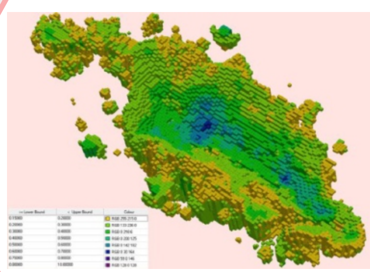
UDC 622

ISSN 2334-8836 (Štampano izdanje)
ISSN 2406-1395 (Online)

Mining and Metallurgy Engineering Bor

2/2023



Published by: Mining and Metallurgy Institute Bor

Mining and Metallurgy Engineering Bor

2/2023

MINING AND METALLURGY ENGINEERING BOR is a journal based on the rich tradition of expert and scientific work from the field of mining, underground and open-pit mining, mineral processing, geology, mineralogy, petrology, geomechanics, metallurgy, materials, technology, as well as related fields of science. Since 2001, published twice a year.

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Printed in: Grafomedtrade Bor

Circulation: 100 copies

Web site

www.irmbor.co.rs

Journal is financially supported by

The Ministry of Science, Technological Development and Innovation of the Republic Serbia
Mining and Metallurgy Institute Bor

ISSN 2334-8836 (Printed edition)

ISSN 2406-1395 (Online)

Journal indexing in SCIndex and ISI.

Published by

Mining and Metallurgy Institute Bor
19210 Bor, Zeleni bulevar 35
E-mail: institut@irmbor.co.rs
Phone: +38130/454-101

Scientific – Technical Cooperation with the Engineering Academy of Serbia

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 622.235(045)=111
DOI: 10.5937/mmeb2302001V

Received: 04.09.2023.
Revised: 02.10.2023.
Accepted: 18.10.2023.

Original Scientific Paper
Mining

Ivica Vojinović[*1], *Miloš Stojanović*[*2], *Dragan Šabaz*[*3]

THE EFFECT OF EXPLOSIVE PROPERTIES ON OPTIMISATION THE DRILL AND BLAST RING DESIGN[**]

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Abstract

The use of underground ring drilling and blasting holes is common, given their compatibility with various mining methods and use in the construction of underground structures like the ore draw bells. Working conditions and rock properties can vary significantly, making it essential to monitor and analyze the blasting results. If necessary, the adjustments and optimizations should be made to the drilling and blasting patterns based on the properties of the used explosives. The aim of this paper is to develop a stopping mining method model using the blastholes, as well as a unique drilling and blasting pattern for excavation the initial slot in the Datamine Aegis. The objective was to compare several types of explosives with different properties in this context, predict the blast outcomes in terms of break radius, and highlight the significance of all explosive parameters in selecting and optimizing a drill and blast ring pattern.

Keywords*: explosive properties, ring blastholes, optimization, Datamine Aegis*

1 INTRODUCTION

Explosive properties directly affect the rock fracturing and production of hazardous gases during blasting. These properties significantly affect the choice of explosives, used in mining operations. In theunderground mining, the mining method also plays a role in this selection, while the explosive properties have a big impact on determining the optimal drilling and blasting pattern [1]. Developement of a new explosive matter is not finished and the new compounds are still being discovered with a goal of aquiring the highly energetic and non sensitive explosives [2, 3]. The used explosive as the carrier of energy, used for task blasting, is the basic means by which the blasting is caried out and on which the success of blasting depends. The blasting geometry depends on energy of the used explosive, and all blasting calculations start fromcexplosive as a known parameter, i.e., they are carried out for known characteristics of explosives. All this means that at the beginning of planning any blasting, the choice of explosives must be made. The choice of explosives is made among those explosive products that can be provided on the market in a certain region. There is no simple formula for selection of explosives, but it is carried out on the basis of certain criteria according to a certain procedure [4].

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[**] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-47/2023-01/ 200052.*

Every production blast in the underground mining must be meticulously planned and monitored. The results should be analyzed, and, if required, the adjustments to the drilling and blasting pattern should be made. This ensures the safety of workers and aims to achieve the optimal results, such as the desired granulation and planned excavation geometry, with minimal impact on the surrounding rock mass.

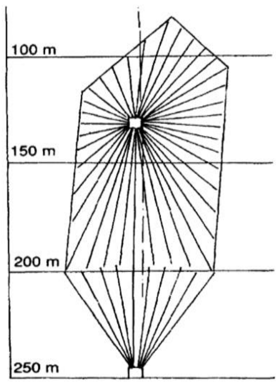
2 RING BLASTHOLES

The ring blastholes or rings, represent a production blasting in the underground exploitation. They can be drilled radially from one or more drilling points down or up, vertically or at an angle (Figure 1a) [1, 5].

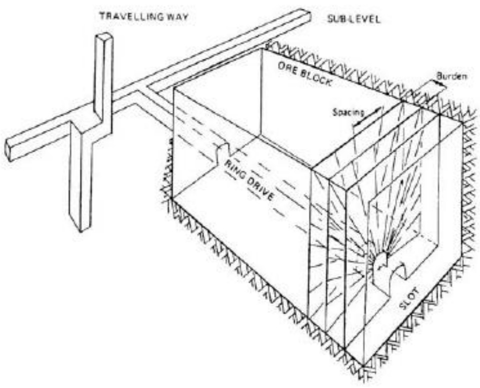
The ring blastholes are used in many caving and open stope mining methods as the production blasting as well as during the construction of specific underground structures (e.g. ore extraction drawbells) [1].

