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Automatic analysis of pit slope stability in clays of quaternary sediments

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Abstract

Introduction. *Preventing landslides of slopes formed by sand and clay of quaternary sediments with a thickness of 40–50 m is an essential task of opencast mining. Possessing significant stability at natural moisture content, rocks drop soil strength in water saturated condition. In some instances, it may cause disequilibrium in the marginal rock mass. The maintenance of slopes (pit edges, waste dumps, dams, mounds, etc.) stability is the most basic requirement imposed on mining enterprises today.*

Research aim *is to improve the accuracy of slopes stability analysis by means of automatic search of the most strained glide surface with the lowest value of slope stability safety factor, both at the design stage and at the stage of emergency control associated with slope stability violation.*

Methodology. The method of analyzing slope stability in the main computational models, including models with low-angle concordant bedding of a natural plane of weakness. The algorithm was implemented by an analytical simulation method in Stable slope (Russ. Ustoichivyi bort) software package.

Results. *Based on the data from slope stability analysis at a polymetallic mine in Altay krai, a graph of slope angle versus slope height in quaternary sediments has been built for various values of the angle of incidence for the contact "quaternary sediments–underlying bedrock".*

Summary. *Slope design procedure involves making laborious polycyclic calculations associated with the selection of the resultant angles of slopes, which will provide stability, for the specified height, mine and geological conditions and physical-mechanical characteristics of the marginal rock mass. Automatic analysis with Stable slope software makes it possible to improve stable slopes parameters computational accuracy when designing mining, by means of an option of searching for the most strained glide surface. Further fundamental improvement of analysis accuracy is possible with 2D geological models of slopes substituted for 3D models with slope stability factor determination by the most critical area. Such 3D models may be developed by geologic sections and geophysical sounding in the areas with abnormal density and water saturation. Besides, analysis accuracy may be improved if the model is developed as far as the real contour of mine profile, lithological types of rock, variability of physical-mechanical properties of rock are concerned.*

Key words: *ground slopes; stability; computational automation; safety factor; limiting equilibrium; back calculation; physical and mechanical properties of soils.*

Introduction. The maintenance of slopes stability is the basic requirement imposed on mining enterprises today [1]. Preventing landslides of slopes formed by clay of quaternary sediments with a thickness of 40–50 m is an essential task. Possessing significant stability at natural moisture content, rocks drop soil strength in water saturated condition. In some instances, it may cause disequilibrium in the marginal rock mass [2, 3].

Charles-Augustin de Coulomb laid the theoretical substantiation of stability computation by formulating the main principles of the limiting equilibrium theory and proved its application to engineering problems. Limiting equilibrium calculation methods were developed by national (V. V. Sokolovskii, S. S. Golushkevich, N. N. Maslov, R. R. Chugaev, G. M. Shakhuniants, V. T. Sapozhnikov, G. L. Fisenko, etc.) and foreign (N. R. Morgenstern, N. Janby, E. Spenser, V. Fellenius, A. Bishop, and Y. M. Cheng and C. K. Lau) scientists [4–8].

