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© D. Brovko[1], A. Bolotnikov[2], A. Romanenko[3]
[1, 2] Kryvyi Rih National University, Kryvyi Rih, Ukraine
[2, 3] Collective enterprise "ACADEMIC HOUSE", Kryvyi Rih, Ukraine
[3] Technical University "Metinvest Polytechnic" LLC, Zaporizhzhia, Ukraine

STUDY OF THE STABILITY OF A ROCK WASTE DUMP ON WEAK SOIL: A CASE STUDY OF THE OXIDIZED QUARTZITE DUMP

© Д.В. Бровко[1], А.В. Болотніков[2], А.О. Романенко[3]
[1, 2] Криворізький національний університет, Кривий Ріг, Україна
[2, 3] Колективне підприємство "АКАДЕМІЧНИЙ ДІМ", Кривий Ріг, Україна
[3] Технічний університет ТОВ "Метінвест Політехніка", Запоріжжя, Україна

ДОСЛІДЖЕННЯ СТІЙКОСТІ ВІДВАЛУ СКЕЛЬНИХ ПОРІД НА СЛАБКОМУ ҐРУНТІ НА ПРИКЛАДІ СКЛАДУ ОКИСЛЕНИХ КВАРЦИТІВ

Purpose. To identify the factors influencing the stability of a rock dump on weak soil, specifically in the case of the oxidized quartzite dump located on the slope of Open Pit Mine No. 3 at PJSC "ArcelorMittal Kryvyi Rih," as well as to determine the stability parameters of this dump based on the obtained data and results of surveying observations.

The methods. Experimental and analytical methods were employed to investigate the engineering-geological and hydrogeological characteristics of the base of the oxidized quartzite dump and the results of surveying observations for surface slope movements.

Findings. Stability parameters of the oxidized quartzite dump were calculated for different values of the safety factor SFS (Safety Factor of Stability), allowing for the determination of optimal design characteristics to ensure its stability and safety. It was found that the values of cohesion and internal friction angle decrease due to rock slides, which is important to consider during the construction and operation of dump structures to ensure safety and minimize risks.

The originality. The scientific novelty lies in the comprehensive approach to studying the stability of a rock dump on weak soil, specifically using the example of oxidized quartzites. The research considers the unique properties of oxidized quartzites and their interaction with weak soils, a topic that has been insufficiently explored in previous studies.

Practical implementation. The comprehensive information obtained about the geological and hydrogeological situation of the area enables effective planning and development of any construction projects on this territory. Considering the impact of rock slides on soil properties allows for the development of effective risk management strategies and minimization of potential negative consequences during construction and operation of the facilities.

Keywords: *mining activity, geomechanics, dump stability, rock formations, weak soil, oxidized quartzites.*

Introduction. Introduction. Rock dumps are an integral part of mining operations, especially in large industrial regions like the Kryvyi Rih area. However, their stability on weak soils raises significant concerns due to the potential for collapses, which can lead to serious ecological and economic consequences. Studying the stability of rock dumps, particularly on weak foundations, is crucial for ensuring the safety and stability of mining activities [1–10].

One of the most critical aspects in this context is the analysis of the geomechanical properties of dump foundations. Oxidized quartzites, commonly used in dumps, can significantly influence the overall stability of the structure due to their specific properties. Understanding the interaction between the foundation and the dumped materials is key to developing effective measures to prevent collapses and stabilize the dumps.

Located on the southern outskirts of Kryvyi Rih, between Open Pit Mine No. 3 and the Inhulets River, is the study area, which forms a peripheral part of the forest plateau. Here, a typical sequence of sedimentary deposits is observed, characteristic of the region. Within the southern outskirts of the study area lie ferruginous quartzites, approaching the surface, where a former quarry was once located and subsequently filled with tailings.

The research conducted in this area included a detailed analysis of hydrogeological conditions and monitoring of deformation processes occurring in the dumps of oxidized quartzites. The results of these studies are crucial for assessing dump stability and developing recommendations for the safe operation of mining facilities.

