Reducing the risk of the collapse of the soil by macro system modeling the slopes stability of the quarries

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Abstract. The urgent task of modern production is to reduce the risks of man-made disasters and, as a consequence, preserve the life and health of workers, material properties and natural environment. In the mining industry, one of the reasons for the high level of injuries and accidents is the collapse of the soil. Macro system modelling of slopes stability of the quarries is based on the compliance with the conditions of physical and mathematical correctness of the application of the model of a continuous medium. This type of modelling allows to choose the safe parameters of the slopes of the quarries and to reduce the risk of collapse of the soil.

1. Introduction

Risk is the probability of harm to the life or health of citizens, property of individuals or legal entities, state or municipal property, environment, life or health of animals and plants taking into account the severity of the harm. Risk is identified with the probability of occurrence of negative events for a certain period of time (usually a year) and the size of the damage in kind (the number of deaths, the area exposed to the dangerous effects, etc.) or monetary terms [1].

Industrial disaster is the major industrial accident, which caused human victims, damage to human health or damage and destruction of objects, material assets in the considerable sizes, and also serious environmental damage [2]. The presence of serious consequences, such as death of people or destruction of objects is a distinctive feature of any disaster.

In accordance with these definitions, the collapse of the soil in the quarry can be attributed to the industrial disaster. Since the collapse of the soil contributes to a variety of factors, to exclude that it is often impossible, the risk of this adverse event is high.

The risk of an adverse event is defined as a measure of risk of adverse events combining the probability of occurrence of the adverse event and its consequences [3].

From a mathematical point of view, the risk R is a function of two variables – frequency F and the consequences U of undesirable event:

$$R = f(F,U). \tag{1}$$

The consequences of undesirable events can be: human casualties, property damage and damage to the environment.

There are more than 7000 quarries for the extraction of ore and non-ferrous metallurgy and gold mining industry and quarries for the extraction of widespread minerals under the supervision in the Russian Federation.

The results of the analysis of the general state of accidents and injuries in the mining industry indicate a high traumatic risk of the industry and a lack of a steady trend towards its decline (figure 1) [4, 5, 6].

The causes of injuries and accidents in the mining industry are of a diverse nature, the collapse of the soil among them occupies about 20% (figure 2).

Adverse factors that affect the level of safety of work in quarries can be divided into three groups: technological, personal and natural factors of the environment.

Let's imagine the technological factors in the form of the following groups:

1. Technological solutions (design and construction);
2. Reliability (optimality) of the engineering structure;

3. Operational technological design of the engineering structure;
4. Controllability of the functioning mode of the engineering structure.

Also here can be attributed mining technical factors (geometric parameters of slopes, the way of loosening of soils, etc.), which affect the stability of soils in the slopes of quarries.

The second group (personal factors) implies compliance with the criteria of reliability (optimality), legislative and regulatory framework for labor protection, industrial safety rules, violation of established rules, erroneous action or inaction of employees involved in this work [5, 6]. These factors are a consequence of the reasons laid down in the individual characteristics of people, namely professional level, psychophysical condition, discipline, personality traits.