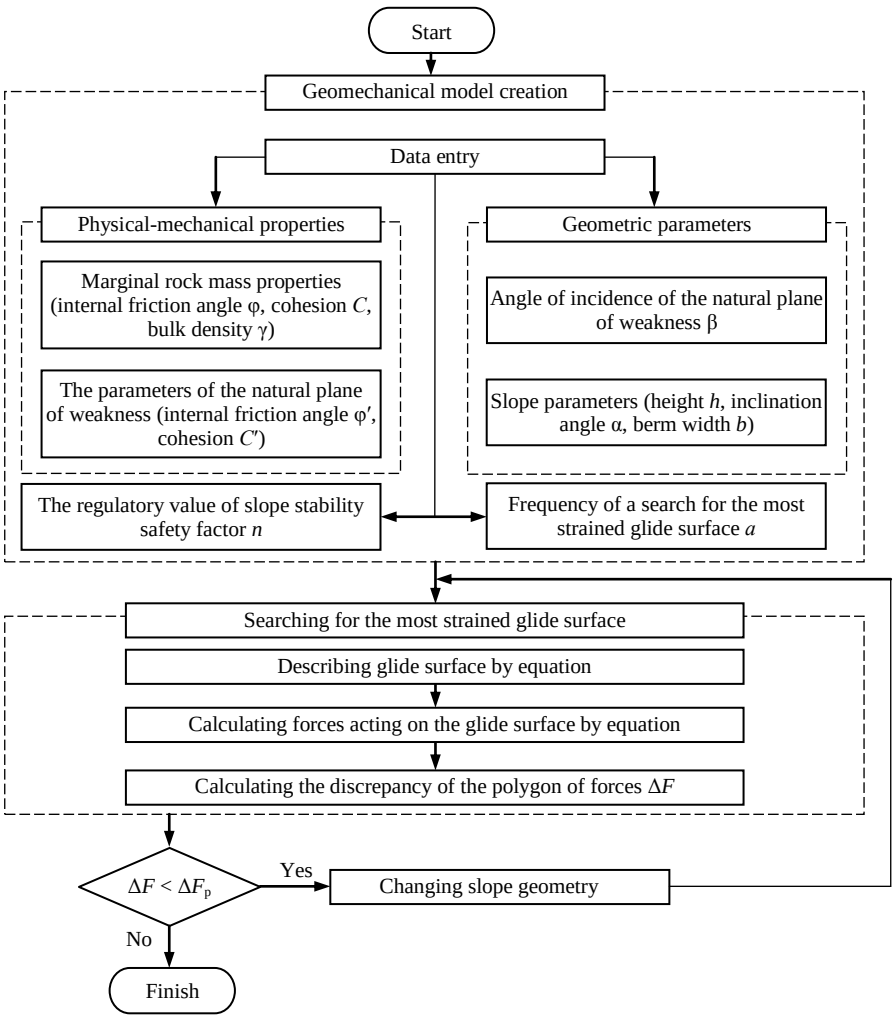

Fig. 1. Algorithm of a soil slope stability analysis
Рис. 1. Алгоритм прогноза устойчивости грунтового откоса

At the present time, a range of software programs has been developed based on these methods, making it possible to quickly assess the stability of slopes in various engineering and geological conditions. GeoStudio Slope/W, Galena, Geo5, GeoStab, RS Slide are the best known [8–11].

The basic idea of the specialized software application can be described by a general algorithm. Firstly, a geometry model of a slope is built: the height and the angle of slope, from which the program automatically builds the section, are specified analytically, and the section is simulated in a vector editor graphically. Secondly, geological conditions are simulated, for instance, using polygonal objects responsible

for a particular geological object with a minimum set of physical and mechanical characteristics required for calculation, or weighted-average characteristics of layers composing the marginal rock mass are specified. After that, stability is assessed with one of the following methods: Bishop's, Morgenstern-Price's, Shakhuniants', Spenser's, Fellinius', etc. [11–14].

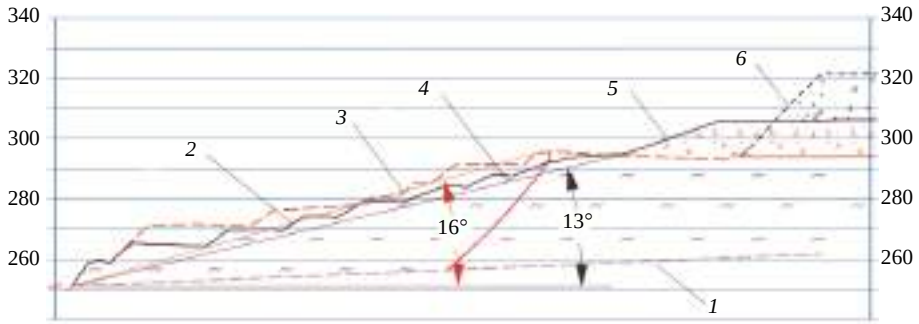

Fig. 2. The section to the back-calculation method:
1 – contact *quaternary sediments–underlying bedrock*; *2* – the position of the slope after the landslide; *3* – the position of the slope before the landslide; *4* – the most strained glide surface in the marginal rock mass; *5* – the position of the waste dump after the landslide; *6* – the position of the waste dump before the landslide

Рис. 2. Сечение к методу обратных расчетов:
1 – контакт *четвертичные отложения–коренные породы*; *2* – положение борта после оползня; *3* – положение борта до оползня; *4* – наиболее напряженная поверхность скольжения в прибортовом массиве; *5* – положение отвала после оползня; *6* – положение отвала до оползня

