colliery Maikubenskiy (Republic of Kazakhstan). The nomograms of slope stability (fig. 4, 5) integrate both geometry parameters and physical properties of the rock mass that allows to quickly determine the *FS* for the target site of open mining without time-consuming calculations and modeling. At the same time, rock properties are reduced to dimensionless form by analogy with the proposed circular chart. If the input data values of the rock strength properties are available via results of laboratory tests, the stable conditions for slopes and open-pit benches can be determined with sufficient precision.

This part describes the use of charts that can be used to determine rapidly the factor of safety of circular failures. These charts have been developed by running many thousands of circular analyses from which a number of dimensionless parameters were derived that relate the factor of safety to the material unit weight, friction angle and cohesion, and the slope height and face angle.

It has been proved that these nomograms provide a reliable estimation for the factor of safety, provided that the conditions in the slope meet the assumptions used in developing the charts. In fact, the accuracy in calculating the factor of safety from the charts is usually greater than the accuracy in determining the shear strength of the rock mass.

Use of the stability charts (Duncan C. Wyllie, 2005) requires that the conditions in the slope meet the following assumptions:

1. The material forming the slope is homogeneous, with uniform shear strength properties along the slide surface.

2. The shear strength τ of the material is characterized by cohesion: c and a friction angle φ, that are related by the equation $\tau = c + \sigma \tan \varphi$ (Mohr-Coulomb failure criterion).

3. Failure occurs on a circular slide surface, which passes through the toe of the slope.

4. A vertical tension crack occurs in the upper surface or in the face of the slope.

5. The locations of the tension crack and of the slide surface are such that the factor of safety of the slope is a minimum for the slope geometry and ground water conditions considered.

6. Ground water conditions vary from a dry slope to a fully saturated slope under heavy recharge.

7. Circular failure charts are optimized for a rock mass density up to 18.9 kN/m^3. Densities higher than this give higher factors of safety, densities lower than this give lower factors of safety. Detailed circular analysis may be required for slopes in which the material density is significantly different from 18.9 kN/m^3.

The charts presented in this paper correspond to the lower bound solution for the factor of safety, obtained by assuming that the normal load is concentrated on a single point on the slide surface.