The phases related to the drilling and blasting of these blastholes are shown in Figure 1b:

- Drift development (one or more) for drilling rings,
- Slot blasting at the end of drift,
- Drilling and blasting of the rings.[1]



a)



b)

Figure 1 *Ring blastholes design around the drilling drifts (a) and ring development phases (b) [1, 5]*

2.1 Selection of explosives

Explosives can be described as the metastable chemical systems, encompassing both compounds and mixtures. They are capable of quickly transitioning to a more stable state under the external effects or impulses. During this transition, they release a significant amount of energy and gaseous products. As these gases expand, they exert force and perform work on their surroundings [3].

The fundamental properties of explosive substances are categorized into physical, chemical, thermochemical, and explosive properties. These characteristics not only determine the application of explosives, but also affect their production and handling processes [3].

Explosives can be classified by their aggregate state into the gaseous, liquid, and solid forms. Among these, the solid explosives are the most commonly used. When choosing explosives, three primary criteria come into play:

- Working conditions – specifically, the ability of the explosives to react effectively under certain conditions;
- Mining characteristics of texplosives, meaning their suitability for the specific blasting purposes;
- Cost implications of drilling and blasting.

The procedure for selecting explosives typically involves three steps:

- Firstly, one must choose from commercially available explosives that can reliably and effectively react under the given working conditions;
- Next, the selection is refined based on the blasting properties of explosives;
- Finally, a comparison is made on the basis of costs associated with using the selected explosives [4].

3 SLOT MODELING IN THE DATAMINE AEGIS SOFTWARE

The Datamine Aegis is one of the best software for modeling and optimization the drilling and blasting of ring blastholes. What sets it apart is an interactive and friendly interface, a multitude of tools and possibilities to improve efficiency [6].

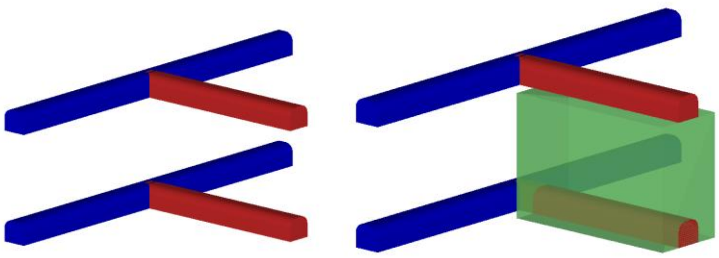
The Aegis software has its own database with collected experiences and parameters from ore deposits and rock enviroments around the world, drills, explosives, detonators and detonation amplifiers. This database allows the user to quickly and easily perform modelling in a similar environment. The user has the possibility to create his/her own database where later modeling or optimization will be even more precise [6].

3.1 Model making methodology

A model of the open stope excavation was created using the ring blastholes with a unique drilling and blasting pattern. Five types of explosives were applied and compared in slot blast simulation in the Datamine Aegis software. In this case, for the purposes of creating a model of drilling and blasting a slot, and in order to compare the results of blasting with several types of explosives, the following objects were created:

- Two main arched drifts with a mutual height distance of 20 m, dimensions of the cross-sections are 4.5 x 4 m (Figure 2a, blue),
- Two arched drifts with a mutual height distance of 20 m, dimensions of the cross-sections are 4.5 x 4 m, lenght 35 m (Figure 2a, red),

Stope model width 12 m, height 20 m and lenght 30 m (Figure 2b, green).



a) b)

Figure 2 *Appearence and position of the main drifts (a) and stope (b)*

3.2 Defining the input parameters

The input data is defined and selected in the database of the Datamine Aegis program. Based on experience, an Atlas Copco Simba 1354 drill with a drilling diametar of 76 mm was selected. The characteristics of a drill were already predefined in the software itself.

Characteristics of the surrounding rock environment were already predefined in the software and correspond to the altered andesite, Table 1. For the purpose of simulation, five different explosives were used: ANFO low strenght, ANFO high strenght, RU emulsion Dyno Nobel, Titan 7000 RU, Subtek Charge E1. Explosives are predefined in the software itself, and their characteristics are given in Table 2.

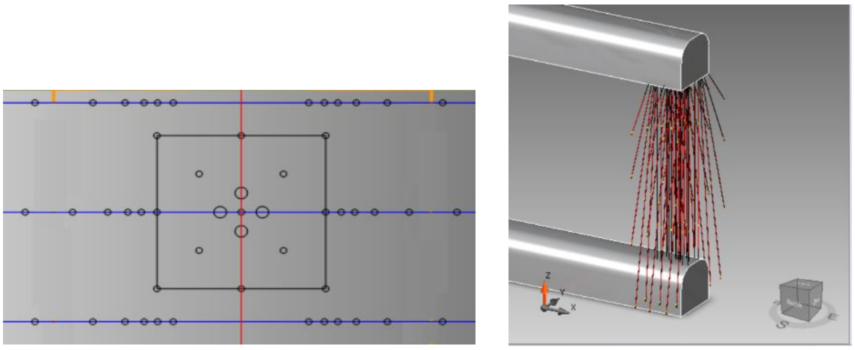
Table 1 *Properties of altered andesite*