It should be noted that the *Rules for ensuring the stability of slopes on coal mines* regulate slope stability assessment according to particular schemes, which take into account engineering and geological conditions of a rock mass by the methods of algebraic and vector superposition of forces. The mentioned methods are scarcely used by present-day stability assessment programs [15]. The authors of the article have developed an algorithm of analytically calculating the equilibrium conditions of a system of forces acting on the elements of the potential glide plane design blocks; the conforms with the Rules for ensuring the stability of slopes on coal mines. The algorithm was implemented in Stable slope (Russ. Ustoichivyi bort) software package. The developed software allows calculating the limiting parameters of inclination of a pit slope flat profile by the methods of limiting equilibrium – algebraic and vector superposition of forces (equilibrium polygon) for various mine geological conditions of a marginal rock mass: the lack of planes of weakness concordant with slope, the presence of low-angle and steep natural planes of weakness concordant with the slope and concordant layer occurrence.

Research aim is to improve the accuracy of slopes stability analysis by means of automatic search of the most strained glide surface with the lowest value of slope stability safety factor, both at the design stage and at the stage of emergency control associated with slope stability violation.

Research methodology. When analyzing the stability of slopes, the methods of limiting equilibrium, back calculation, and analytical simulation are used. Back calculation is the most reliable way to determine the shearing resistance of rock in a massif from the mine survey of natural failures. The method is based on the fact that up to the moment of failure, rock equilibrium in a slope is described by the equality of retention (friction and cohesion) forces and shearing forces.

After landsliding, when cohesive forces of the glide surface are no longer in force, there is equilibrium between the caved masses, when shearing forces are balanced only

by frictional forces. Thus, for each block, two equations with two indeterminates, angle of internal friction φ_i and soils adhesion C_i, can be solved.

After that, an algorithm of soil slope stability analysis is considered which is prevailing in the conditions of opencast geotechnology of a computational model with low-angle concordant bedding of a natural plane of weakness by limiting equilibrium method, i.e. vector superposition of forces.

The algorithm includes the following basic stages (fig. 1):

– specifying rock mass physical and mechanical properties, geometric parameters, regulatory value of slope stability safety factor, and the frequency of a search for the most strained glide surface;

– developing potential glide surfaces, calculating forces and building the polygon of forces;

– selecting the most strained glide surface.

Table 1. Physical-mechanical characteristics of rock in quaternary sediments and the indicators of resistance to shear on the contact of rocks

Таблица 1. Физико-механические характеристики пород четвертичных отложений и показатели сопротивления сдвигу по контакту пород

Indicator	Bulk density γ, kN/m^3	Internal friction angle φ, degrees	Cohesion *C*, kN/m^2
Quaternary sediments	19.2	17	17.6
Contact *quaternary sediments–underlying bedrock*	–	8	6.9

The calculation results in the discrepancy ΔF which is compared with the permissible value of ΔF_{p}:

$$\Delta F_{\text{p}} = k\sum_{i=1}^{n}\gamma_i V_i,$$

where k – the error of the grapho-analytical calculation accepted in the range within 0.01–0.02; γ_i – bulk density of soil, kN/m^3; V_i – the volume of the design block, m^3.

With $\Delta F < \Delta F_{\text{p}}$ stability is not ensured with the specified stability safety factor. In this case, the input original data are updated and the calculation is made again.

Compared to the *Rules for ensuring the stability of slopes on coal mines* which restrict the quantity of potential glide surfaces by the labour intensity of hand calculations (not less than three), the developed algorithm allows specifying any frequency of an increment in the width of the possible sliding wedge – the function of search for the most strained glide surface which insures the improvement of slope stability analysis accuracy.

Results. Research object is the north-eastern slope of an open pit in quaternary sediments of a polymetallic ore deposit in Altai krai (the enterprise is not named due to confidentiality concerns). The deposit is mined by opencast, and as of June 2018 the open pit had slope height of about 205 m with the resultant angles of 19°–28°. The upper part of the slope is composed of the strata of quaternary sediments with a thickness of 20 to 44 m with a resultant inclination angle of 10°–30°. The external dumps, Western and Eastern, are situated at the marginal zone of the open pit. The natural relief with pit oriented inclination serves as a base of dumps. The central part of the Eastern dump is piled on the old streambed. The river is shallow, and its upper part dries up in the

summer. Treatment plants are located at the northern edge of the open pit. In June 2017, in the section area (fig. 2), land sliding was recorded in quaternary sediments.

