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PROBLEMS OF DUMPING TECHNOLOGY IN THE INUNDATED OPEN PIT SPACE IN CONDITIONS OF SURFACE DEFORMATION

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Abstract. Challenge. The objective of this research is to determine the minimum permissible safety berm for loading and mining equipment operation, ensuring safe and efficient dumping under the shear in recent dumping, subsidence of dump rock mass and fractures.

Research methods. Analytical and statistical analyses of the previously obtained results, simulation modeling, and in situ surveys of the research object were performed.

Scientific originality. Depending on the working progress, the dumping mode is specified for inundated slopes. The dependence of the stability factor on the safety berm size is specified. According to theoretical research results, the components of the forces acting on the slickensided surface are obtained.

Practical implications. Residual volumes of rock storage under the current technology using the available equipment were determined by calculations. Geomechanical analyses were conducted to determine the minimum permissible safety berm for loading and mining equipment. They revealed the dependence of stability factor on the size of the safety berm and identified that the minimum permissible safety berm for loading and mining equipment under the dumping conditions in the inundated open pit No. 1 of ArcelorMittal Kryvyi Rih PJSC with a standard stability factor (SF) (1.15) is 34 meters. The obtained results prove the possibility of using the existing equipment and applying the dumping technology in the rock deformation mode, subject to developing technological schemes ensuring safe and efficient dumping. For further dumping using the available equipment in the mined space of inundated open pit No. 1, it is required to perform research to determine safety zones or develop alternative ways and technologies of waste rock storage in open pit No. 1 applying the available equipment reducing the dumping cost and increasing the efficiency of using residual mine workings.

Keywords: inundated open pit, dumping, internal dump, shears, deformations, slope stability, excavator, sliding wedge, stability factor, K–MINE.

1. Introduction

Mining operations on the internal single–tier dumping in the inundated space of the open pit are characterized by difficult mining conditions caused by shear in recent fill dump stopes, dump rock subsidence and fracturing at the working unloading platforms when using walking excavators [8, 10, 11]. Similar conditions will affect mining operations during the deep open pit liquidation after disconnecting the pit drainage and restoring the levels of the depressed surface of groundwater. Therefore, the area of residual mine workings (RMW) will significantly expand. Reducing the areas of residual mine workings (mining reclamation) is a requirement of the Law of Ukraine "On Land Protection", as well as current regulations [2, 9] and requires the development of technological schemes for ensuring mining safety.

Today, the internal single–tier dumping is performed in the inundated space of the open pit No. 1 of ArcelorMittal Kryvyi Rih PJSC, which is characterized by the danger of mining operations due to the shears and dump rock subsidence, as well as fracturing spreading on the working unloading platforms, which significantly limits the use of technical equipment, including walking excavators. This restriction is due to the spread of fractures for 30 meters and more from the inundated open pit crest.

The problem of safe mining during dumping in the open–pit inundated space in terms of shears and subsidence of dump rock mass is associated with scientific and practical objectives of pit wall stability and internal dumps, observations on the renewal dynamics of the depressed surface levels of groundwater in the deep open pits, and the development of technological schemes for mining reclamation of residual mine workings.

2. Methods

The use of land disturbed by mining is the most pressing challenge, but, unfortunately, the experience of using residual mine workings in deep open pits is insignificant (open pit No. 2 of PJSC Central GOK, West–Balaklava open pit of JSC «Balaklavskoe RU») [1]. Moreover, there is no experience in backfilling deep open pits inundated more than 0.3 of the pit wall height. The current norms, rules and requirements related to internal dumping do not contain recommendations for the conditions of the inundated open pit [2]. The accumulated experience of dumping at the considered research object is as follows: in the inundated open pit No. 1 of ArcelorMittal Kryvyi Rih PJSC since 1997, starting with the unloading of dump trucks through the protection embankment under the slope into the water, by the EKG–4U excavator at the border with the sliding wedge and to the use of ESH–6/45 walking excavator [3–5].