Properties of altered andesite	
Density	2.403 g/cm³
RMR	51
RQD	23
JRC	17
P wave speed	3778.21 m/s
S wave speed	1943.87 m/s
Jung's elasticity model	23.97
Poisson's ratio	0.32

Table 2 *Explosives properties predefined in the Aegis software*

Name	**Description**	**Density g/cm³**	**Specific density cm³/g**	**Velocity of detonation m/s**	**Internal bulk energy MJ/m³**	**Thermochemical energy Cal/g**
ANFO Low strength	Mix of granular ammonium nitrate and diesel fuel	0.95	1.053	3654.4	1492.85	880
ANFO High strength	A mixture of emulsion matrix and ANFO explosive made of porous ammonium nitrate	1.2	0.833	4000	2135.83	1056
RU Emulsion Dyno Nobel	Pumped emulsion explosive	1.2	0.833	5931.2	3423.037	686.4
Titan 7000 RU	Pumped emulsion explosive	1.2	0.833	4427.7	2285.484	690
Subtek charge E1	Pumped emulsion explosive	1.2	0.833	5796	5574.65	1179.2

New parameters are defined for the 500 g pentolite detonation booster manufacured by TRAYAL in the Aegis database. Drilling and blasting pattern was optimized for application the ANFO low strength explosive and applied in further simulation for other types of explosives with the aim of showing the different impact of the explosives when using the same pattern and without its optimizing it (Figure 3).



a) *b)*

Figure 3 *Slot drilling and blasting pattern showed in the axonometry (a) and plan (b)*

In order to better understand the individual results and their effects on the stope a prism model was first created that represents the ideal result, that is, the ideal volume that should be crated after slot blasting. After defining all the input parameters and creating the model, a blasting simulation was performed for each type of explosive using the Analyzer option.

The model of the ideal volume was compared with the individual blasting results via the *Create comparison* option. In this way, it is possible to see the intersection of the two models, volume obtained by blast simulation and ideal volume (Figure 4).

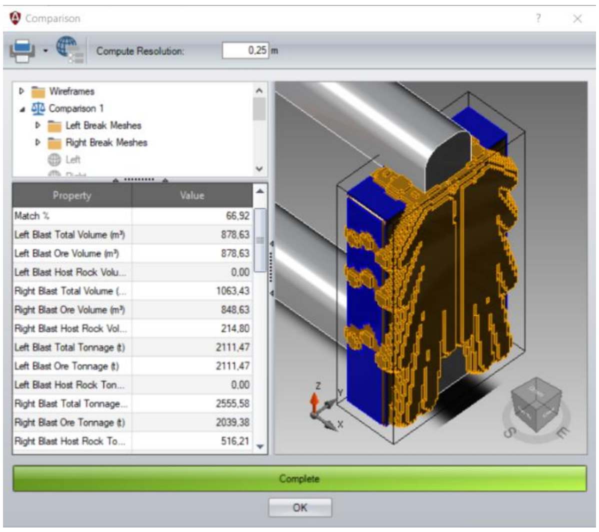


Figure 4 *Comparison of the two models, volume obtained by blast simulation (brown colour) and ideal volume (blue colour)*

4 RESULTS AND DISCUSSION

The following results were obtained by the blasting simulation, and presednted in tables below for each type of explosive.

The dependence of brake radius of the explosive on the characteristics of the explosives can be observed from Table 3.

Table 3 *Parameters affecting brake radius*

Explosive/Parameters	**Density (g/cm³)**	**Thermochemical energy (Cal/g)**	**Internal bulk energy (MJ/m³)**	**Detonation speed (m/s)**	**Brake radius (m)**
ANFO low strength	0.95	880	1492.85	3654.4	1.23
ANFO high strength	1.2	1056	2135.83	4000	1.59
RU emulsion Dyno Nobel	1.2	686.4	3423.04	5931.2	2.88
Titan 7000 RU	1.2	690	2285.48	4427.7	1.85
Subtek charge E1	1.2	1179.2	5574.65	5796	2.78

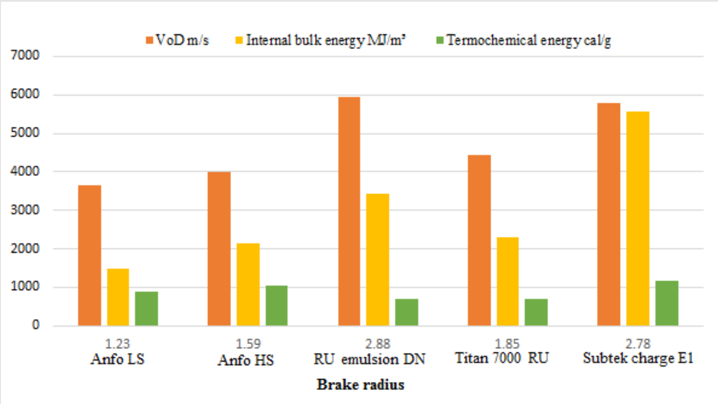


Figure 5 *Dependence of brake radius on explosive properties*

Table 4 *Model comparison results*

Name	**ANFO Low strenght**	**ANFO High strenght**	**RU Emulsion Dyno Nobel**	**Titan 7000 RU**	**SUBTEK charge E1**
Match (%)	66.92	63.06	35.26	56.28	33.87
Blast volume Vm (m³)	1063.43	1331.1	2561.71	1555.12	2422.63
Ideal volume model Vi (m³)	878.63	878.63	878.63	878.63	878.63
Total volume diference (m³)	184.8	452.47	1683.08	676.49	1544

Based on the obtained results, the ratio between the ideal volume model and volume, obtained by blasting simulation, was calculated as follows :

$$a = \frac{V_i}{V_m}$$

where :

a – ratio between the ideal volume and volume obtained by blasting,

V_i – ideal volume,

V_m – volume obtained by blasting.