Main part. The study area is located on the southern outskirts of Kryvyi Rih in Dnipropetrovsk Region, between the open pit mine No. 3 and the Inhulets River. It lies within the peripheral region of the forest plateau, at its junction with the left slope of the Inhulets River valley, characterized by a typical sequence of sedimentary deposits for the Kryvyi Rih region. Ferruginous quartzites approach the surface on the southern edge of the study area, where a quarry was previously located and subsequently filled with tailings.

The research area is situated within a gently sloping southward plain towards the Black Sea Basin, with surface elevations ranging from +88.42 to +102.46 meters. Based on lithological-stratigraphic structure and previous hydrogeological studies, the following aquifers and complexes can be distinguished:

– Quaternary aquifer horizon;

– Neogene aquifer horizon;

Aquifer complex of fractured zones of crystalline rocks of the Lower Proterozoic.

The hydrogeological conditions in the study area have been significantly altered due to the development of iron ore deposits. Mining dewatering operations and the construction of rock dumps have had a substantial impact on the hydrodynamic structure of groundwater flows within the aquifer horizons and complexes in the open pit mine vicinity.

Currently, the operating open pit mines of PJSC "ArcelorMittal Kryvyi Rih" and PJSC "Southern Mining and Processing Plant" play a crucial role in shaping the groundwater regime in the surveyed area. As a result of their operation, aquifers within Quaternary and Neogene deposits are nearly drained near the edges of the quarries and extended around the waste rock dumps. Serving as collectors of atmospheric precipitation, their impact is predominantly evident during the spring snowmelt and intense rainfall periods.

Additionally, the aquifers of Cenozoic deposits in the quarry areas are currently being influenced primarily by anthropogenic factors, including infiltration of atmospheric precipitation into the formed waste rock dumps and filtration losses from water-bearing communications. There exists a negative balance between the inflow of water from the waste massif and their drainage along the quarry periphery, leading to a slight but continuous decline in groundwater levels.

Analyzing the nature of water inflows into the quarries, long-term observations have established that their maximum manifestation is directly dependent on the amount of atmospheric precipitation. Thus, under the influence of water pumping from the quarry dewatering systems of active quarries, a technogenic regime of groundwater has formed in the study area. The drainage of the aquifer in the fractured zone of the Lower Proterozoic crystalline rocks has led to a decrease in pressures, resulting in the formation of depression cones.

According to the modeling of changes in the hydrogeological situation within the studied area due to the impact of the oxidized quartzite storage dump, the following results were obtained:

– In the area of the formed oxidized ore dump, a groundwater dispersion dome is forecasted to form, with maximum elevations in its central part. The rise in the groundwater level within the dump area will not exceed 0.5–1.0 meters.

– Changes in the groundwater levels of the aquifer in the fractured zone of crystalline rocks in the study area will be predominantly noticeable near the filled quarry on the slope of the Inhulets River. By the end of the forecast period, the groundwater level rise in the center of the filled quarry will reach +18 meters.

– The physico-mechanical characteristics of the base rocks of the oxidized quartzite dump at the edge of quarry No. 3 of PJSC "ArcelorMittal Kryvyi Rih" were determined based on the results of research conducted by the "EnergoProekt" Institute. The assessment of the main indicators of the physico-mechanical properties of the soils in the study area was carried out according to the results of laboratory studies (geotechnical tests), as provided by the Program, and geophysical works (radioisotope logging).

During the laboratory studies, the main focus was on determining the strength characteristics of the soils, which determine the stability of the dumps within the area.

Sixteen engineering-geological elements were identified within the study boundaries. The studies conducted in the area comply with current standards and regulations regarding the determination of soil properties.

During drilling, the strength of the sedimentary (or technogenic) cover was determined, and the upper layer of bedrock (iron quartzites) was uncovered. The thickness of the sedimentary cover ranges from 12.3 to 29.3 meters. At depths of 1.5–5.0 meters, technogenic soils were encountered. Below, at depths of 8.7–14.6 meters, loess-like light silty clays, which are collapsible, are prevalent, and further below are Pliocene deposits of the Pontian stage, consisting of sands and clays. These deposits lie unevenly on the weathering crust.

Under natural conditions, the hydrogeological situation in the study area is determined by the presence of three aquifers associated with Quaternary and Neogene deposits, as well as the weathering crust and the fractured zone of crystalline rocks. The natural hydrogeological regime in the study boundaries is disrupted by the water drainage system, which ensures the operation of quarry No. 3. As a result, the aquifer associated with the technogenic and loess-like soils is redirected to the lower horizons.

