UDC 504.06:624.131.543:519.673 DOI: https://doi.org/10.15407/geotm2024.170.100

ASSESSMENT OF THE STABILITY OF A COAL-MINING ENTERPRISE'S ROCK DUMP AFTER RECLAIMATION

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Abstract. The article considers an approach to the use of geomechanical parameters of the stability of slopes of dump systems as a component of a comprehensive environmental assessment of mining enterprises to be liquidated. Performing a geoecological assessment is necessary to establish the possibility and effectiveness of carrying out eco-oriented works during the conservation, closure and liquidation of mining enterprises. Numerical calculations are demonstrated on the example of a representative object - the tailings massif of the SE "Zarichna Mine" of the Mezhyrichan deposit of the Lviv-Volyn coal basin. The materials of the environmental impact assessment project (EIA) of the liquidation of this mining enterprise were used as initial data. The given structure of waste object analysis and calculations of sustainability indicators can be the basis for creating a standard procedure for geoecological assessment of slope systems of mining enterprises at various stages of existence - from design to liquidation. It is also possible to build a methodology standard for the relevant sections of the EIA of enterprises that have large-scale slope systems in their structure. The limit state (equilibrium) methods were used as methods of calculating the stability coefficient of dump slope systems. The results of the calculations show fairly close values of the stability coefficient for all methods. This is primarily due to their similar methodological basis. It is advisable to direct further research to the application of calculation methods based on other principles of building a geomechanical shear model, namely methods of the mechanics of solid deformable body and numerical approaches for solving the calculation part of stability models. It is also advisable to expand the structure of factors taken into account in geomechanical models of stability by adding submodels of hydrosphere-filtration, atmospheric-climatic, seismic and other phenomena. Based on the calculation, recommendations were made for further maintenance of the geomechanical properties of the dump in an environmentally hazardous state. Monitoring and technological measures of eco-safety in the conditions of adverse natural atmospheric, hydrospheric, climatic phenomena and reclamation works are defined.

Keywords: comprehensive assessment of the environmental safety of dump systems, the coefficient of stability of the slope system, models of the stability of rock massifs, closure of mining enterprises.

1. Introduction

The activities of coal mining enterprises in Ukraine, which have been going on for more than 250 years, have led to an increase in the technogenic load on the environment. A significant part of Ukraine's territory, and in some regions up to a third of their territory, is allocated to mining enterprises that extract minerals by underground and open-pit methods - quarries of the Dnipro lignite basin and mines of the Lviv-Volyn basin and Central and Western Donbas.

The largest number of coal industry waste heaps is concentrated in Dnipropetrovsk and Donetsk regions and in the Lviv-Volyn basin. Over the course of their existence, waste heaps pollute the air, soil, and surface groundwater, change their size and morphology, are affected by exogenous processes, and burn. In addition, it should be noted that more than 8 billion tons of waste have been accumulated, which are placed on the earth's surface and are environmentally hazardous.

This situation is inherent in both existing enterprises and liquidated ones. Therefore, the conservation and closure of mining enterprises are the urgent problems in mining regions. The overwhelming majority of closed enterprises have rock dumps of different structure and configuration. In many cases, the dumps are reclaimed at the closure stage. Depending on the set of physical and chemical characteristics, the degree of environmental impact of dump systems at the closure stage is determined. In order to reduce natural and man-made hazards, a comprehensive environmental assessment of waste dumps is required. A component of the assessment of geo-environmental safety of dump systems is the determination of geomechanical parameters of slope stability in the initial state and after reclamation.

The aim of the study is to assess the stability coefficient of a coal mine dump after reclamation and to determine recommendations for further maintaining the geomechanical properties of the dump in an environmentally hazardous state.

The need to calculate the stability of the slopes of the mine waste heap is due to possible changes in its geomechanical state as a result of the cessation of the main production processes and the planned reclamation.

Characterization of engineering and geological conditions. In geological terms, the field of Zarichna Mine is located on the Mezhyrichan deposit of the Lviv-Volyn coal basin. The relief of the area under consideration is calm. Absolute surface elevations range from +195 m to +206 m.