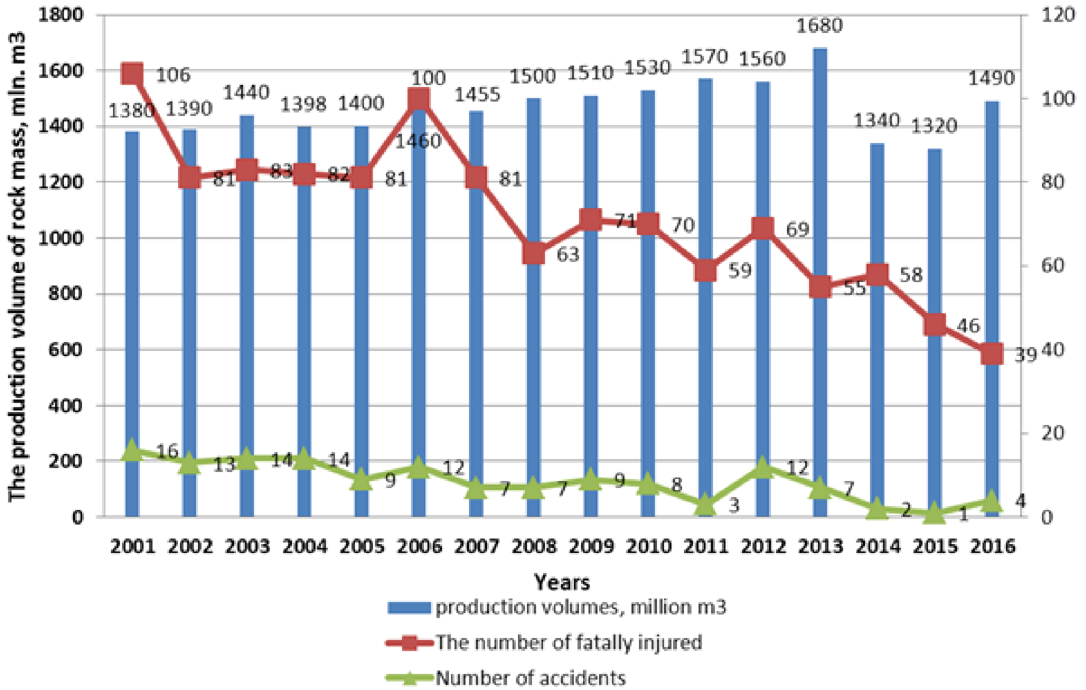

Figure 1. The dynamics of injuries and accidents in the mining and non-metallic industry

Environmental factors imply natural factors that can cause not only caving or landslides, but also human errors. This group of factors includes the following: climatic – air temperature, rainfall, wind regime; geological – composition, structure and strength properties of rocks, hydrogeological – the presence of surface water and aquifers, water cut, etc [7].

The prolonged standing of the slopes in the stress-strain state increases the risk of the occurrence of a technogenic catastrophe. One of the main reasons for this situation is unjustifiably chosen parameters of the slope, as well as inadequate actions of maintenance personnel. Therefore, in order to prevent dangerous situations, it is necessary to develop engineering and technological solutions, which should include issues related to the use of sound methods for selecting safe slope parameters with a specified safety factor and ensuring safety and labor protection in the development of soils in quarries [8].

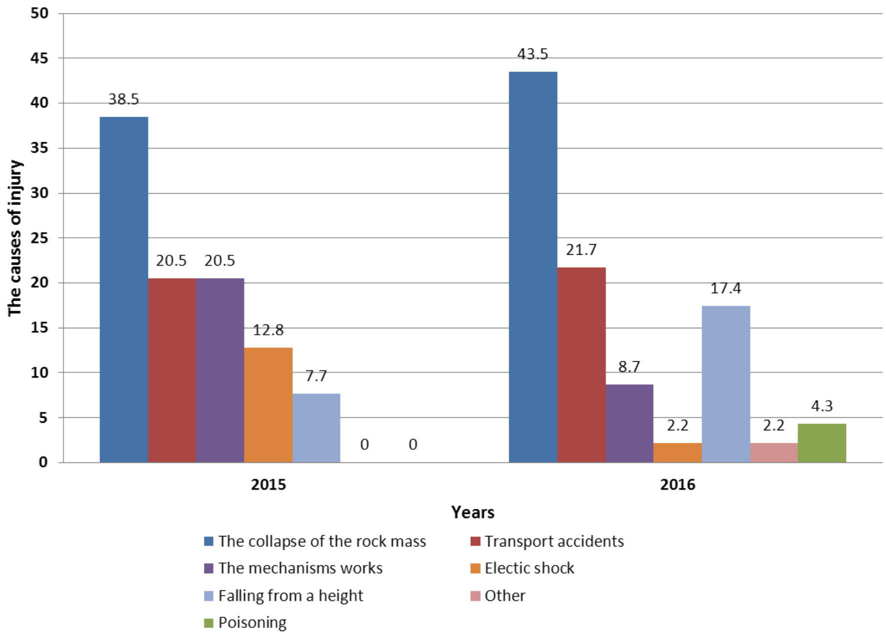

Figure 2. Percentage distribution of accidents by types of causes incidents in the mining and non-metallic industry