Figure 6 shows the ratio of ideal volume model and volume of the blasting model as a function of the applied powder factor in order to determine the smalest powder factor.

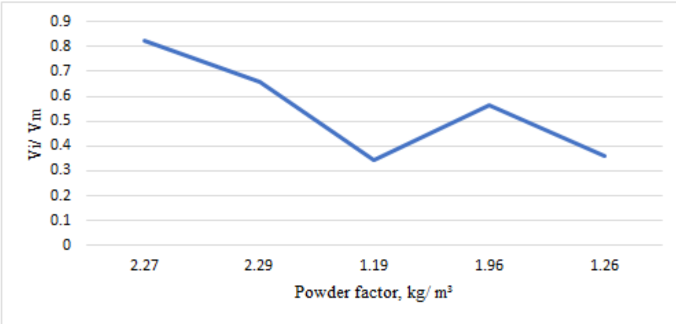


Figure 6 *The ratio of ideal volume model and volume of the blasting model as a function of the applied powder factor*

For the obtained minimum value of the powder factor of 1.19 kg/m^3, a volume of 2561.71 m^3 was obtained by simulation for the RU Emulsion Dyno Nobel explosive. For the obtained maximum value of powder factor consumption of 2.29 kg/m^3, a value of 1331.1 m^3 was obtained for the ANFO high strenght explosive.

It is shown that, although the internal energy of the Subtek charge E1 explosive is 5574.65 MJ/m^3 and that of the RU Emulsion Dyno Nobel is 3423.04 MJ/m^3, the RU Emulsion Dyno Nobel for a given blasthole diameter has a higher velocity of detonation of 5931.2 m/s and creates a larger brake radius compared to the others and is 2.88 m. This directly shows the importance of effect of each explosive parameter when calculating the radius of its effect and optimizing the drilling and blasting pattern.

From relation: $V_m : q_m = V_i : q_i$

follows: $q_i = \frac{q_m * V_i}{V_m}$

Calculation of the required powder factor is given in Table 5.

Table 5 *Required powder factor*

Name	Required powder factor for V_i, q_i (kg/m^3)
ANFO low strength	1.88
ANFO high strength	1.51
RU emulsion Dyno Nobel	0.41
Titan 7000 RU	1.11
Subtek charge E1	0.46

It can be seen from Table 5 that the minimum required powder factor for obtaining an approximately ideal volume is 0.41 kg/m^3 RU emulsion Dyno Nobel explosive. This can be obtained by adequately modifying the drilling and blasting pattern. Possible changes can be: changing the diameter of drillholes, changing the lenght and angle of drilling or by decking. From an economic point of view, the goal of every mining company is to achive the maximum profit and minimum costs. Bearing this in mind, the optimization of drilling and blasting operations may have different results compared to these if the cost price of explosives is taken in to account.

Due to this reason, during exploitation, it is important to take into account all factors and, if necessary, make the appropriate changes to maximize results and safe working conditions.

5 CONCLUSION

This scientific paper, using the five models in the Datamine Aegis software, demonstrated the impact of characteristics of five different explosives on blasting outcomes. It also emphasized the importance of considering all explosive parameters when optimizing the drilling and blasting patterns.

During the planning phase of drilling and blasting operations, it is crucial to account for the full spectrum of explosive characteristics. Moreover, if there is a change in drilling geometry or switch in the type of explosive used, the appropriate optimizations must be made. Poorly blasting operations can cause the significant risks to the personnel, equipment, underground infrastructure, and production processes. Such oversights can also lead to the adverse economic repercussions. Certainly, solving these tasks requiers a constant control of works, keeping work logs and own databases. One should never rely on a single approach to the problem solving. The most successful outcomes are typically achieved through a blend of hands-on experience, precise calculations, and advanced software simulations.

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 622.271:626.877(045)=111
DOI: 10.5937/mmeb2302009R

Received: 17.07.2023.
Revised: 05.10.2023.
Accepted: 12.10.2023.

Original Scientific Paper
Mining

Radmilo Rajković[*1], *Daniel Kržanović*[*2], *Miomir Mikić*[*3],
Milenko Jovanović[*4], *Sandra Milutinović*[*5]

STABILITY ANALYSIS OF THE INTEGRATED WASTE DUMPS OF THE OPEN PITS ŽUTA PRLA AND BRSKOVO NEAR MOJKOVAC[**]

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Abstract

The lead and zinc ore are expected to be mined at the open pits Žuta Prla and Brskovo near Mojkovac, Montenegro. During ore mining and flotation processing, the waste from the open pits and tailings from pre-concentration (DMS) and flotation tailings are produced. Two integrated waste dumps are planned in the immediate vicinity of the open pits for disposal of these materials. This paper presents the geotechnical tests of the base of these waste dumps, as well as the tests of deposited materials, and calculation of their stability in accordance with the current legal regulations.