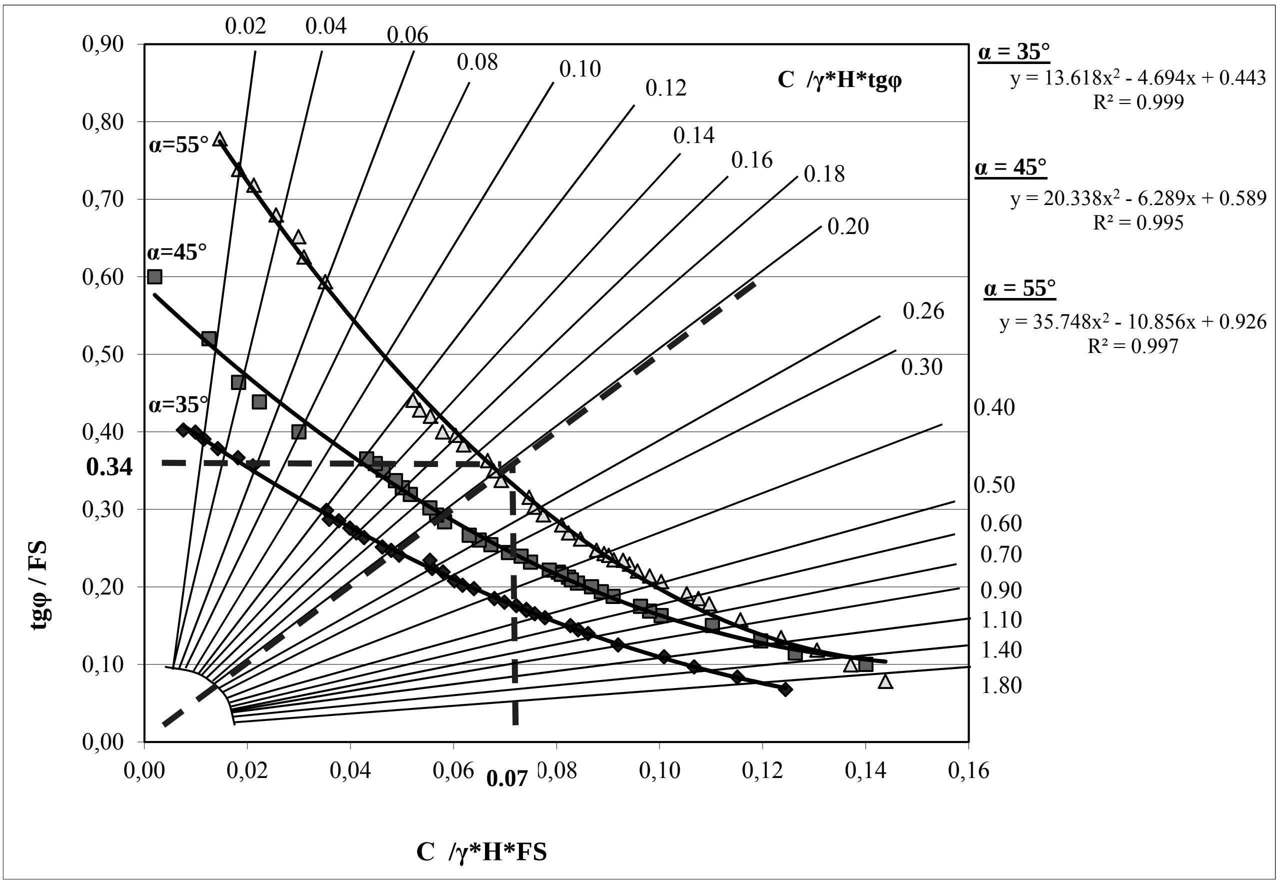

Fig. 4. Slope stability nomogram with explanations to Example 1

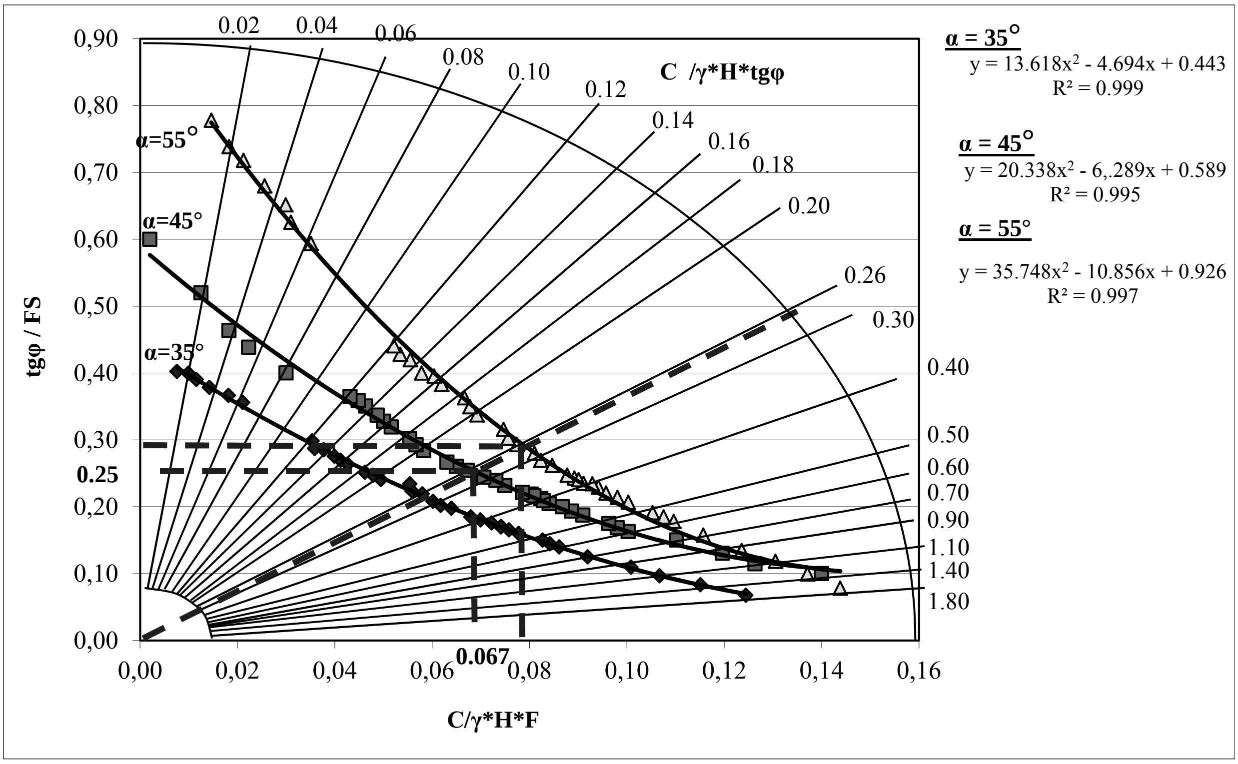

Fig. 5. Slope stability nomogram with explanations to Example 2

In order to use the charts to determine the factor of a slope safety, the steps outlined here should be followed.