With slope height of 44 m, the resultant angle made up 16°, the angle of incidence for the contact *quaternary sediments–underlying bedrock* made up 2°. Up to June 2018 the slope flattened up to 13°, dragging into the landslide the first 27 m high horizon of the Eastern dump situated in the marginal zone of the open pit at the distance of 70 m from the upper edge.

In the course of engineering and geological investigation, four engineering and geological elements (EGE) have been singled out: EGE 1 – loamy soil of black or black brown color; EGE 2 – loam of hard and low-plastic texture with the veinlets of carbonate salts and patches of ferruginization; EGE 3 – loam of high-plastic texture, yellowish brown with the patches of ferruginization; EGE 4 – loam of fluid-plastic texture, yellowish brown with the patches of ferruginization .

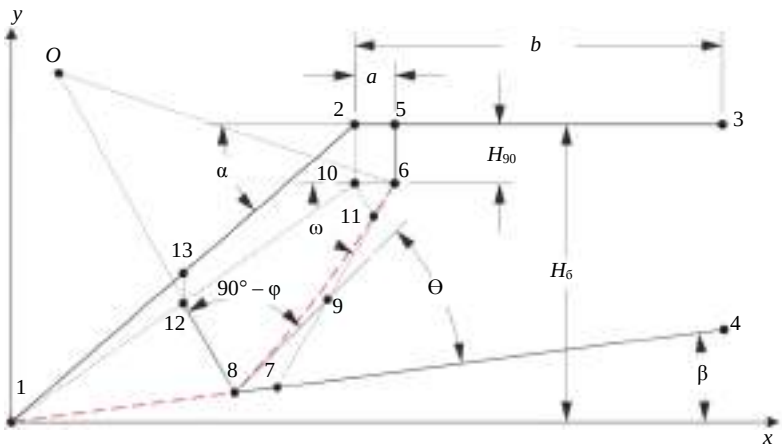

Fig. 3. Section of a slope
Рис. 3. Профиль борта

For engineering and geological elements EGE 2 and EGE 3 composing the greater part of the geological section, the regulatory values of the angle of internal friction φ vary from 21° to 24°, bulk density γ – from 18.5 kN/m^3 to 19.9 kN/m^3 with average values of 22.5°, and 19.2 kN/m^3 correspondingly. The regulatory value of cohesion *C* is 12.7 kN/m^2. For engineering and geological element EGE 4, underlying EGE 2 and EGE 3, the regulatory values of internal friction angle φ, cohesion *C* and bulk density γ correspondingly are 17°, 17.6 kN/m^2 and 19.2 kN/m^3. The analysis of the engineering and geological instigations has shown that the strata of quaternary sediments is composed by the loams from top downward from hard and low-plastic to fluid-plastic texture. The main reason for landslide was the overwetting of quaternary sedimentary rocks. The sources of water are the following: the ancient streambed, treatment plants, rain and melt water. Due to low filtration properties, the water absorbed by clay does not percolate at the slope but increases water saturation up to the complete swelling and transition into free-flowing. Due to rock density reduction, plastic deformations develop, tension joints occur parallel to the edge of the slope, and gradual subsidence of the spalled block is observed. Joints eventually become wider and deeper with further landslide.

With the method of back calculation on section, the indicators of shear resistance on the contact *quaternary sediments–underlying bedrock* (table 1) have been determined.

The calculation of slope parameters is made according to the scheme of low-angle concordant bedding of the contact *quaternary sediments–underlying bedrock* in Stable slope software package.

The section of a slope (fig. 3) in Stable slope software package is built by describing its elements (slope, berm, natural plane of weakness, glide surface) by algebraic equations (table 2).