The geological structure of the area under consideration includes sedimentary deposits of the Devonian, Carboniferous, Jurassic, Cretaceous and Quaternary systems. The Bashkirian stage is represented by sandstones, sandy clay and clay shales. Sometimes the deposits are entirely represented by a sandstone thickness with a coal seam up to 0.3 m thick. The main commercial coal content of the area under consideration belongs to the upper part of the Serpukhivska Suite. The bedrock of the industrial seams is mainly represented by mudstone with a thickness of 0.05–0.26 m.

The upper Cenomanian aquifer is widespread and confined to the upper, intensely fractured zone of the Cenomanian marl. It is located at depths ranging from 20 m to 90 m. The horizon is under pressure.

The Carpathian region of Ukraine, which includes Lviv region, is characterized by uneven seismic activity. The Zarichna mine is located on the low-seismic Eastern European and partially on the Western European platforms, so negative seismic processes are not expected [1].

General characteristics of the waste management. The total area of the site and waste heap is 43.2777 hectares. The area of the waste heap is 18.1857 hectares according to the State Act for the right of permanent land use Series I-LV No. 001676-194 dated December 27, 2001.

The sanitary protection zone of the waste heap is 500 meters wide and has been maintained. The characteristics of the waste heap according to the passport are shown in Table 1.

Geotechnical characteristics of the waste heap reclamation. The waste heap has a lined slope surface, which is over 80% self-grown, which, according to clause 4.11 of the SOU 10.1.00174125.011:2007, allows not to carry out mining reclamation works in this area.

The waste heap was planned on the basis of technical specifications issued by Zarichna Mine in accordance with the requirements of SOU-N10.1-05420037-001:2007 “Rules for Biological Reclamation of Waste Heaps at Coal Mines in

Ukraine".

Table 1 Characteristics of the waste heap

No.	Name of indicators	Unit of measurement	Rock dump
1.	Capacity	thousand m^3	3364
2.	Height	m	40.9
3.	Filling the slopes of the dumps	deg.	29
4.	Dump area	thousand m^2	154.0
5.	Bulk weight of the dumped mass	kg / m^3	2290

The waste heap on the southern side is partially dismantled (10200 m^3) to backfill underground structures. The project stipulates that the rock from the dump (volume - 42000 thousand m^3) will be used to level the surface of the waste heap and backfill the tract. A layer of imported potentially fertile soil (PFS) with a thickness of h - 0.5 m is applied to the planned surface of the waste heap.

Reclamation of the mine's waste heaps is carried out for sanitary and hygienic purposes. The surface of the dumps is preliminarily planned with a bulldozer-ripper in the amount of 27.320 thousand m^3. The planned surface of the dumps and slopes is covered with 64,690 thousand m^3 of PFS.

2. Methods and theoretical part

Description of the methodology for calculating the stability of the slopes of the waste heap. The components of the methodology for calculating the stability of the slopes of the dump are methods for determining the geomechanical stability coefficient and the standard safety factor.

The Bishop (Cray), Filenius, and Yanbu methods were used to calculate the geomechanical stability of the dump slopes. Common to these methods is the assumption of a circular cylindrical shape as a potential shear surface and the division of the landslide body into a certain number of vertical compartments.

Bishop (Cray) method. This method takes into account the horizontal forces that occur between separate compartments of the landslide body. The difference of the Bishop method is that it takes into account the equations of force moments rather than forces themselves. That is, the sum of the moments of all forces relative to the center of the sliding curve radius should be zero [11,12].