The absolute levels of the groundwater horizon are recorded within the range of 75.98–79.79 meters (at a depth of 12.3 to 22.7 meters). The impermeable layer of the horizon consists of Pontian clays, weathering crust deposits, and iron quartzites. The general direction of the groundwater flow is towards the Ingulets River.

The determined physico-mechanical properties of the soils for both consolidated-drained and unconsolidated-undrained states show that the main characteristics of the internal friction angle and relative cohesion for soils in the identified engineering-geological element (EGE) – 16 (heavy, silty, calcareous, hard, and semi-hard loam) practically do not change (under loads from 0.5 to 0.9 MPa), with even an increase in the relative cohesion index within the range of 15–20%. This phenomenon can be explained by the natural moisture content of the considered soils (W = 0.155), which is slightly below the plasticity limit (W_p = 0.190).

It can be assumed that the degree of moisture in the EGE – 16 soils, which are located directly above the EGE – 19 sands, will increase to the plasticity limit and above, leading to a significant decrease in their strength properties. It should be noted that at the beginning of the design phase, the values of the physico-mechanical properties of the weak layer soils for different EGEs at a confidence probability of 0.95 were within the following ranges:

– for consolidated, drained (CD) soils:
  – cohesion – C = 0.009–0.076 MPa;
  – internal friction angle – ρ = 13–31°.
– for unconsolidated, undrained (UU) soils:
  – cohesion – C = 0.003–0.063 MPa;
  – internal friction angle – ρ = 12–22°.

After the activation of the landslide process, the frequency of monitoring for deformation processes on the site was increased to once every 2–4 days.

Systematic observations were conducted on 12 working benchmarks in the studied area: No. 105-108 (level +100 m), No. 145-148 (level +140 m), No. 171, 172 (level +170 m), No. 181, 182 (level +180 m).

The results recorded the displacement velocities of the working benchmarks ranging from 10–44 mm/day. During the observation period, the total displacement of the working benchmarks was recorded within the range of 0.5–0.65 meters.

The observed displacement velocities were between 10-50 mm per day. The direction of the displacement vectors of the working benchmarks indicates the formation of several sliding surfaces, starting at levels (+180 m) and (+170 m).

The sliding surfaces have a steep form in the active pressure prism area (average angle observed in the vectors is 55°) and a gentle form after the break at the base, contacting the weak layer (angle of inclination in the resistance prism area is within 3–4°).

The greatest displacement was recorded for benchmark No. 172, located at level (+170 m), with a displacement of 0.709 meters over 30 days, corresponding to an average speed of 23.6 mm/day.

The most critical sliding surface is the one starting at level (+170 m).

When selecting the calculation method, current regulatory documents on the stability of pit slopes and dumps were followed, specifically the methodological guidelines [1].

Based on the conducted analysis of the engineering-geological and hydrogeological characteristics of the oxidized quartzite dump foundation, as well as the observed surface landslides, the following was determined:

A weak inclined layer extends at the base of the oxidized rock dump, with an inclination angle of around 40° towards the diversion channel of the Inhulets River.

Within the oxidized quartzite dump, a series of sliding surfaces are formed, creating cracks at levels (+180) and (+170), with a steep fall into the mass (angle observed in vectors is about 55°).

At the contact with the weak layer, the sliding surface breaks and its angle coincides with the inclination angle of the weak layer at the base.

Given the above, the most suitable scheme for calculating the stability of the considered site, according to the methodological guidelines [1], is the scheme presented in section 9.2.1 [1], where stability is calculated using the polygon of forces method.