The subsidence deformations of the dump rock mass during backfilling are related to the creation of a retaining wedge at the underwater part of the dump under the influence of hydrostatic weighing on the rock pieces and the formation of voids between the pieces. Therefore, the rock pieces falling into the water face their resistance and, depositing on the surface of the underwater slope, form voids in between. Their volume increases with the accumulated filling layers of the dump. In addition, the physical and mechanical property values of the watered filling layers (the angle of natural slope and cohesion between the pieces) become smaller than in the dry state [5].

The research on the impact of groundwater on slope stability revealed the following: the changes in the stressed rock mass influenced by water and flow forces; changes in the mechanical properties of rocks; the occurrence of slope deformations in the sliding wedge.

The engineering methods based on the theory of limiting equilibrium applied to specific mining and geological conditions, considering the data in situ and the results of the modeling performed, are used to assess the degree of influence of inundation on slope stability [5–6]. A particular term for the stability of inundated slopes is the combined inundation of the residual open–pit excavations with the internal dump [5]. Water and flow forces while calculating the slope stability are considered when analyzing the seepage direction, and its influence is as follows: from the side of the rock mass is from the formation of the depressed surface of groundwater in the possible sliding wedge slope, and from the side of the inundated mined space is from the inundation of the possible sliding wedge slope.

The safety factor of the inundated slope is estimated by the following formula (1) [8]:

$$n = \frac{\sum_{i=1}^{n} (Ni - D + G) \cdot tg\phi + Ci \cdot Li}{\sum_{i=1}^{n} (Ti + G)} \quad (1)$$

where Ni and Ti are the mass components of the calculation blocks applied on the slickensided surface, considering the rock density; D is total weight water and flow force, MPa, acting perpendicularly to the slickensided surface sections, Li; G is the hydrostatic pressure, MPa, applied to the inundated slope surface, and is considered in the calculation blocks along the slickensided surface; φ is the internal friction angle in the dry and water–saturated state, deg; Ci is the adhesion (cohesion) of rocks, MPa.

Waste formation backfilling into the water was followed by the dump base creation in the underwater position with the slope angles of the slope in situ within 15–340 [3]. The reason for the formation of a subsidence wedge within the excavation stope is the deformation of the weak underwater base of " weighted " rocks caused by the embankment rock mass stress of the waste.

Considering the numerous deformations observed by the company's thrust fault control service and based on the results of hydromechanical modeling of the inundated dump on a unique stand, the researchers concluded that it is essential to use a walking excavator with a dumping radius of at least 100 m, ensuring safe mining.

Currently, dumping into the waste space of open pit No. 1 is performed only in the southern pit wall area by the ESh–11/70 walking excavator. Backfilling of open pit No. 1 is provided by PJSC PE "Techmash" according to the project "Reconstruction and Development of Open Pits No. 2 bis and No. 3 of the ArcelorMittal Kryvyi Rih PJSC Mining Department to Maintain the Productivity of Mining Raw Ore at the Rate of 30 Million Tons p.a. for the Period from 2020 Until the End of Mining in Inhuletskyi District and Tsentral'no–Gorodskoy Rayon". Adjustment of the geological and mining part of the project was drafted by KAI LLC in 2021. This equipment ensures safe dump operation only for a certain period of time, having a limited scope of work and taking into account the operating parameters of ESH–11/70 excavator, the maximum possible storage capacity when using the dumping method in the rock deformation [7] is about 7 million m3, and, without applying this technology, is 2.8–3 million m3 ensuring safe dump operation for 2–3 years.

3. Results and discussion

The underground water inundation of the deep open pit to a depth of more than 0.6 of the height of its walls and the constant increase in the water level caused dangerous conditions for the use of walking excavators with a dumping radius of less than 45 m for internal single–tier dumping. Due to the high cost of using sturdy excavators and their imperfection, there was a need to develop technological schemes for internal dumping into the mined space of deep open pits under groundwater level recovery, ensuring safe and efficient mining in the controlled disposal using the available equipment.

Considering the level of dump inundation over the past 16 years (Fig 1, Table 1), we can assume that the average annual rise in water level is 2.6 m, with a more intensive rise observed over the past six years of 2.8 m p.a.