The stability factor according to the Bishop method is equal:

$$K_{st} = \frac{M_{hd}}{M_{sh}} = \frac{1}{\sum_{i=1}^{n}(P_i \cdot \sin\alpha_i)} \sum_{i=1}^{n} \frac{P_i \cdot \mathrm{tg}\phi_i + c_i \cdot b_i}{\cos\alpha_i (1 + \frac{\mathrm{tg}\alpha_i \mathrm{tg}\varphi_i}{K_{st}})}, \quad (1)$$

where K_{st} – slope stability coefficient; M_{hd} – total holding moment; M_{sh} – total shear moment; P_i – is the weight of the i-th compartment; n – is the number of compartments; α_i – is the angle of inclination of the *i*-th compartment to the horizon, deg; φ_i – is the angle of internal friction of the soil within the *i*-th compartment, deg; c_i – is the specific cohesion of the soil within the *i*-th compartment, kPa; b_i – is the length of the sliding surface in the *i*-th compartment..

In formula (2), the value of K_{st} is present in both parts of the equation, so to solve this equation, one should use the method of successive approximations (iterations) [11,12].

The Filenius method. The peculiarity of the calculation scheme for the Filenius method is the assumption that the state of limit equilibrium is observed only at points along the sliding surface, and the landslide body is a rigid body that is not subject to deformation [9,12].

The position of the most dangerous sliding surface was determined by selecting the center of the sliding surface in numerous calculations for possible cases.

The condition for the equilibrium of a landslide body is the equality of the holding and shear forces. The safety factor is equal to:

$$K_{st} = \frac{\sum_{i=1}^{i=n} (P_i \cdot \cos\alpha_i \cdot \text{tg}\varphi_i + c_i l_i)}{\sum_{i=1}^{i=n} P_i \cdot \sin\alpha_i}, \tag{2}$$

where l_i – is the length of the sliding surface in the *i*-th compartment.

Yanbu method. The Yanbu method satisfies both the conditions of equilibrium of forces and moments and is applicable to sliding surfaces of any shape [10,12].

The slope stability coefficient K_{st} is determined by the formula:

$$K_{st} = \frac{\sum_{i=1}^{n} (c_i \cdot b_i \cdot \frac{1}{\cos\alpha_i} + N_i \text{tg}\phi_i) \cdot \frac{1}{\cos\alpha_i}}{\sum_{i=1}^{n} P_i \cdot \text{tg}\alpha_i}, \tag{3}$$

where N_i – is the vertical component of the weight force of the *i*-th compartment, kPa.

Determination of the safety factor. When searching for a dangerous shear surface, the dependence for the safety factor is used [8]

$$k_S = \frac{R}{F} \geq [k_S], \tag{4}$$

where $k_S \geq [k_S]$ – is the permissible (normalized) value of the stability factor; R – is the generalized calculated value of the forces (or their moments) of the ultimate shear resistance along the surface under consideration; F – is the generalized calculated value of the active forces (or moments of these forces) relative to the center of the sliding surface.

In general, in the vast majority of cases, the stability coefficient of waste heaps during the transitional period of operation is accepted not lower than the standard one, which is in the range of 1.05–1.25.

Initial data for the calculation of the stability of the slopes of the waste heap. Initial data were compiled based on the data from the liquidation project materials and research results from various information sources.

The Zarichna mine waste heap is located within the mine field. The mine dumps are composed of mudstones (60–65 %), siltstones (20–25 %), sandstones (10 %), coal shale, coal and pyrites (up to 2 %). [2]. Taking into account the fact that the rock of the waste heap is in a mixed, quasi-homogeneous state, the average rock properties were used to calculate the stability of the waste heap slopes (Book 1 of the project).

Table 2 summarizes the averaged values of the properties of the rocks that make up the waste heap based on information sources.

Table 2 – Average properties of the waste heap rocks

Name of engineering and geological elements	Accepted substance content, %	Adhesion C, kPa	Internal friction angle φ, deg
Argillite	65	70	21
Alevrolite	23	80	25
Sandstone	10	77	33
Coal shale	1	65	18
Hard coal	0.5	100	29
Pyrites	0.5	90	35
Averaged values		73.2	23.2

Summarizing the above, the following strength parameters were used to calculate the stability of the waste heap: density – 2.34 t/m^3 (22.9 kN/m^3); angle of internal friction – 32°; cohesion – 7.4 t/m^2 (73.2 kPa).