Table 2. Algebraic equations of slope section elements
Таблица 2. Алгебраические уравнения элементов профиля борта

Slope element	Equation	Key
Slope	$y_i = x_i \mathrm{tg}\alpha_i$	α – slope inclination angle, degrees; H_s – slope height, m; β – the angle of incidence of the natural plane of weakness, degrees
Berm	$y_i = H_s$	
Natural plane of weakness	$y_i = x_i \mathrm{tg}\beta$	

The algebraic equations used to create the section of a slope are limited by the points: 1, 2 – lower and upper edges of the slope; 3 – the border of the terrace (berm); 4 – the border of the natural plane of weakness; 5, 6 – tension joint borders; 6, 7, 8, 9 – points on the tangent lines of the smooth curved part of glide surface. Glide surfaces are built from point 5 along the whole width of berm *b* with the specified value of possible sliding wedge *a*. From the terrace (berm) of a slope, vertical tension joint terrace the size of H_{90} is formed.

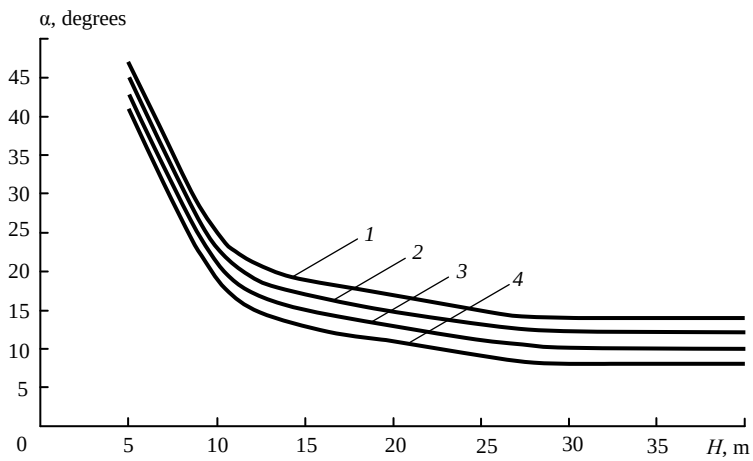

Fig. 4. A graph of slope angle *α* versus slope height *H* in quaternary sediments at the angles of incidence β of *quaternary sediments–underlying bedrock*:
1 – β = 0°; *2* – β = 2°; *3* – β = 4°; *4* – β = 6°
Рис. 4. График зависимости угла откоса α от высоты борта *H* в четвертичных отложениях при углах падения контакта β *четвертичные отложения–коренные породы* в выработку:
1 – β = 0°; *2* – β = 2°; *3* – β= 4°; *4* – β= 6°

In the lower part, glide surface coincides with the natural plane of weakness (between points 1 and 8), in the upper part, circular cylindrical surface (between points 6 and 8) is inscribed between tangent lines at angles ω and θ. The borders of the design blocks are determined by the glade surfaces of the second class: for the first block – points 10 and 11, for the second block – points 8 and 12. At the place of second class glide surface exposure, vertical tension joint terrace is formed (points 2–10 and 13–12). The determination of the vectors of forces acting on possible sliding wedge, as well as

the development of a polygon of forces are also carried out analytically. The calculation results in the discrepancy of the polygon of forces for the specified value of stability coefficient. Closure of the polygon of forces characterizes the equilibrium of retention and shearing forces.

According to the results of the calculation, a plot (fig. 4) showing the dependence between slope angle α and slope height *H* in the quaternary sediments at various angles of incidence for the contact *quaternary sediments–underlying bedrock* with the use of Stable slope software package. The results were compared with the values of stable slopes angles presented in the graph of *Appendix 5* of the *Rules for ensuring the stability of slopes on coal mines* (table 3).

Table 3. Values of inclination angles α according to the developed algorithm and *Appendix 5* of the *Rules for Ensuring the Stability of Slopes on Coal Mines*

Таблица 3. Значения углов откосов α согласно разработанному алгоритму и *Приложению 5 Правил обеспечения устойчивости откосов на угольных разрезах*

H, m	5	10	15	20	25	30	35	40
β = 0°	46.8	25.1	18.9	17.1	15.2	14.3	14.1	13.8
	44.3	19.3	15.2	13.5	12.7	12.6	12.5	12.1
β = 2°	44.8	22.9	16.8	15.1	13.1	12.2	11.9	11.7
	40.0	18.2	14.4	12.9	12.0	11.7	11.6	11.2
β = 4°	42.8	20.9	14.8	13.1	11.1	10.2	9.9	9.7
	35.8	17.1	13.6	12.3	11.5	11.1	10.7	10.3
β = 6°	40.8	18.9	12.8	11.1	9.1	8.2	7.9	7.7
	32.7	16.6	13.3	12.0	11.4	10.9	10.4	9.6

In the numerator – the values calculated with Stable slope software, in the denominator – the values determined according to the graphs of *Appendix 5* of the *Rules*.