In this case, to solve the task, it will be divided into two stages:

1. Reverse calculations of the physico-mechanical properties of the weak layer foundation;

2. Calculations of the parameters of the oxidized quartzite dump that ensure its stability based on the obtained data.

Calculations of the maximum permissible height of the oxidized quartzite dump should be carried out using formula (1), as recommended by the methodological guidelines [1].

$$H = \frac{2k'_n \sin 2\alpha \sin(\omega_n - \beta)}{\gamma \sin(\alpha - \beta)\left[\frac{(1 - \sin\rho_n)\sin(\alpha - \beta)}{\cos(90 - \omega_n - \beta)} - 2\cos\beta \sin(\omega_n - \alpha)(\mathrm{tg}\rho'_n \cos\beta - \sin\beta)\right]}, \text{ m} \quad (1)$$

$$\omega_n = 45 + \frac{\rho_n}{2}, \text{ degree} \quad (2)$$

where k_n, k_n' – the cohesion coefficients in the dump rock and the foundation, respectively, reduced by the normative SFS (Safety Factor of Stability), t/m^2; ρ_n, ρ_n' – the internal friction angles of the rocks in the dump and the foundation, respectively, reduced by the normative SFS, degree; α – the slope angle of the dump, degree; β – the slope angle of the weak foundation layer, degree.

According to the methodological guidelines [2] on monitoring the stability of pit walls and dumps, as well as the relevant instructions [3], reverse (refinement) calculations of the physical and mechanical properties of the rocks at the base of the oxidized quartzite dump of PJSC "ArcelorMittal Kryvyi Rih" were performed. In accordance with the aforementioned methodological guidelines [2], for pit walls exhibiting landslide processes such as cracks, fissures, and constant displacement rates of working benchmarks, the Safety Factor of Stability (SFS) for reverse calculations is assumed to be SFS = 1.1.

Considering that the reverse calculations require determining two unknowns – the cohesion coefficient and the internal friction angle – a series of calculations was performed for each sliding surface, establishing the relationship between the cohesion coefficient and the internal friction angle of the rocks at the base of the oxidized quartzite dump.

During the calculations, the following values were used based on the basic characteristics of the rocks:

– Bulk density of quartzites in the dump body: $\gamma = 2.7$ t/m^3

– Cohesion coefficient of the accumulated rocks: $C = 0$ MPa

– Internal friction angle: $\rho = 35°$.

The dependencies obtained for the considered sliding surfaces after the calculations are shown in Figures 1 and 2.

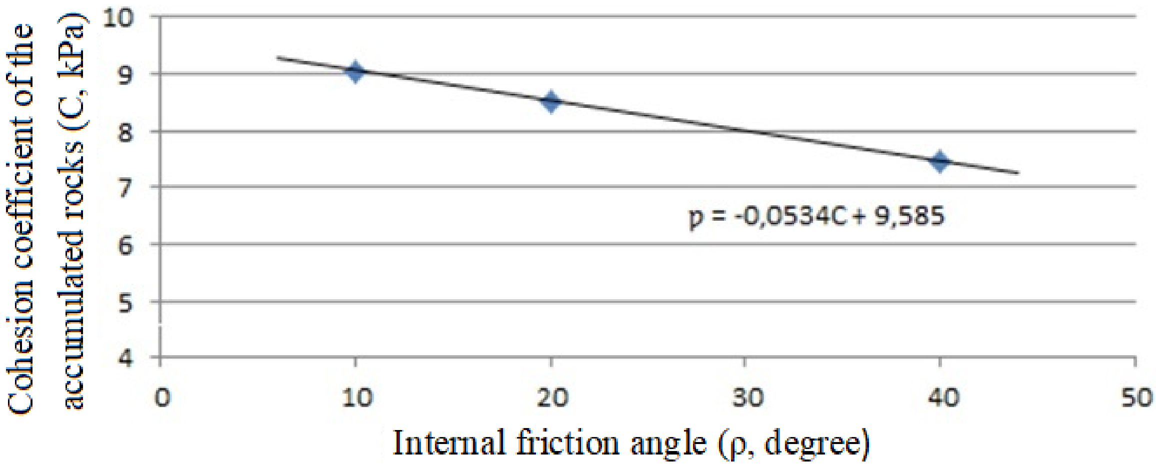

Fig. 1. Dependence of the angle of internal friction (ρ, degrees) on cohesion (C, kPa), obtained from inverse calculations for a slope at a height of 80 m (elevation +180 m): $\rho = -0.0534C + 9.585$ – equation of the relationship