3. Results and discussion

Results of calculations of the stability of the dump slopes. Calculations of the stability of the slopes were performed taking into account static loads. Hydrological and seismic factors were not taken into account, given the rather significant depth of groundwater and low seismicity of the area. The calculations considered several options for the location of possible slip curves, for each of which a safety factor was determined. The centers of the slip curve radii were determined using a square grid area [3×3].

Based on the above characteristics of the reclamation works, geological sections 3-3 and 5-5 (according to the data of the liquidation project materials) were selected as the most representative sections for the calculation. The results of calculations for geological sections 3-3 (left slope) and 5-5 are presented graphically in Figures 1–5.

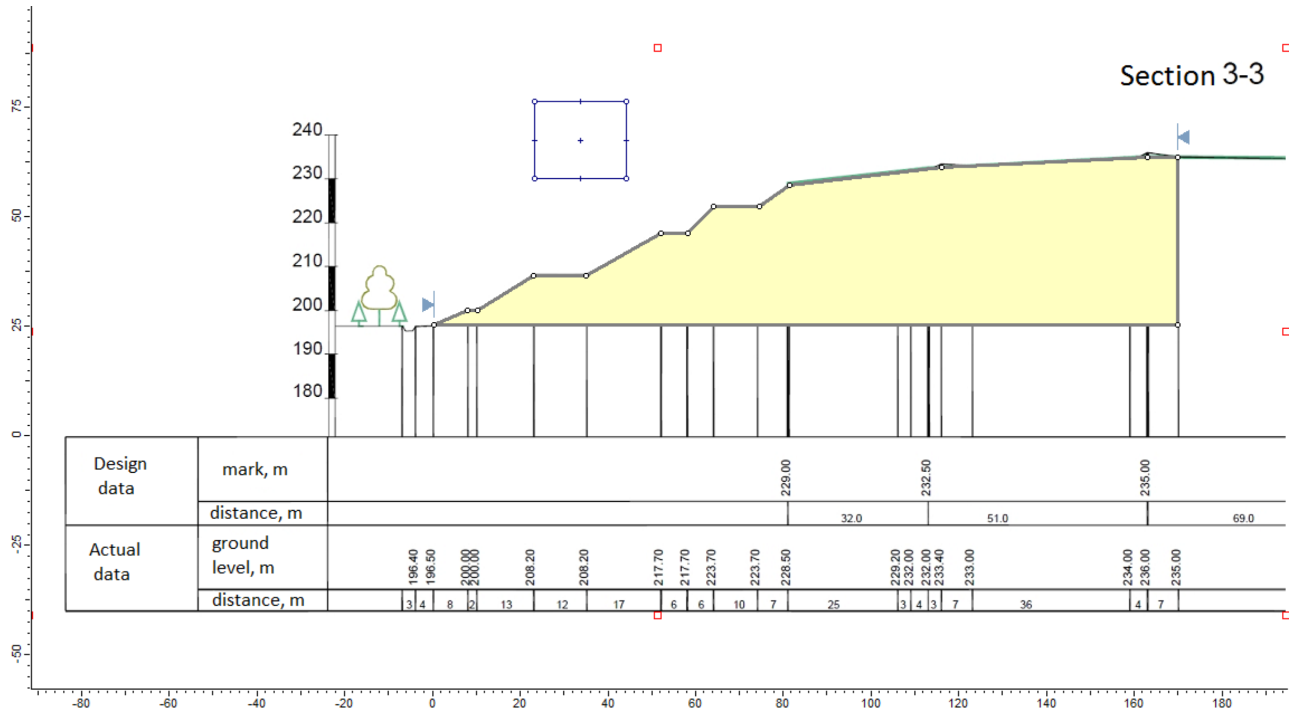

Figure 1 – Design scheme for the calculation of section 3-3 (left slope)