2. Results and discussion

Calculation of the maximum permissible parameters of the slopes is based on the choice of the geomechanical model of the soil array. The development of a geomechanical model of a soil massif is based on the study of the physical and mechanical properties of soils as constituents of a geological structure model [9, 10, 11].

Arrays of rocks of small quarries correspond to models of continuous medium, which completely abstract from the discrete structure of matter.

The desire for such a schematization of rock arrays is conditioned by the desire to use effectively the well-developed mathematical apparatus of differential and integral calculus. From the physical point of view, the use of the model of a continuous medium is justified if the smallest of the considered volumes of material preserves the «representativeness» of its mechanical properties as the integral effect of many micro particles, that is, inequality must be fulfilled [12]:

$$\sqrt[3]{\Delta V} >> d_{\mathrm{m}}, \tag{2}$$

where V is the volume of the material; d_m is the characteristic size of the microstructure elements.

The study of the mechanical behavior of arrays using the model of a continuous medium provides for an operation of integration over the volume of the array in question. From this point of view, the volume of the material ΔV is geometrically regarded as an infinitesimal object. In practice, this should be reduced to the fulfillment of inequality:

$$\sqrt[3]{\Delta V} << L , \tag{3}$$

where L is the characteristic size of the array under study.

Inequality (2) can be treated as a physical condition, and inequality (3) is the mathematical correctness of the application of the continuous medium model when choosing safe slope parameters.

The particle sizes are commensurately small in comparison with the size of the studied sections, which reach tens and hundreds of meters, which causes inequalities (2) and (3) to be satisfied.

As a result of the conducted studies, we found that for homogeneous arrays it is recommended to use a circular cylindrical slip surface, which is the most dangerous.

In the development of soils for calculating the slope stability factor of slopes, the position of the potential slip surface in a homogeneous slope is determined by the laws of the static nature of the granular medium [13, 14, 15].

The scheme for calculating the slope stability factor is shown in figure 3.

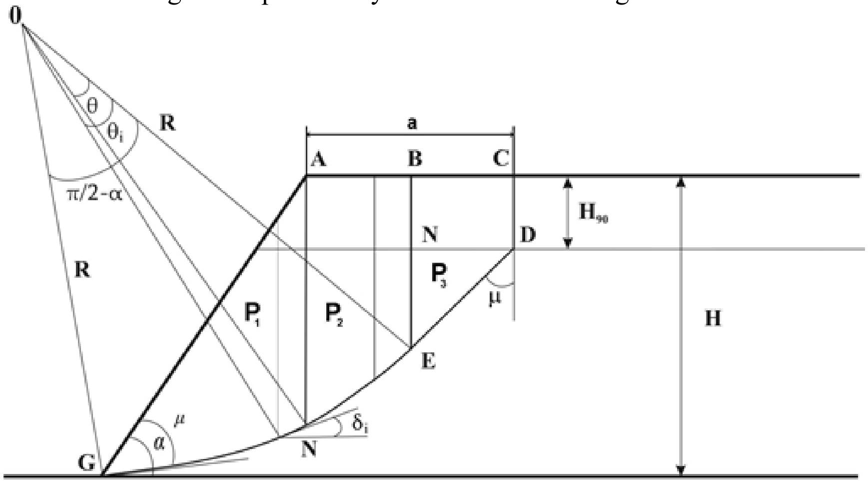

Figure 3. Scheme for calculating the slope stability factor

The stability factor of a homogeneous slope, taking into account the expansion of the forces due to the action of the self-weight of the soil, on the restraining and shearing, is determined by the following analytic expression:

$$n = \frac{tg\left[\sum P_i \cos\delta_i + P_1 \sin\left(\mu + \frac{\theta}{2}\right) + P_2 \sin\mu\right] + c(l_1 + l_2 + l_3)}{\sum P_i \sin\theta_i + P_1 \cos\left(\mu + \frac{\theta}{2}\right) + P_2 \cos\mu}, \quad (4)$$

where φ is the angle of internal friction of the soil;

P_i is the weight of the elementary column of soil at the i-th point of the curvilinear portion of the slip line;

δ_i is the angle of inclination of the tangent at the i point of the curvilinear portion of the slip line;

P_1, P_2 – weight of prism of reference pressure ABEN and weight of prism of active pressure BCDE accordingly;

$$\mu = 45^0 - \frac{\varphi}{2}, \quad (5)$$

θ is the angle contracted by the chord NE;

c – cohesion of the soil that forms the escarpment;

l_1 – length of the section of the circular cylindrical sliding surface GN;

l_2, l_3 – the lengths of two straight sections NE and ED, respectively.

Based on the scheme, which is shown in Figure 3, the radius of the sliding surface of the prism of a possible collapse is:

$$R = \frac{(H - H_{90}) \cdot tg\mu + H \cdot ctg\alpha}{\cos\mu - \sin(\alpha - \mu) + tg[\cos(\alpha - \mu) - \sin\mu]}, \quad (6)$$

$$H_{90} = \frac{2c \cdot ctg\mu}{\gamma}; \quad (7)$$

where H is the height of the slope of the ledge;

α is the angle of the slope of the ledge;

H_{90} – height of the elastic layer of soil;

γ is the density of the soil.

The width of the prism of the possible collapse of the AC at the upper platform is determined from the following expression:

$$a = 2\{R[\cos\mu - \sin(\alpha - \mu)] - Hctg\,\alpha\}. \quad (8)$$

After a number of mathematical transformations, we obtained analytical expressions for a more accurate determination of the slope stability factor of the slope. The developed mathematical apparatus for calculating the coefficient of stability of a homogeneous slope, allowed to create a program for calculating the safe parameters of slopes "Slope1".

This program allows you to calculate the safe parameters of slopes within a few seconds for a given stability factor. These calculations were the basis for plotting the graphs of the dependence of the nominal height of the slope H' on the angle of slope of the slope α and the conditional width of the prism of possible collapse.

Figures 4 – 7 show the graphs plotted taking into account the following characteristics c = 1 t/m^2, γ = 1 t/m^3, φ = 200.

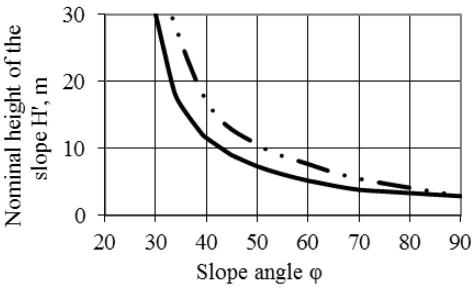

Figure 4. Graph of the dependence of the nominal height of the slope H 'on the slope angle of the slope at φ = 200 and the safety factor n = 1.0 (1 – graph plotted with the help of the Slope program, 1, 2 – graph constructed using the VNIMI method)

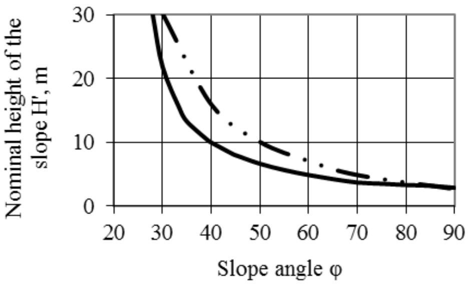

Figure 5. Graph of the dependence of the nominal height of the slope H' on the slope angle at φ = 200 and the safety factor n = 1.15. (1 – a graph constructed with the help of the Slope program, 1, 2 – a graph constructed using the VNIMI method)