Step 1: Select rock strength parameters applicable to the material forming the slope.

Step 2: Calculate the value of the dimensionless ratio $c/(\gamma{*}H{*}\tan\varphi)$ and find this value on the outer circular scale of the chart.

Step 3: Follow the radial line from the value found in step 2 to its intersection with the curve which corresponds to the slope angle.

Step 4: Find the corresponding value of $\tan\varphi/\mathrm{FS}$ or $c/(\gamma{*}H{*}\mathrm{FS})$, depending upon which is more convenient, and calculate the factor of safety.

Example 1. We consider the slope at overburden soft rock dump with a face angle $\alpha = 55°$ (fig. 4). The minimum required factor of safety of the slope is 1.3. It is needed to find the maximum accepted height of the slope, assuming the following overburden rock properties: density $\gamma = 17.0\,\mathrm{kN/m^3}$, cohesion $c = 35\,\mathrm{kPa}$ and friction angle $\varphi = 24°$.

The value of $c/(\gamma{*}H{*}\tan\varphi) = 0.21$ and the corresponding value of $\tan\varphi/FS = 0.445/1.3 = 0.343$, for $\alpha = 55°$ slope. At the point of intersection of the perpendicular and the horizontal axis, the corresponding dimensionless parameter is obtained: $C/\gamma{*}H{*}FS = 0.07$. Hence, maximum accepted slope height is $H = 35\,\mathrm{kPa}/17.0\,\mathrm{кN/m^3}{*}1.3{*}0.07 = 22.6\,\mathrm{m}$.

Example 2. It is needed to evaluate the factor of safety of the slope as a result of its flattening with changing angle of inclination from 55° to 45° and with the permanent slope height $H = 20\,\mathrm{m}$. The physical properties have the following values: volume weight $\gamma = 18.6\,\mathrm{kN/m3}$, angle of internal friction $\varphi = 24°$ and cohesion $c = 44\,\mathrm{kPa}$ (fig. 5).

On the arc axis the corresponding value of dimensionless parameter is calculated: $C/\gamma{*}H{*}\tan\varphi = 44\,\mathrm{kPa}/18{,}6\,\mathrm{kN/m^3}{*}20\,\mathrm{m}{*}\tan 24 = 0{,}27$. From this point the section towards the origin of coordinates is lined. At the intersection point with the curves for $\alpha = 55°$ and $\alpha = 45°$ the values of dimensionless parameters $C/\gamma{*}H{*}\mathrm{FS}$ are calculated and FS values respectively. So for the case of $\alpha = 55°$ the value $C/\gamma{*}H{*}\mathrm{FS} = 0.078$, and $FS = 1.52$; for $\alpha = 45°$ the value $C/\gamma{*}H{*}\mathrm{FS} = 0.067$, and $FS = 1.78$.

So the above nomograms present one of possible and useful engineering tools for determining limit values of the cohesion and the angle of internal friction for soft overburden rocks to achieve desired *FS* values.

Conclusions. Despite the considerable variety of methods of the slope stability design with assumption of circular cylindrical sliding surface, their main disadvantage is associated with their applicability to homogeneous slopes. In actual geological conditions of surface mining the slope area is exposed to the combined impact of natural and anthropogenic factors, which requires development of advanced techniques and approaches to slope stability issues.

Application of the nomograms is a valuable engineering tool for comprehensive evaluation of the geomechanical assessment of rock massif and slope design, which allows to accurately determine the optimum angles of the slope inclination and choose its rational geometrical parameters considering geological, hydrogeological and technological factors.

References / Список літератури

1. Mokritskaya, T.P. (2013), “Some possibilities of description of loess massif properties variability in conditions of weak technogenetic disturbance”, *Naukovyi*

Visnyk Natsionalnoho Hirnychoho Universutetu, no. 2, pp. 5–10.

Мокрицкая Т.П. Некоторые возможности описания изменчивости свойств лессового массива в условиях слабой техногенной нарушенности / Т.П. Мокрицкая // Наук. вісн. Нац. гірн. ун-ту. – 2013. – № 2. – С. 5–10.

2. Shahshenko, A.N. & Pustovoitenko, V.P. (2004), *Mekhanika gornykh porod* [Rock Mechanics], Novyi druk, Kyiv, Ukraine.

Шашенко А.Н. Механика горных пород / А.Н. Шашенко, В.П. Пустовойтенко. – К.: Новий друк, 2004. – 400 с.