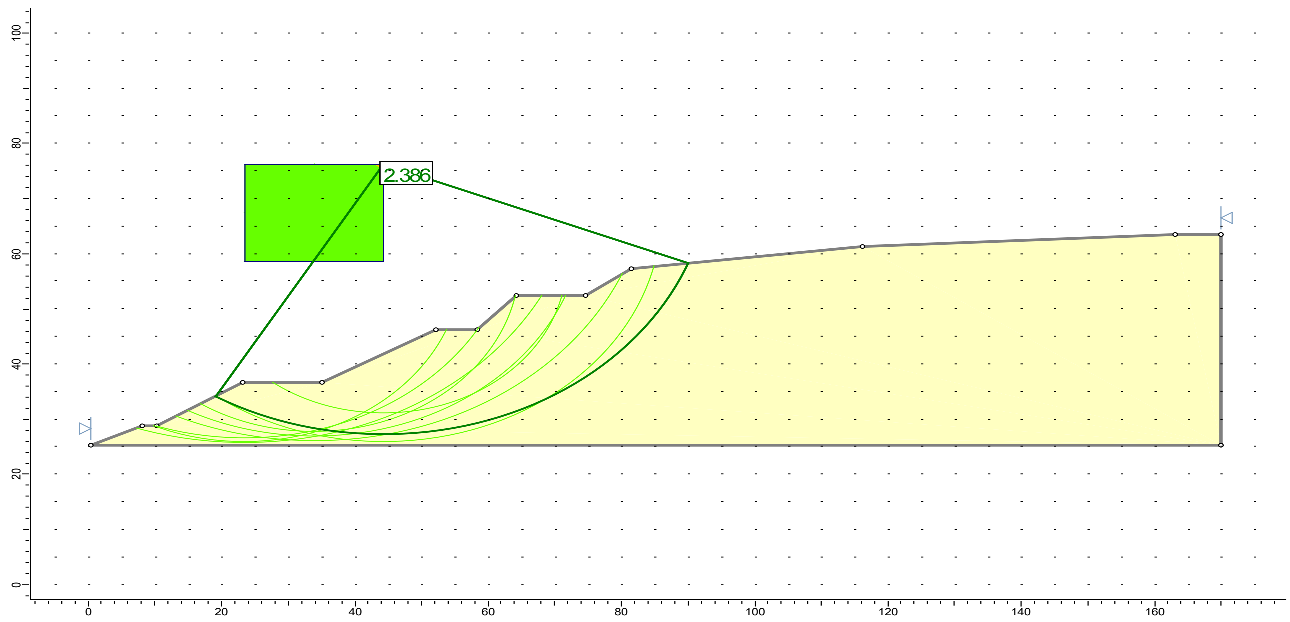

Figure 2 – Minimum shear surfaces and global minimum stability factor based on the results of the calculation for section 3-3 (left slope)