Keywords: *integrated waste dumps, open pits Žuta Prla and Brskovo, geomechanical tests, stability calculation*

1 INTRODUCTION

The integrated waste dumps are constructed so that the waste from open pits is disposed towards the outer edges of the floors. Between the deposited waste from the open pits and ground, the cassettes are formed of tailings from the pre-concentration (DMS) in which the flotation tailings are deposited. Transport and disposal of waste from the open pits and DMS is carried out by trucks, and delivery of flotation tailings and filling of cassettes is done by hydrotransport.

The integrated Žuta Prla waste dump is formed up to an elevation of K +1.100 m with floors 10 m high. The maximum height of waste dump is 150 m. The Brskovo integrated waste dump is formed up to an elevation of K +1.125 m, also with floors 10 m high. The maximum height of the Brskovo waste dump is 175 m. Figure 1 shows a typical vertical cross-section of a floor of the integrated waste dumps, and Figure 2 shows a typical cross-section of a cassette.

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[**] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-47/2023-01/ 200052.*

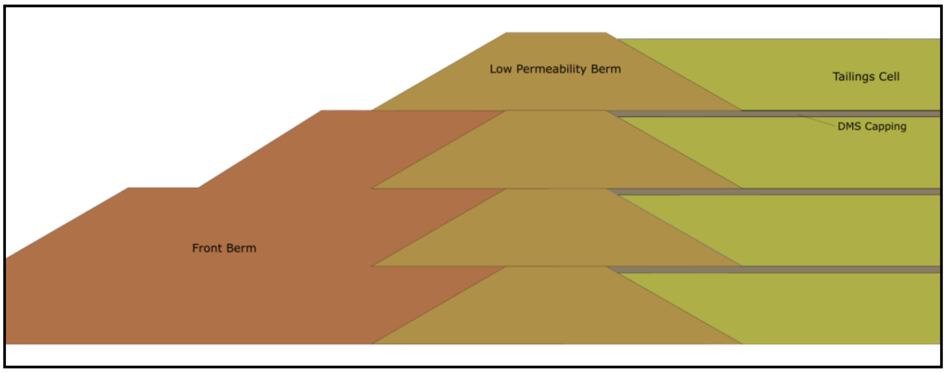

Figure 1 *Typical cross-section of an integrated waste dump floor*

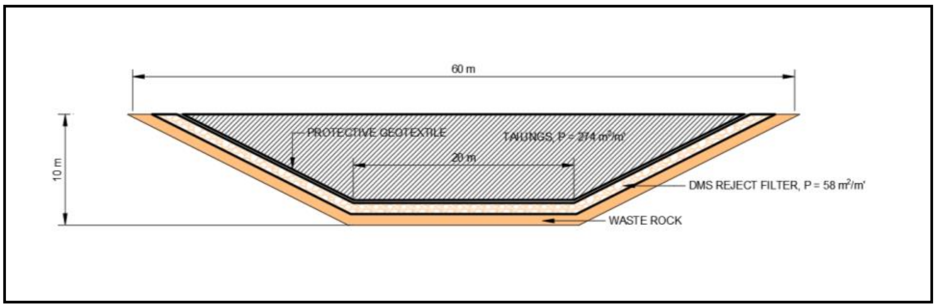

Figure 2 *Typical cross-section of a cassette*

2 GEOTECHNICAL TESTS OF A FOUNDATION

During 2020 year, the geotechnical investigations were carried out at the site of open pits and integrated waste dump sites [1]. The following work program was implemented:

- Realization of a geotechnical drilling;
- Geotechnical logging and characterization of the rock mass and definition of the model;
- Determination of the geotechnical domains;
- Defining the geotechnical input parameters by domain.

Five different working environments have been identified:

- Carbonates and Keratophyres Transition;
- Carbonates and Keratophyres Fresh;
- Volc - sediments Shales & Schists Transition;
- Volc - sediments Shales & Schists Fresh;
- Volc - sediments Shales & Schists Foliation Planes.

The results of these geotechnical tests are shown in Tables 1 and 2. Based on these parameters, the RocLab program, Figure 3, determined the calculation parameters for the stability calculation for each analysis profile.