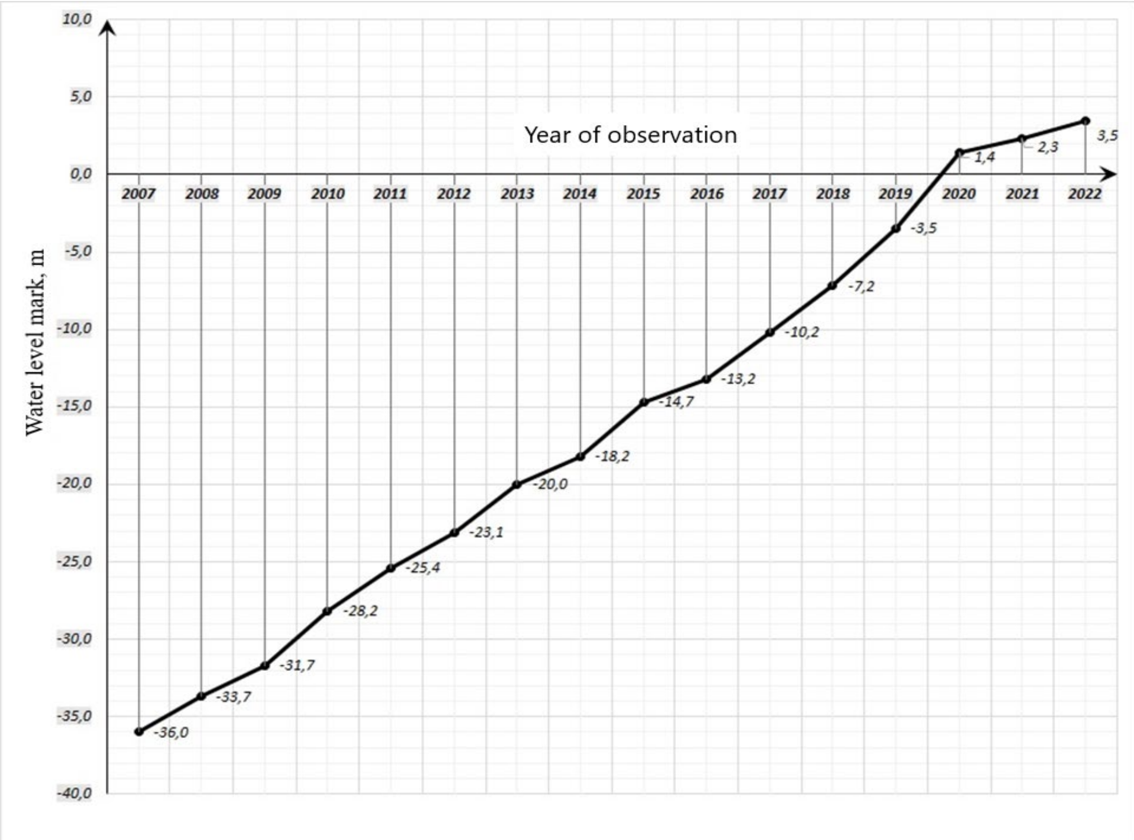


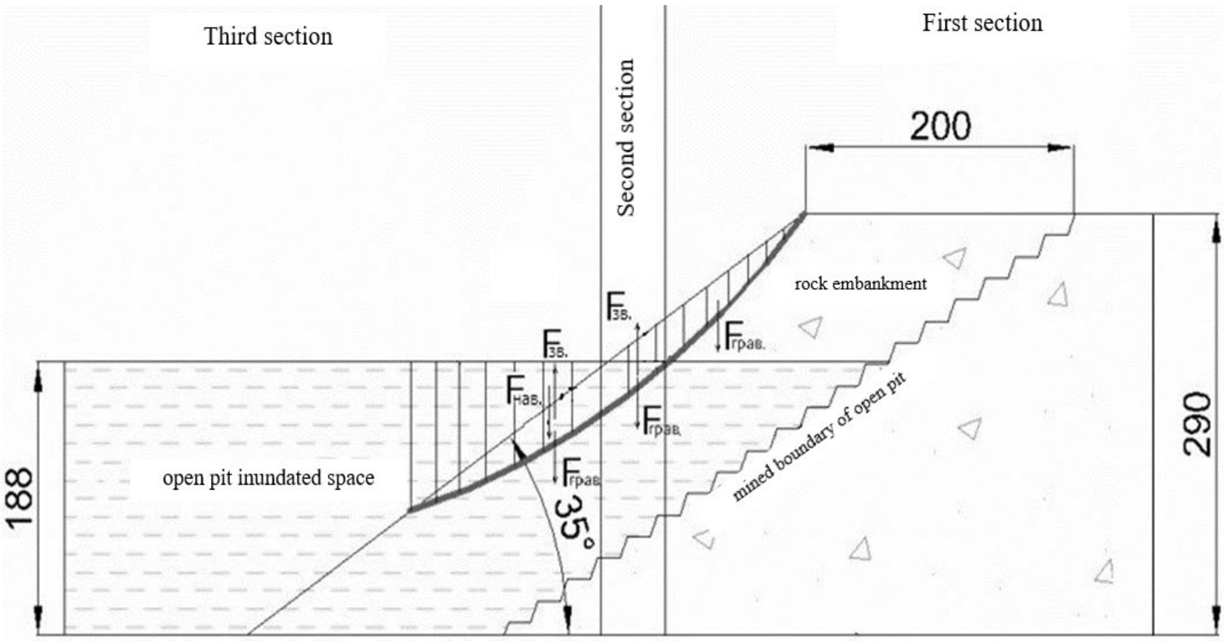
Figure 1 – Dynamics of water level rise in the inundated open pit No. 1 for the last 16 years

Table 1 – Water level increase in the inundated open pit No. 1 for the last 16 years

Year of observation	Water level mark, m	Increase in water level, m
2007	–36.0	36.0
2008	–33.7	2.3
2009	–31.7	2,0
2010	–28.2	3.5
2011	–25.4	2.8
2012	–23.1	2.3
2013	–20.0	3.1
2014	–18.2	1.8
2015	–14.7	3.5
2016	–13.2	1.5
2017	–10.2	3.0
2018	–7.2	3.0
2019	–3.5	3.7
2020	1.4	4.9
2021	2.3	0.9
2022	3.5	1.2

The inundated base is the biggest challenge in calculating the minimum permissible safety berm. According to the guidelines [2, 9], the calculation of the stability of inundated slopes is based on the fact that the total pit wall stability during the open pit inundation changes as a result of weighing and loading of water in the open pit basin and depends on the position of the water surface for filter slopes. It is noted that the worst condition of the total stability of the open pit walls occurs when the open pit is inundated by 1/3 of its depth and less if this part of the wall is created of filter rocks. In this case, the safety factor is reduced by 10–25% compared to the non–inundated slope. When the water level rises by more than 1/3 of the wall height, the wall stability increases; when the open pit is highly inundated, the safety factor of the slope is 25–40% higher than the safety factor of the non–inundated open pit.

The component of the confining and shearing forces affecting the inundated dump slope was identified (Fig. 2).



F_{grav} - gravity force, kN; F_{hyd} - hydrostatic weighing force, kN; F_{load} - load force, kN.

Figure 2 – The main forces affecting the inundated slope of the single–tier dump

In Fig. 2, the main forces affecting the inundated slope of the dump are shown. According to the available physical data, the total part of the slope can be divided into three sections based on the current forces:

— in the first section (above–water), the force component forms the confining and shearing forces acting on the expected slickensided surface, which is caused by the rock weight;

— in the second section (inundated), the force component forms confining and shearing forces acting on the expected slickensided surface due to the rock weight and the weighing force;

— in the third section (underwater), the force component forms the confining and shearing forces acting along the expected slickensided surface, which is caused by the rock weight, the water weighing force and the on–bottom weight of the water volume above the slope.

Based on the considered mechanism of the acting forces on the inundated slope, the equations of the confining (2) and shear (3) forces acting on the slickensided surface, applicable for calculations by the method of algebraic addition of forces, were determined [3, 5, 6].