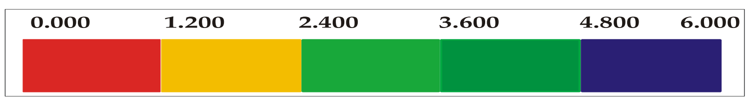

Figure 3 – Graphical scale of gradation of the safety factor level

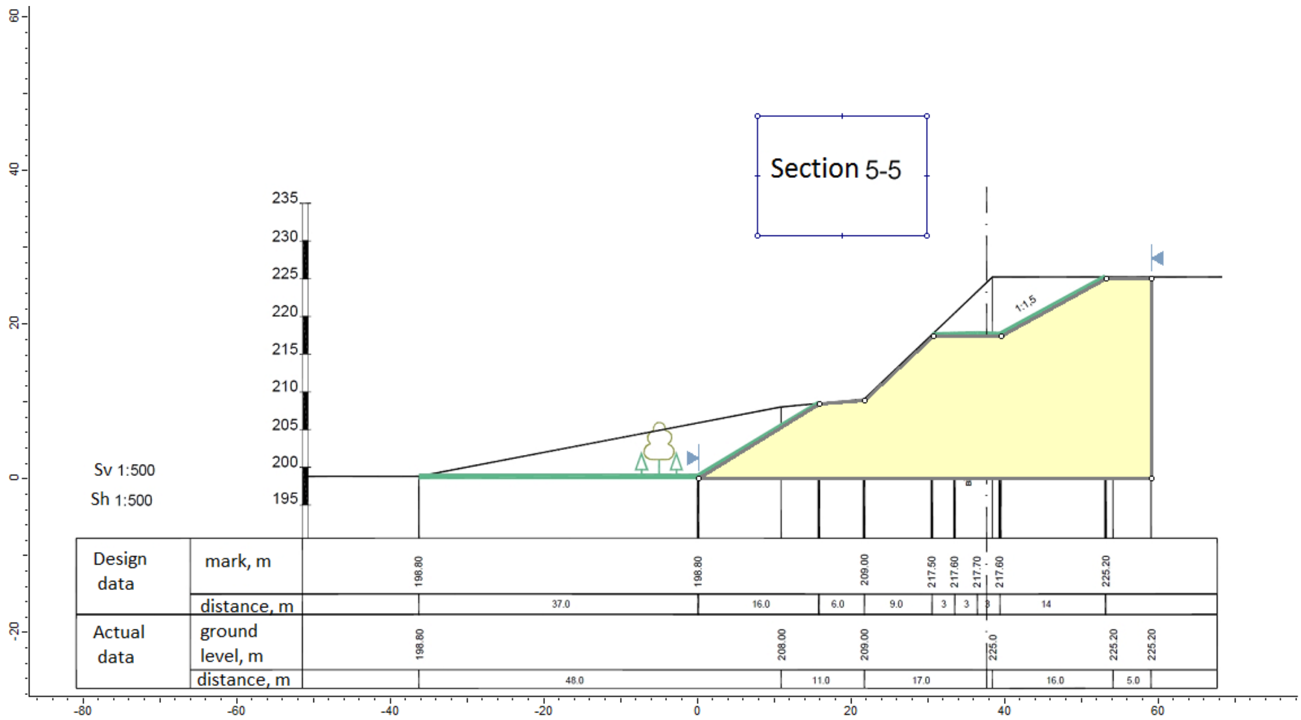

Figure 4 – Design scheme for the calculation of section 5-5

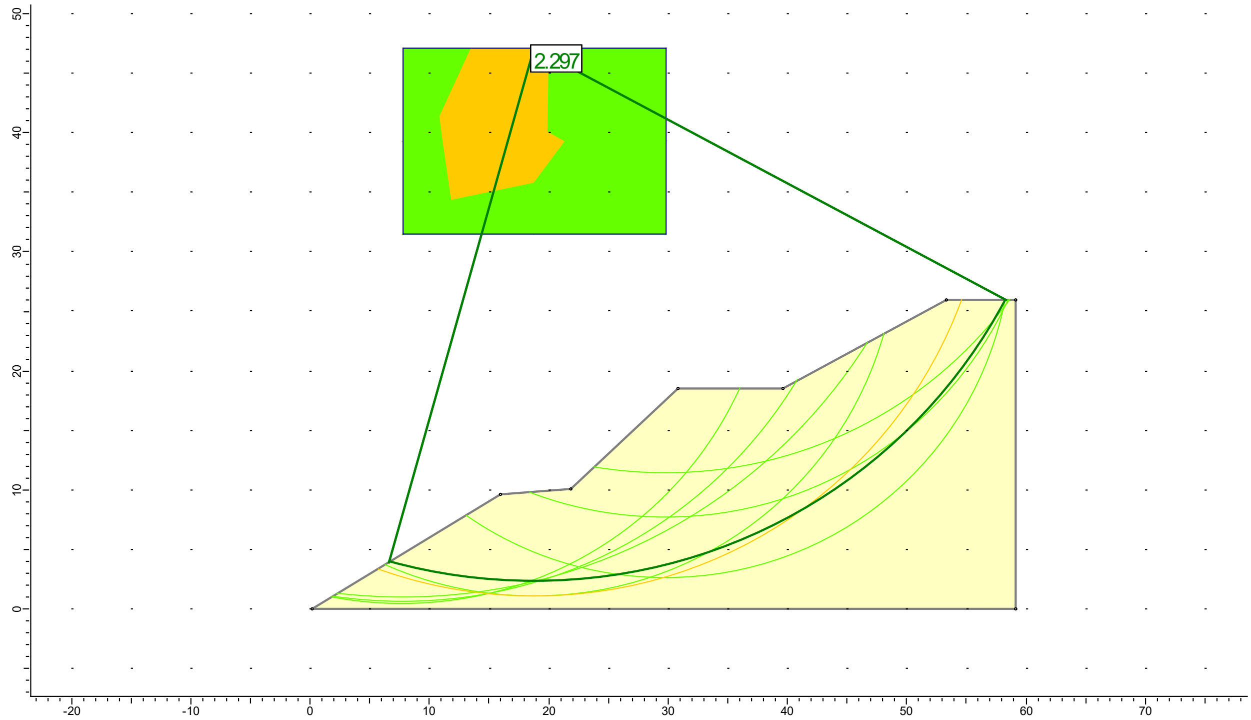

Figure5 – Minimum shear surfaces and global minimum of the stability factor based on the results of the calculation in section 5-5

Numerical results of calculations for all geological sections are presented in Table 3.

The minimum values of the slope stability factor (in bold italics in the table) of the dump exceed the maximum regulatory stability factor in the range from 1.8086 to 2.1506 for different cross-sections and calculation methods. Based on the results of the calculations, it can be concluded that after reclamation, the slopes of the waste heap will be in a stable condition.

Table 3 – Results of calculations of the stability coefficient of the heap

Design section	Method	Minimum value of the slope stability coefficient	Safety factor relative to the maximum regulatory stability factor (1.25)
Section 3-3 left slope	Fellenius	2.4662	1.9730
	Bishop (Cray)	2.6882	2.1506
	Yanbu	***2.3864***	1.9091
Section 3-3 right slope	Fellenius	2.3076	1.8461
	Bishop (Cray)	2.3754	1.9003
	Yanbu	***2.2608***	1.8086
Section 5-5	Fellenius	2.3629	1.8903
	Bishop (Cray)	2.4709	1.9767
	Yanbu	***2.2973***	1.8379

4. Conclusions

Based on the results of the studies and calculations, recommendations were developed to ensure safe landslide conditions at the dump. Taking into account the general methodological difficulties in the reliability of calculation methods, difficulties in determining fully adequate initial data, a rather significant discrepancy in the initial data of the properties of the waste heap rocks, the possibility of negative hydrological and other phenomena, it is necessary to provide a number of recommendations for maintaining a safe landslide condition of the waste heap.

The loss of stability of the waste heap in the form of landslides, collapses, floods, and subsidence is a consequence of waste heap deformations. The main factors affecting the stability of the slopes of the dump under consideration are the possible negative impact of hydrostatic and hydrodynamic effects of groundwater and atmospheric water on the rock mass and the dangerous dynamic effect of mining equipment on the rock mass. The most dangerous abnormal climatic phenomenon that contributes to the occurrence of sinkholes is a combination of high ambient temperatures and high-intensity precipitation, which dramatically disrupts the thermodynamics and hydrology of the dump.

The main socio-technological consequences of soil mass sliding may include accidents of equipment used for reclamation, threats to health and life of production personnel involved in reclamation works, filling of adjacent territory with shear masses, destruction of structures, engineering and road communications.

The main environmental impacts of shear processes are contamination of the ground surface and soil with dump materials and damage to the biological systems of the surrounding area, depending on the scale of the landslide. Hydrological contamination is possible in the event of an abnormally sharp rise in the water table above the base of the dump or in the event of abnormal precipitation, which, combined with high fracture, can lead to seepage of waste materials into aquifers.