Table 1 *Geomechanical parameters at the Žuta Prla site*

Domain	Footwall (Carbonates and Keratophyres)		Hanagingwall (Volc-sediments Shales & chists		
Sector	**Transiton**	**Fresh**	**Transiton**	**Fresh**	**Foliation planes**
Unit weight (kN/m^3)	24	26	25	27	27
UCS (MPa)	40 (24-48)	65 (40-80)	18 (12-24)	30 (20-40)	-
GSI	42 (21-63)	57 (43-71)	34 (22-46)	43 (31-55)	-
Mi	10 (7-13)	15 (10-20)	8 (6-10)	12 (9-15)	-
E (MPa)	6 000	10 000	1 926	3 210	-
V	0.27	0.27	0.32	0.32	-
D	-	0.3	-	0.3	-
C	-	-	-	-	60 (40-80)
Phi	-	-	-	-	25 (22-28)

Table 2 *Geomechanical parameters at the Brskovo site*

Domain	Keratophyre		Volc-sediments		
Sector	**Transiton**	**Fresh**	**Transiton**	**Fresh**	**Foliation planes**
Unit weight (kN/m^3)	25	27	25	27	27
UCS (MPa)	22 (10-34)	66 (40-80)	22 (10-34)	38 (18-58)	-
GSI	32 (20-44)	57 (43-71)	32 (20-44)	42 (32-54)	-
Mi	10 (7-13)	15 (10-20)	10 (7-13)	12 (9-15)	-
E (MPa)	2 040	10 000	2 040	3 400	-
V	0.24	0.27	0.24	0.24	-
D	-	0.3	-	0.3	-
C	-	-	-	-	60 (40-80)
Phi	-	-	-	-	25 (22-28)

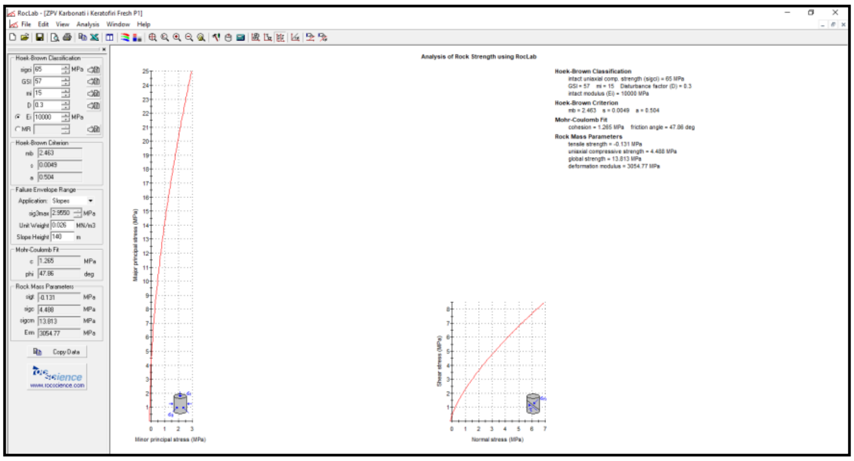

Figure 3 *Determination of calculation parameters for stability calculation in the RocLab program*

3 TESTS OF DISPOSED MATERIAL

During 2021, the tests were carried out on disposed material of in integrated landfills - waste from the open pits, DMS material and flotation tailings [2].

Based on the experience, it is assumed that the waste from the open pits will have a compacted dry density of 2.00 t/m^3. It is expected that the permeability of waste from from the open pits will be of the order of 10^{-4} to 10^{-5} m/s.

The DMS material characterization includes the Atterberg limits for material passing through a 425 µm sieve and material passing through a 75 µm sieve. The results in all cases were that the material was non-plastic. The compaction tests indicate the low optimum moisture contents (4 to 5%) and maximum dry densities of 1.87 and 1.90 t/m^3. It is assumed that these densities will also be in the disposed DMS and that the average density will be 1.9 t/m^3. Permeability for this granular material is likely to be 10^{-2} to 10^{-3} m/s on the basis of typical values for sand and gravel mixtures.

Flotation tailings are defined as a slime-clay-sized material that is expected to have a low permeability, most likely on the order of 10^{-7} to 10^{-8} m/s. Based on the previous experience, it was assumed that the dehydrated tailings after consolidation reaches a dry density of the order of 1.55 t/m^3.

Calculation parameters for calculating the stability of disposed materials are shown in Table 3.

Table 3 *Calculation parameters for calculating the stability of disposed materials*

Material	Volume weight, kN/m^3	Cohesion, kPa	Angle of natural hold, °	Pore water coefficient
Open pit waste	20.0	0	35	0.1
DMS	18.6	0	26	0.0
Flotation tailings	15.2	0	29	0.4

4 STABILITY CALCULATION

The stability calculation of integrated landfills was done with the Slide v6.0 program from the company Rocscience, under the conditions of limit equilibrium, according to the methods of Bishop and Morgenstern-Price [3 - 9].

The stability was checked in the static and dynamic conditions for an earthquake occurence with a return period of 475 years according to the Eurocod 8. The calculation was made on two profiles for the most unfavorable case, that is, for the highest height of the landfill. The geological profiles, on which the stability calculation was performed, are shown in Figures 4 and 5.

Figures 6-9 show the output interface of the Slide v6.0 program for stability calculation using the Morgenstern-Price method. Figures show the sliding planes for which the stability coefficient is the smallest. For all other sliding planes on each profile, the stability coefficient is higher than shown one. A summary of the stability calculation results is shown in Table 4.