The wide use of the method of algebraic addition to calculate the bench, pit walls and dumps stability is due to its ease, sufficient reliability of the results obtained, and wide practical use. This method was successfully implemented in the K–MINE: Stability Analysis (license: OGR series No. 54057760 dated March 2018) and helps performing automated calculations of the safety factor for current mining and geological conditions.

$$F_c = \sum_{j=1}^{n} (\gamma_j \cdot V_{n.j} \cdot cos\phi_j - \rho \cdot V_{wb.j} \, cos\phi_j + \rho \cdot V_{wa.j} \cdot cos\phi_j) \cdot tg\alpha_j + \sum_{j=1}^{n} C_j \cdot l_j \, , \quad (2)$$

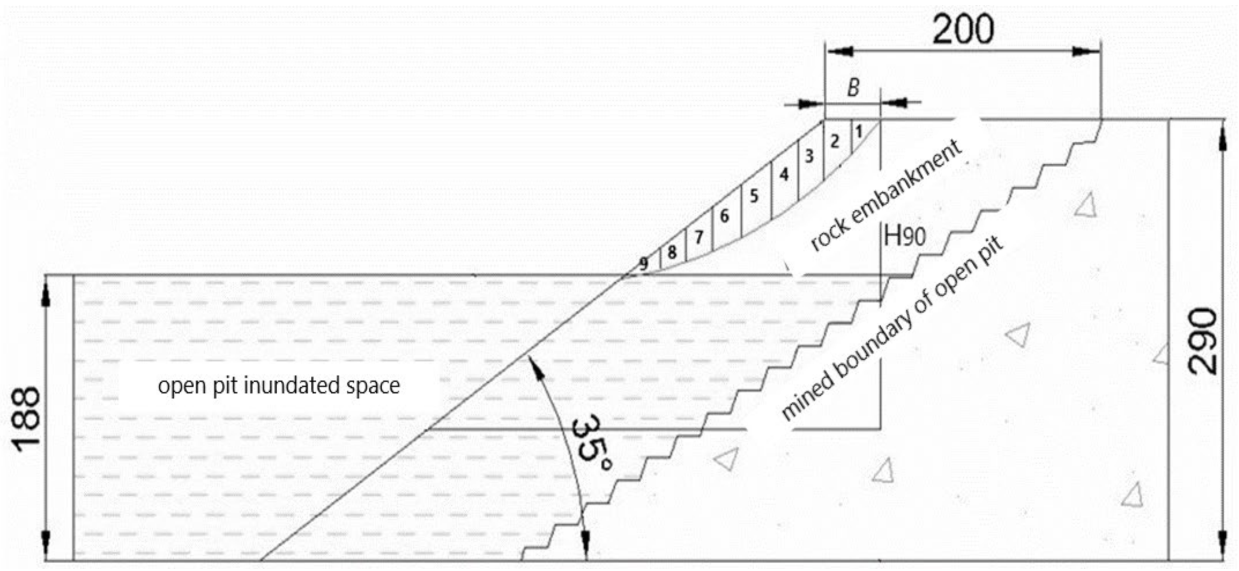
$$F_s = \sum_{j=1}^{n} (\gamma_j \cdot V_{n.j} \cdot sin\phi_j - \rho \cdot V_{wb.j} \, sin\phi_j + \rho \cdot V_{wa.j} \cdot sin\phi_j), \quad (3)$$

where γ_j is the specific gravity of rock within the calculation block, N/m^3; $V_{n.j}$ is the rock volume of the calculation block, m^3; l_j is the slickensided surface length within a particular calculation block, m; ϕ_j is the angle between the horizontal and the tangent to the curve at the point that is the middle of the base of the calculation block, deg.; C_j is the molecular cohesion within a given calculation block, Pa; α_j is the angle of internal friction within a particular calculation block, deg; ρ is the bulk density of water, N/m^3; $V_{wb.j}$ is the volume of water in the calculation block below the slope line, m^3; $V_{wa.j}$ is volume of water in the calculation block above the slope line, m^3; n is the number of calculation blocks on which the sliding wedge is divided, units.