A discrepancy between the values obtained with the help of the two methods is 14 %. It is explained by the fact that the graphs of *Appendix 5* of the *Rules for ensuring the stability of slopes on coal mines* are applicable for the conditions when the cohesion of rocks in the transverse direction to bedding *C* is five times as high as the cohesion along the planes of weakness *C'*, consequently, they cannot be applied in the instance under consideration.

Summary. Slope design procedure involves making laborious polycyclic calculations associated with the selection of the resultant angles of slopes, which will provide stability, for the specified height, mine and geological conditions and physical-mechanical characteristics of the marginal rock mass. Automatic analysis with Stable slope software makes it possible to improve stable slopes parameters computational accuracy when designing mining, by means of an option of searching for the most strained glide surface.

Further fundamental improvement of analysis accuracy is possible with 2D geological models of slopes substituted for 3D models with slope stability factor determination by the most critical area. Such 3D models may be developed by geologic sections and geophysical sounding in the areas with abnormal density and water saturation. Besides, analysis accuracy may be improved if the model is developed as far as the real contour of mine profile, lithological types of rock, variability of physical-mechanical properties of rock are concerned.

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Автоматизированный прогноз устойчивости борта карьера в глинистых породах четвертичных отложений

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Реферат

Введение. *При открытой геотехнологии весьма важной является задача предотвращения оползней бортов, сложенных песчано-глинистыми породами четвертичных отложений мощностью 40–50 м. Обладая достаточной устойчивостью при естественной влажности, во влагонасыщенном состоянии породы резко снижают прочностные характеристики, что в ряде случаев способно привести к нарушению равновесного состояния прибортового массива. Обеспечение устойчивости откосных сооружений (бортов карьеров, отвалов, дамб, насыпей и др.) является важнейшим требованием, предъявляемым к современным горнодобывающим предприятиям.*

Целью работы *является повышение точности прогноза устойчивости откосов за счет автоматизированного поиска наиболее напряженной поверхности скольжения, которой соответствует наименьшая величина коэффициента запаса устойчивости как на стадии проектирования горных работ, так и при ликвидации аварийных ситуаций, связанных с нарушением устойчивости откосов.*

Методология. *Использована методика прогноза устойчивости откосов основных расчетных схем, в том числе схемы при пологом согласно с откосом залегании естественной поверхности ослабления. Алгоритм реализован посредством аналитического метода моделирования в программном комплексе «Устойчивый борт».*

Результаты. *По результатам прогноза устойчивости борта карьера полиметаллических руд Алтайского края построен график зависимости угла откоса от высоты борта в четвертичных отложениях при естественной влажности для различных значений угла падения контакта «четвертичные отложения–коренные породы».*

Выводы. *Процедура проектирования откосов заключается в выполнении трудоемких многоцикличных расчетов, связанных с подбором для заданной высоты, горно-геологических условий и физико-механических характеристик прибортового массива результирующих углов откосов, при которых будет обеспечиваться устойчивость. Автоматизированный прогноз с помощью программного комплекса «Устойчивый борт» позволяет повысить точность расчета параметров устойчивых бортов при проектировании горных работ за счет функции поиска наиболее напряженной поверхности скольжения. Дальнейшее принципиальное повышение точности прогноза возможно на основе перехода от плоских геологических моделей бортов к объемным с определением коэффициента устойчивости по наиболее опасному сечению. Построение подобных объемных моделей можно реализовать путем формализации данных геологических разрезов и геофизических зондирований зон, аномальных по плотности и влагонасыщенности. Кроме того, повышение точности прогноза возможно при доработке модели в направлении учета реального контура профиля горных работ, литологических типов пород, изменчивости физико-механических свойств пород.*

Ключевые слова: *грунтовые откосы; устойчивость; автоматизация расчета; коэффициент запаса; предельное равновесие; обратные расчеты; физико-механические свойства грунтов.*

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