The most recommended measures to prevent the occurrence of negative factors of shear processes are monitoring the condition of the waste heap to detect dangerous cracking, significant changes in the shape of the waste heap, primarily the occurrence of slope angles beyond the normative limits, and anti-landslide measures of various levels.

Monitoring of the landfill surface is particularly important:

- during the period of landfill reclamation and disposal;
- in case of groundwater level rise and possibility of the landfill flooding, especially during seasonal floods;
- during periods of significant abnormal precipitation, mudflows and snowstorms;
- during the period of possible abnormal seismic activity in the neighboring regions;
- during abnormal climatic events.

During the period of reclamation, the main anti-shear measure is to maintain the technologically defined shape of the dump surface in accordance with current data on the geomechanical properties of the dump massif.

In all cases of dangerous hydrological phenomena (flooding, floods, abnormal precipitation, etc.), the main anti-shear measure is to reduce the water content of the massif by constructing drainage networks.

As current, situational, and additional measures, it is advisable to use the following: securing the surface of the dump with greenery, using stone riprap, water-insulating injections of the cracks, artificial measures to compact and secure soils (such as cementation), mechanical fastening of slopes with piles and dowels, and the construction of retaining structures (in the form of earthen stops and buttresses).

Anti-seismic measures include the above-mentioned anti-shear methods for securing the slope surface, the characteristics of which are calculated taking into account the expected seismic action.

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ОЦІНКА СТІЙКОСТІ ПОРОДНОГО ВІДВАЛУ ВУГЛЕДОБУВНОГО ПІДПРИЄМСТВА ПІСЛЯ РЕКУЛЬТИВАЦІЇ

Медведєва О., Рябко А., Остапенко Н., Пронько О., Жанакова Р.

Анотація. У роботі розглянутий підхід до використання у якості складової комплексної екологічної оцінки гірничих підприємств, що ліквідуються, геомеханічних параметрів стійкості укосів відвальних систем. Виконання геоекологічної оцінки необхідно для встановлення можливості та ефективності проведення екоорієнтованих робіт при консервації, закритті та ліквідації гірничих підприємств. Чисельні розрахунки продемонстровані на прикладі репрезентативного об’єкту - відвального масиву ДП «Шахта «Зарічна» Межирічанського родовища Львівсько-Волинського кам'яновугільного басейну. У якості вихідних даних використовувались матеріали проекту оцінки впливу на довкілля (ОВД) ліквідації даного гірничовидобувного підприємства. Наведена структура аналізу відвального об’єкту та розрахунків показників стійкості може являтись основою для створення стандартної процедури геоекологічної оцінки укісних систем гірничих підприємств на різних етапах існування – від проектування до ліквідації. Також можлива побудова стандарту методики відповідних розділів ОВД підприємств, що мають у своєму складі масштабні укісні системи. У якості методів розрахунку коефіцієнту стійкості відвальних укісних систем були використані методи граничного стану (рівноваги). Результати розрахунків показують досить близькі значення коефіцієнту стійкості для усіх методів. Це пов’язано, насамперед, з їх подібною методологічною основою. Подальші дослідження доцільно спрямувати на застосування методів розрахунку на інших принципах побудови геомеханічної моделі зсуву, а саме методах теорії твердого деформованого тіла та чисельних підходах вирішення розрахункової частини моделей стійкості. Також доцільно розширення структури факторів, що враховуються у геомеханічних моделях стійкості шляхом доповнення підмоделями гідросферо-фільтраційних, атмосферно-кліматичних, сейсмічних та інших явищ. На основі розрахунку побудовані рекомендації щодо подальшого підтримання геомеханічних властивостей відвалу у екологічно небезпечному стані. Визначені моніторингові та технологічні заходи екобезпеки в умовах несприятливих природних атмосферних, гідросферних, кліматичних явищ та робіт з рекультивації.

Ключові слова: комплексна оцінка екобезпеки відвальних систем, коефіцієнт стійкості укісної системи, моделі стійкості гірських масивів, закриття гірничих підприємств.