3. Duncan C. Wyllie & Christopher W. Mah (2005), *Rock Slope Engineering: Civil and Mining*, Taylor & Francis e-Library, London and New York.

Керування станом масиву гірських порід і прогнозування стійкості укосів і бортів кар’єрів є однією з найважливіших інженерних задач із забезпечення безпеки й ефективності робіт при відкритій розробці родовищ корисних копалин. У цей час розроблено близько 300 методів, що дозволяють вивчати геомеханічні процеси в укосах кар’єрів і прогнозувати їх стійкість з урахуванням впливу природних та техногенних факторів.

Мета роботи. Розробка нового методичного підходу до комплексної оцінки стійкості прибортових і насипних масивів порід.

Методика. У роботі використаний аналіз існуючих методик розрахунку стійкості укосів, добре апробованих на практиці. Наведені основні аналітичні рішення задач стійкого укосу, що базуються на гіпотезах плоскої й круглоциліндричної поверхні ковзання. Більш детально розглянуте застосування номограм стійкості укосів, що базуються на інтегрованому підході оцінки стану схилів з урахуванням гірничо-геологічних умов і геометричних параметрів.

Результати. Отримані в результаті чисельного моделювання номограми стійкості укосів з безрозмірними величинами дозволяють з високим ступенем надійності визначати стійкі геометричні параметри прибортового масиву порід з обліком геологічних, гідрогеологічних і технологічних факторів.

Наукова новизна. У результаті багаторазових етапів чисельного моделювання геомеханических процесів у зсувному схилі розраховані значення коефіцієнта запасу стійкості стосовно до бортів кар’єру й відвалів розрізу Майкубенский (Республіка Казахстан), що дозволило розробити номограму стійкості укосів для мінливих гірничо-геологічних і гірничотехнічних умов даного родовища.

Практична значимість. Розробка й застосування номограм стійкості укосів є корисним інженерним інструментом, що дозволяє оперативно визначати раціональні геометричні параметри уступів стосовно до конкретних гірничо-геологічних умов родовища й керувати станом прибортового масиву гірських порід на кар’єрі.

Ключові слова: *стійкість бортів кар’єрів та відвалів, відкрита розробка родовищ корисних копалин, укос, зсув, коефіцієнт запасу стійкості, критерій міцності Кулона-Мора, номограма стійкості укосу*

Управление состоянием массива горных пород и прогнозирование устойчивости откосов и бортов карьеров является одной из важнейших инженерных задач по обеспечению безопасности и эффективности работ при открытом способе разработки месторождений полезных ископаемых. В настоящее время разработано около 300 методов, позволяющих изучать геомеханические процессы в откосах карьеров и прогнозировать их устойчивость с учетом влияния естественных и техногенных факторов.

Цель. Разработка нового методического подхода к комплексной оценке устойчивости прибортовых и насыпных массивов пород.

Методика. В работе использован анализ существующих методик расчета устойчивости откосов, хорошо апробированных на практике. Приведены основные аналитические решения задачи устойчивого откоса, основанные на гипотезах плоской и круглоцилиндрической поверхности скольжения. Детально рассмотрено применение номограмм устойчивости откосов, базирующихся на интегрированном подходе к оценке состояния склонов с учетом горно-геологических условий и геометрических параметров.

Результаты. Полученные в результате численного моделирования номограммы устойчивости откосов с безразмерными величинами позволяют с высокой степенью надежности определять устойчивые геометрические параметры прибортового массива пород с учетом геологических, гидрогеологических и технологических факторов.

Научная новизна. В результате многократных этапов численного моделирования геомеханических процессов в оползневом склоне определены значения коэффициента запаса устойчивости применительно к бортам карьера и отвалам разреза Майкубенский (Республика Казахстан), что позволило разработать номограмму устойчивости откосов для изменчивых горно-геологических и горнотехнических условий данного месторождения.

Практическая значимость. Разработка и применение номограмм устойчивости откосов является полезным инженерным инструментом, позволяющим оперативно определять рациональные геометрические параметры уступов применительно к конкретным горно-геологическим условиям месторождения и управлять состоянием прибортового массива горных пород на карьере.

Ключевые слова: *устойчивость бортов карьеров и отвалов, открытая разработка месторождений полезных ископаемых, откос, оползень, коэффициент запаса устойчивости, критерий прочности Кулона-Мора, номограмма устойчивости откоса*

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