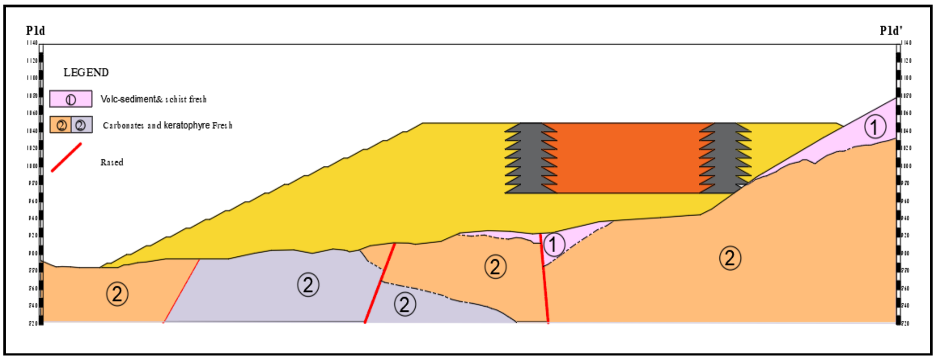

Figure 4 *Geological profile of the Žuta Prla integrated landfill*

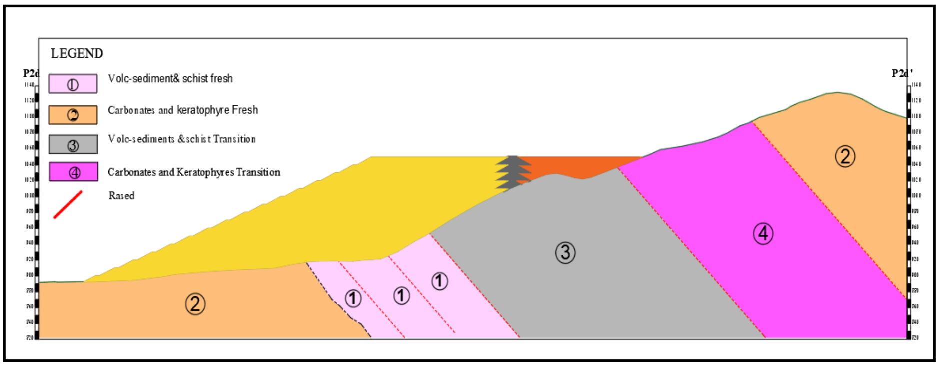

Figure 5 *Geological profile of the Brskovo integrated landfill*

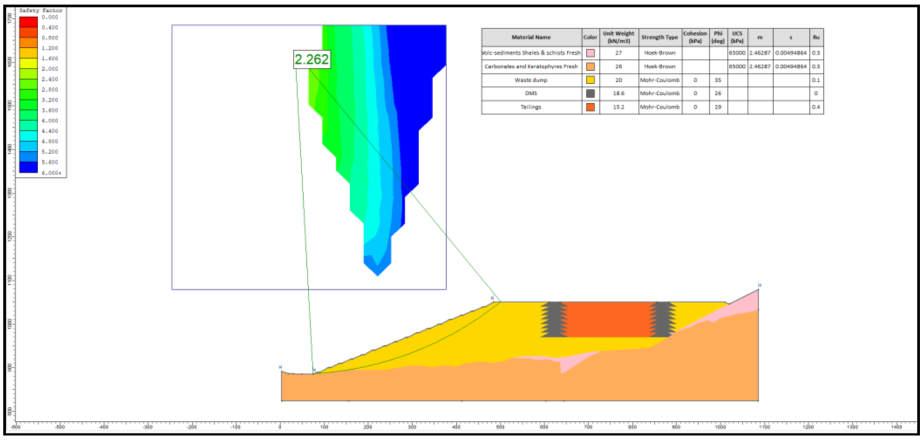

Figure 6 *Stability calculation of the Žuta Prla integrated landfill in static conditions*

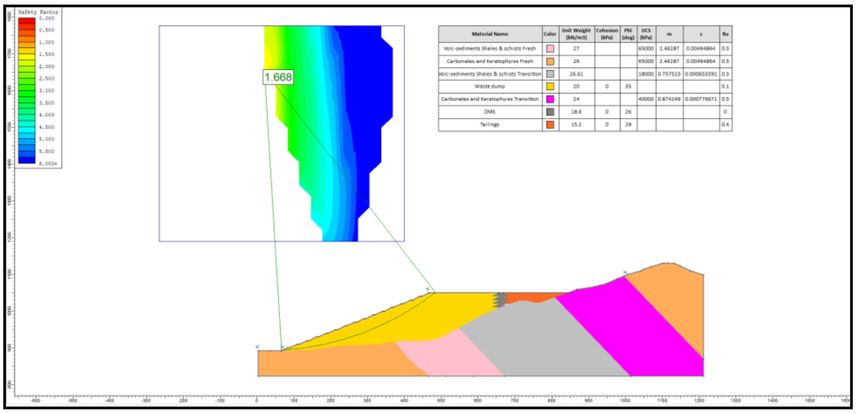

Figure 7 *Stability calculation of the Brskovo integrated landfill in static conditions*