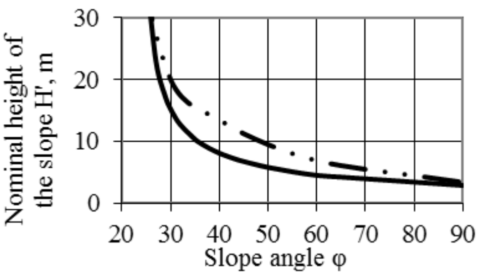

Figure 6. The graph of the dependence of the nominal height of the slope H 'on the slope angle at φ = 200 and the safety factor n = 1,2. (1 – a graph constructed with the help of the Slope program, 1, 2 – a graph constructed using the VNIMI method)

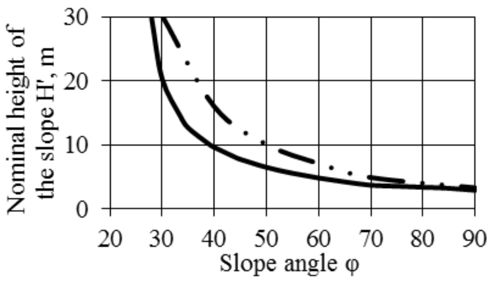

Figure 7. The graph of the dependence of the nominal height of the slope H' on the slope angle at φ = 200 and the safety factor n = 1.3 (1 – a graph constructed with the help of the program Slope, 1, 2 – a graph constructed using the VNIMI method)

Analysis of the results of the comparison shows that the parameters of the slopes, calculated using the graphs developed by VNIMI, are overestimated from 10 to 50%, which is inadmissible, since in this case the coefficient of stability is in fact lower than the normative by 15%.

Dependences of the nominal height of the slope H on the angle of slope of the slope α and the conditional width of the prism of the possible collapse, obtained with the help of the developed technique, make it possible to increase the reliability of the calculation of the safety factor by 20% in comparison with the graphical method developed by VNIMI [15, 16] risk of slope collapse by 20%.

3. Conclusion

The conducted analysis of industrial injuries and accidents in the mining industry showed a high level of traumatic danger of the industry and the absence of a stable tendency to reduce it. It has been established that about 20% of accidents in the mining industry are caused by caving and collapsing of quarry pit slopes, and the main reasons for the occurrence of caving in or collapse are unjustifiably chosen slope parameters, as well as inadequate actions of maintenance personnel.

It was revealed that the calculation of the maximum permissible parameters of the slopes is based on the choice of the geomechanical model of the soil array, the development of the geomechanical model of the soil massif is based on the study of the physical and mechanical properties of soils as constituent parts of the geological structure model.

As a result of the conducted studies, we found that for homogeneous massifs it is recommended to use a circular cylindrical slip surface, which is the most dangerous.

Analytical expressions are obtained for a more accurate determination of the slope stability factor of the slope. A program has been developed for calculating the safe parameters of slopes «Slope1».

The graphs of the dependence of the nominal height of the slope H 'on the slope angle α and the conditional width of the prism of possible collapse have been constructed, it has been established that the slope parameters calculated using the graphs developed by VNIMI are overestimated from 10 to 50%, which is inadmissible, since in this case, the safety factor will actually be lower than the normative by 15%.

Dependences of the nominal height of the slope H on the angle of inclination of the slope α and the conditional width of the prism of possible collapse, obtained with the help of the developed technique, make it possible to increase the reliability of the calculation of the safety factor by 20% in comparison with the graphical method developed by VNIMI and reduce the risk of collapse of slopes by 20% .

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