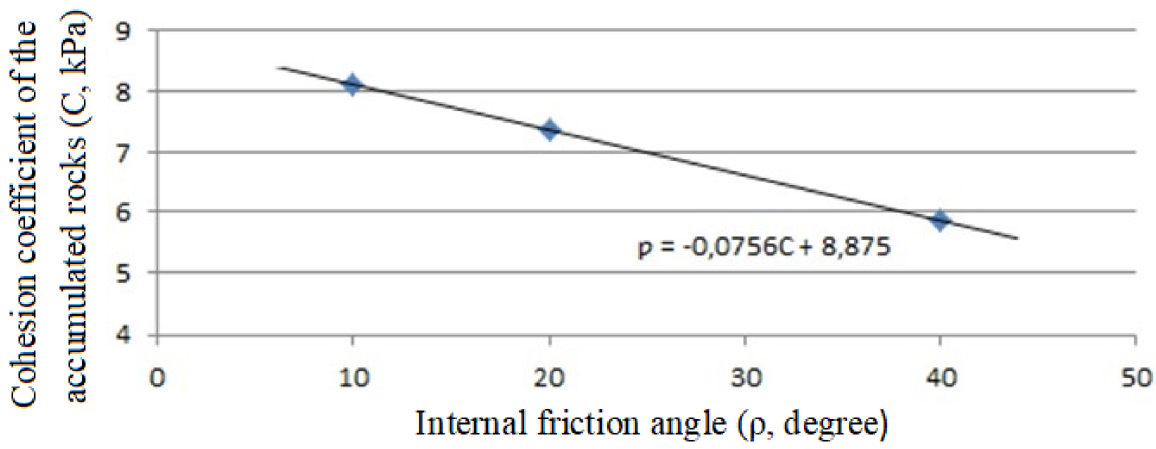

Fig. 2. Dependence of the angle of internal friction (ρ, degrees) on cohesion (C, kPa), obtained from inverse calculations for a slope at a height of 70 m (elevation +170 m): $\rho = -0,0756C + 8,875$ – equation of the relationship

During the analysis of these data, average values of the physico-mechanical properties of the weak layer rock foundation can be calculated as follows:

- cohesion – C = 22 kPa;
- angle of internal friction – ρ = 8.73°.

Calculation of the parameters of the oxidized quartzite composition, ensuring its stability using the specified factor of safety, was performed using expressions (1) and (2) recommended by the guidelines [1].

The calculations utilized initial data presented in Table.

Table

Initial data for calculating parameters of the oxidized quartzite composition

№	SFS	γ, т/м^3	ρ_n, degree	k_n, t/m^2	ρ'_n, degree	k'_n, t/m^2
1	1,0	2,7	35	0	8,73	2,2
2	1,2	2,7	29,2	0	7,27	1,83
3	1,3	2,7	26,9	0	6,72	1,69

The calculated data determined dependencies of maximum slope angles based on the slope height. Figure 3 shows the relationship for SFS = 1.2, and Figure 4 for SFS = 1.3.

The calculated data determined dependencies of maximum slope angles (αmax) on the slope height (H_y). Figure 3 illustrates the relationship for SFS = 1.2, and Figure 4 for SFS = 1.3.