Considering the data in situ (Fig.1, Table 1), geomechanical calculations (Fig.3, Table 2) were performed in the K–MINE: Stability Analysis (license: series OGR No. 54057760 dated March 2018) to determine the minimum permissible safety berm for the operation of loading and mining equipment, which resulted in the dependence of the safety factor on the safety berm size in the dumping conditions to the inundated open pit No. 1 of ArcelorMittal Kryvyi Rih PJSC.

The minimum permissible safety berm for mining equipment was determined using step–by–step calculations of the safety factor with a step of berm size within 10 meters.

During the calculations, the cohesion forces of embankment rocks were accounted equal to 20 kPa, as well as the internal friction angle of embankment rocks equal to 32 degrees.



1,2,3...9 is the number of the calculation block; B is the minimum permissible safety berm, m; H90 is the height of the vertical rupture created within the safety berm, m

Figure 3 – Scheme for calculation of the minimum permissible safety berm for mining equipment operation

Table 2 – Calculation of confining and shearing forces for a given design berm

Block No.	Volume, m^3	Site arc length, m	Site slope angle, deg.	Bulk density, N/m^3	Confining force, N	Shearing force, N
Set design safety berm, 30 m						
1	82	18	48	24500	1200001	1492978
2	488	29	45	24500	5862751	8454169
3	638	24	38	24500	8176763	9623405
4	707	24	34	24500	9453233	9686060
5	747	25	30	24500	10403907	9150750
6	642	24	23	24500	9527246	6145810
7	485	22	20	24500	7417227	4064054
8	324	19	19	24500	5069973	2584360
9	152	26	17	24500	697118	86659
				Total over surface	57808221	51288244
				Safety factor	1.13	
Set design safety berm, 40 m						
1	250	32	46	24500	3298683	4405956
2	644	27	40	24500	8092577	10141903
3	724	23	36	24500	9427090	10426135
4	788	24	32	24500	10710621	10230621
5	797	25	26	24500	11466646	8559854
6	776	23	23	24500	11395612	7428580
7	500	22	21	24500	7586231	4390007
8	315	19	18	24500	4966403	2384839
9	170	26	16	24500	3021761	1148030
				Total over surface	69965624	59115925
				Safety factor	1.18	

Considering the data in Table 2 and the value of the normative safety factor for operating slopes with a lifetime of up to 3 years, equal to 1.15, the calculation by interpolation was performed. It revealed that the minimum permissible safety berm for the mining equipment operation is 34 m for the normative safety factor.

Therefore, for the safe operation of loading and mining equipment during dumping in the inundated open pit No. 1 at the ArcelorMittal Kryvyi Rih PJSC, the minimum permissible safety berm is 34 meters.

The selection method calculated the maximum permissible stress on the soil by loading and mining equipment at a distance of 34 meters and more from the slope crest.

The permissible stress of loading and mining equipment on the wall surface of inundated open pit No. 1 was determined by reverse calculations with increasing weight of the upper block within 34 meters from the slope crest with the set stability factor equal to 1.15 (Table 3).

Table 3 – Calculation of confining and shearing forces at a distance of 34 meters and more from the slope crest, considering the stress* from loading and mining equipment

Block No.	Volume, m^3	Site arc length, m	Site slope angle, deg.	Bulk density, N/m^3	Confining force, N	Shearing force, N
1	460	32	46	24500	5531977	8106960
2	644	27	40	24500	8092577	10141903
3	724	23	36	24500	9427090	10426135
4	788	24	32	24500	10710621	10230621
5	797	25	26	24500	11466646	8559854
6	776	23	23	24500	11395612	7428580
7	500	22	21	24500	7586231	4390007
8	315	19	18	24500	4966403	2384839
9	170	26	16	24500	3021761	1148030
Total over surface					72198918	62816929
Safety factor					1.15	
* — the maximum additional specified stress on the soil is 857.5 MPa.						