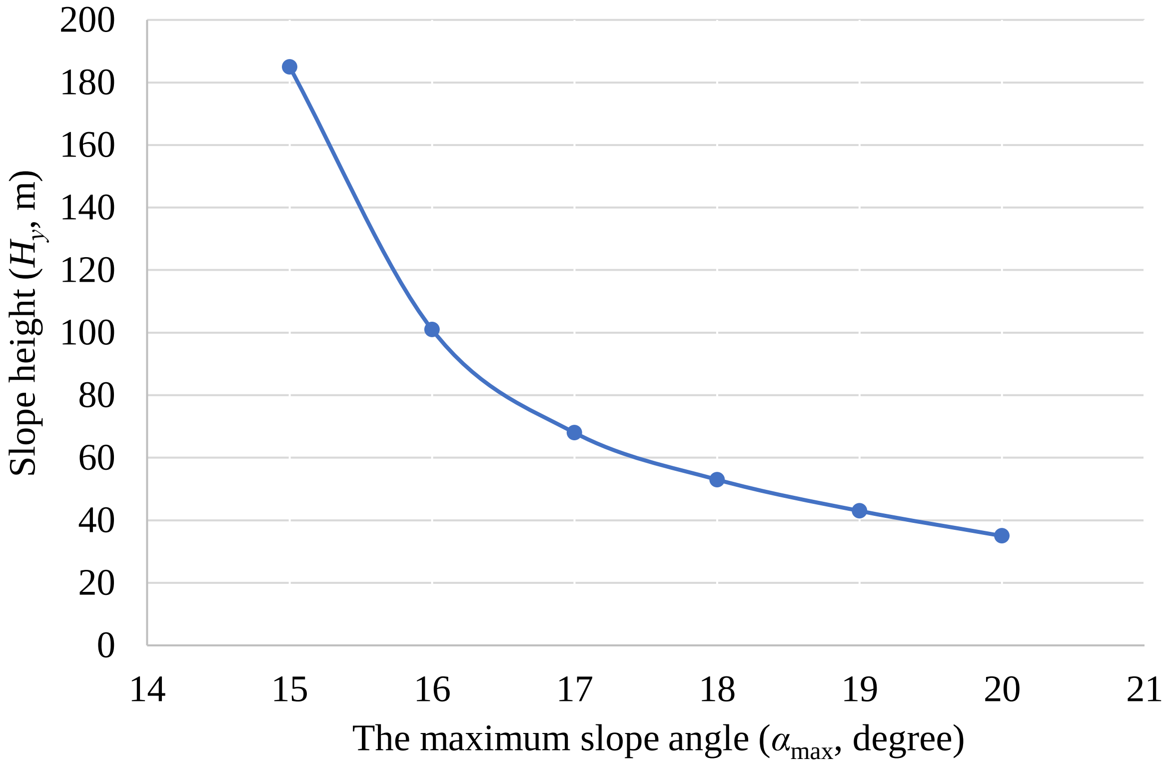

Fig. 3. Parameters of the embankment composed of oxidized quartzites with a specified SFS = 1.2

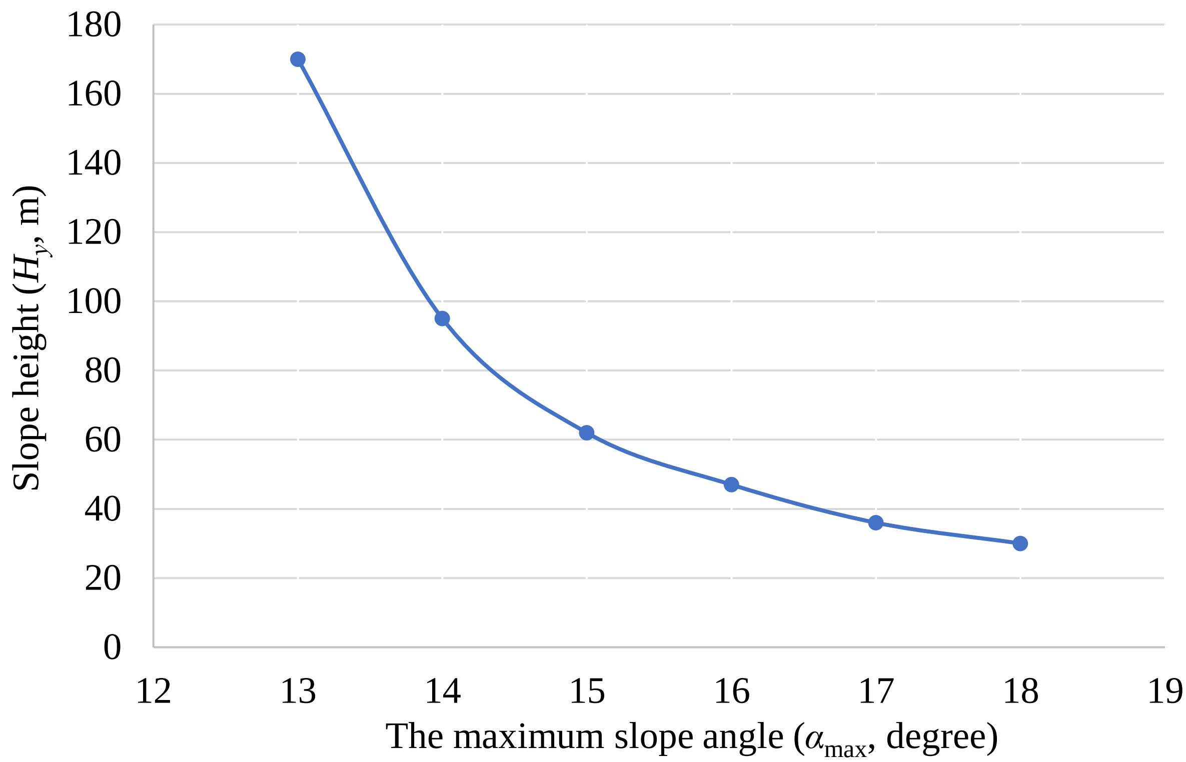

Fig. 4. Parameters of the embankment composed of oxidized quartzites with a specified SFS = 1.3

Conclusions. The research has confirmed that the stability of rock waste dumps on weak soil largely depends on the physico-mechanical properties of materials and operational conditions. Identified patterns can be utilized for the design and operation of waste dumps.

Based on the analysis of engineering-geological and hydrogeological characteristics of the foundation of oxidized quartzite at the edge of quarry No. 3 of PJSC "ArcelorMittal Kryvyi Rih" and the results of surveying observations on the displacement of the surface of the oxidized quartzite dump, the following has been established:

1. Observed displacement rates range from 10 to 50 mm per day.

2. The direction of displacement vectors indicates the formation of several slip surfaces originating from the elevations at +180 m and +170 m.

3. Based on inverse geomechanical calculations to determine the physico-mechanical properties of the weak layer at the base of the oxidized quartzite dump, the following values were obtained:

cohesion – C = 22 kPa;

angle of internal friction – ρ = 8.73°.

4. Calculations of the deposition parameters of the oxidized quartzite dump in its proximity to the Ingulets River perimeter channel have identified dependencies of the maximum permissible slope height on the slope angle (see Fig. 3, 4) with a specified factor of safety.

5. Based on the rock slide, a decrease in the initial values of cohesion C and angle of internal friction ρ, which were adopted as initial data in the design of the formation

of the oxidized quartzite dump, has been determined. Therefore, systematic monitoring of rock slide is necessary during the construction and operation of dumping facilities.

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АНОТАЦІЯ

Мета. Визначення чинників, що впливають на стійкість відвалу скельних порід на слабкому ґрунті, зокрема на прикладі складу окислених кварцитів , що розташований на борту кар'єра № 3 ПАТ "АрселорМіттал Кривий Ріг", а також визначення параметрів стійкості цього складу на основі отриманих даних та результатів маркшейдерських спостережень.

Методика. Для дослідження були використані експериментальні та аналітичні методи, проведення аналізу інженерно-геологічних та гідрогеологічних характеристик основи складу окислених кварцитів та результатів маркшейдерських спостережень за зсувами поверхні борту.

Результати. Розраховані параметри стійкості складу окислених кварцитів для різних значень коефіцієнта запасу стійкості (КЗС), що дозволяє визначити оптимальні характеристики конструкції для забезпечення її стійкості та безпеки. Виявлено, що величини зчеплення та кута внутрішнього тертя зменшуються внаслідок зсуву гірських порід, що важливо враховувати під час будівництва та експлуатації насипних споруд для забезпечення безпеки та мінімізації ризиків.

Наукова новизна. Полягає в комплексному підході до вивчення стійкості відвалу скельних порід на слабкому ґрунті, зокрема на прикладі окислених кварцитів. Дослідження враховує специфічні властивості окислених кварцитів і їхню взаємодію зі слабкими ґрунтами, що є недостатньо дослідженою темою у попередніх роботах.

Практична значимість. Отримана комплексна інформація про геологічну та гідрогеологічну ситуацію на місцевості дозволяє здійснити ефективне планування та розробку будь-яких будівельних проектів на даній території. Врахування впливу зсуву гірських порід на властивості ґрунтів дозволяє розробити ефективні стратегії управління ризиками та мінімізувати можливі негативні наслідки під час будівництва та експлуатації споруд.

Ключові слова: *гірнича діяльність, геомеханіка, стійкість відвалів, скельні породи, слабкий ґрунт, окислені кварцити.*