4. Conclusions

The current technology of dumping rock waste into the mined inundated space of open pit No. 1 ensures the dump operation for 2–3 years. Backfilling of the internal dump is performed only in the southern wall section by ESH–11/70 walking excavator. Backfilling of open pit No. 1 is provided by PJSC PE "Techmash" according to the project "Reconstruction and Development of Open Pits No. 2 bis and No. 3 of the of ArcelorMittal Kryvyi Rih PJSC Mining Department to Maintain the Productivity of mining Raw Ore at the Rate of 30 Million Tons p.a. for the Period from 2020 Until the End of Mining in Inhuletskyi District and Tsentral'no–Gorodskoy Rayon". Adjustment of the geological and mining part of the project was drafted by KAI LLC in 2021.

Geomechanical calculations were performed to determine the minimum permissible safety berm for the loading and mining equipment which resulted in the dependence of the safety factor on the safety berm size. As a result, it was founded that the minimum permissible safety berm for the loading and mining equipment operation, under the dumping conditions in the inundated open pit No. 1 of ArcelorMittal Kryvyi Rih PJSC with the normative stability factor equal to 1.15 is 34 meters.

The obtained results prove the possibility of using the existing equipment and applying the dumping technology in the rock deformation mode, subject to the development of technological schemes ensuring safe and efficient dumping.

For further dumping using the available equipment in the mined space of inundated open pit No. 1, it is required to perform researches to identify safe zones or develop alternative methods, technologies of waste storage in open pit No. 1 using the available equipment to comply with the safety rules of mining and reduce dumping costs.

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ПРОБЛЕМИ ТЕХНОЛОГІЇ ВІДВАЛОУТВОРЕННЯ В ЗАТОПЛЕНИЙ ПРОСТІР КАР'ЄРУ В УМОВАХ ДЕФОРМАЦІЇ ПОВЕРХНІ

Імашев А. Ж.,Кебал Я.В., Кебал А.О.

Анотація. Мета. Метою даної роботи є визначення мінімально допустимої берми безпеки для роботи навантажувального і гірничо–транспортного обладнання забезпечуючи безпечне і ефективне відвалоутворення за умови виникнення зсувних явищ у свіжевідсипаних відвальних заходках, осідання поверхні відвального масиву і тріщини.

Методи дослідження. Проведенні аналітичні і статистичні дослідження раніше отриманих результатів, виконане імітаційне моделювання, проведенні натурні обстеження об'єкту дослідження.

Наукова новизна. Уточнено режим відвалоутворення при підтоплені відкосів в залежності від просування фронту робіт. Встановлено залежність коефіцієнта запасу стійкості від величини берми безпеки. За результатами теоретичних досліджень визначено складові діючих на поверхні ковзання сил.

Практична значимість. Шляхом розрахунків визначені залишкові об'єми складування скельних порід за діючою технологією із застосуванням наявного обладнання. Проведені геомеханічні розрахунки щодо визначення мінімально допустимої берми безпеки для роботи навантажувального і гірничо–транспортного обладнання, за результатами яких встановлено залежність коефіцієнта запасу стійкості від величини берми безпеки і визначено, що мінімально допустима берма безпеки для роботи навантажувального і гірничо–транспортного обладнання в умовах відвалоутворення у затоплений кар'єр №1 ПАТ «АрселорМіттал Кривий Ріг» з нормативним коефіцієнтом запасу стійкості (КЗС) (1,15) становить – 34 метри. Отриманні результати доводять можливість використання наявного обладнання із застосуванням технології відвалоутворення в режимі деформації порід, при умові розробки технологічних схем, котрі забезпечать безпечне та ефективне відвалоутворення. Для подальшого відвалоутворення з використанням наявного обладнання у відпрацьований простір затопленого кар'єру № 1, необхідно виконати дослідження для визначення безпечних зон або розробки альтернативних способів та технологій складування розкривної маси в кар'єр № 1 з використанням наявного обладнання, що зменшить собівартість відвалоутворення і підвищить ефективність використання залишкових гірничих виробок.

Ключові слова: затоплений кар'єр, відвалоутворення, внутрішній відвал, зсувоутворення, деформації, стійкість укосів, екскаватор, призма зсуву, коефіцієнт запасу стійкості, K–MINE.

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