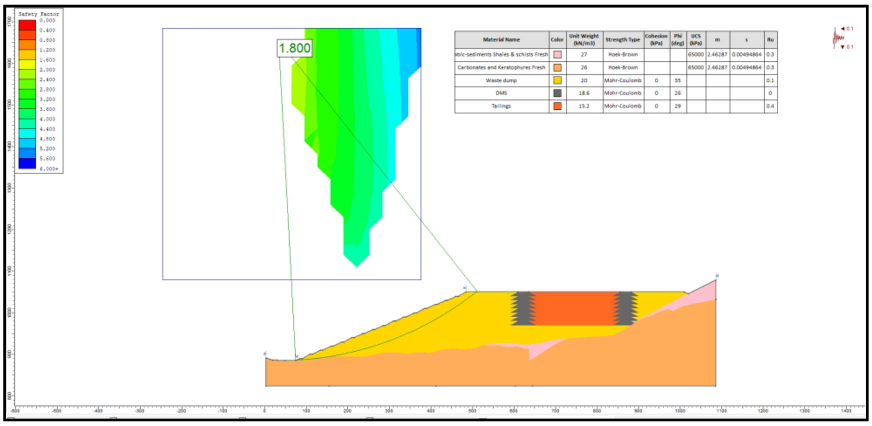

Figure 8 *Stability calculation of the Žuta Prla integrated landfill in dynamic conditions*

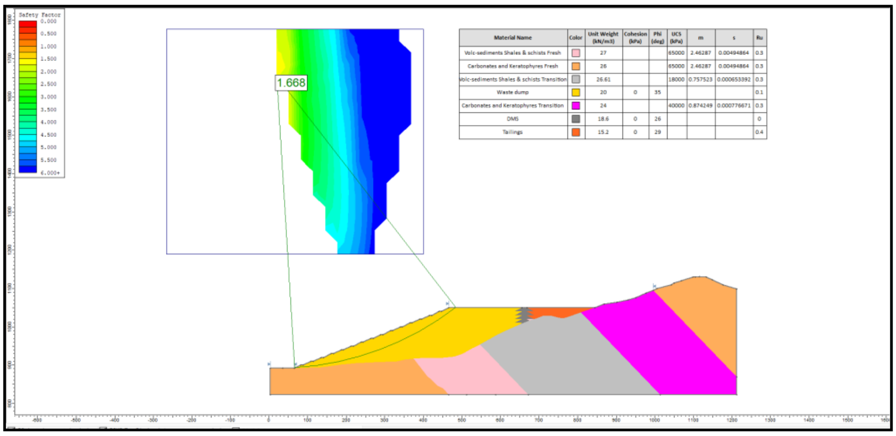

Figure 9 *Stability calculation of the Brskovo integrated landfill in dynamic conditions*

Table 4 *Stability calculation results*

Profile	F_s by Janbu method	F_s by Morgenstern-Price method
1d-1d' static	2.153	2.262
2d-2d' static	1.665	1.668
1d-1d' dynamic	1.697	1.800
2d-2d' dynamic	1.110	1.156

5 CONCLUSION

By comparison the calculated safety coefficients with the minimum allowed values defined by the Rulebook on technical norms for the open pit exploitation of mineral deposits ("Official Gazette of SFRY", Nos. 4/86 and 62/87), the conclusion is that all the obtained values are above the legal minimum which for the final slopes of the landfill is F_{smin} = 1.30.

By comparison the obtained safety coefficients of flotation tailing dump dams with the permitted minimum coefficients, prescribed by the technical conditions for the design of embanked dams and hydrotechnical embankments - SRPS U.C5.020 (former JUS), which for the embanked dams over 15 m in height is a minimum of F_s = 1.50 in the case of constant static load, that is, F_s = 1.00 in the case of occasional dynamic load for an earthquake occurence, it can be concluded that the safety coefficients for the static and dynamic loads are above the minimum prescribed values according to the analysis profiles of combined landfills.

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MINING AND METALLURGY INSTITUTE BOR ISSN: 2334-8836 (Štampano izdanje)
UDK: 622 ISSN: 2406-1395 (Online)

UDK: 626.877:622.79(045)=111
DOI: 10.5937/mmeb2302017M

Received: 28.08.2023.
Revised: 13.10.2023.
Accepted: 17.10.2023.

Original Scientific Paper
Mining

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POSSIBILITY OF REHABILITATION AND OVERHANG THE DAM 6 AT THE "VALJA FUNDATA" TAILING DUMP IN MAJDANPEK[**]

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Abstract

In order to enable further overhang of the flotation tailing dump and its exploitation in the safe and stable conditions up to the designed elevation of K+545 m altitude, since the stability coefficients in a part of the tailing dump next to PS Kaludjerica are below the minimum due to a wide seepage front through the outer slope of the embankment, its rapid rehabilitation is necessary. In this paper, the problems affecting the rehabilitation and further overhang of the tailing dump are present.

Keywords: *tailing dump, slope stability, rehabilitation, overhang*

1 INTRODUCTION

The tailing dump "Valja Fundata" dates back to 1961 and is the main tailing dump, named after the stream of the same name, Valja Fundata. This tailing dump was formed in the valley of the "Valja Fundata" stream, which begins immediately in front of the Copper Flotation in Majdanpek and extends in a direction of the south for about 1300 m, where two new branches flow into it. At a distance of about 1800 m, this valley changes its direction towards the west, where it joins another larger branch. Then, at about 2400 m from the Copper Flotation, this valley widens considerably and joins a new branch, which eventually ends with a rocky limestone barrier.

Most of the Valja Fundata valley (85%) is built of impermeable rocks such as andesites, pyroclasts, conglomerates and crystalline schists. The above-mentioned valley is closed by a natural barrier - a limestone massif, which rests on crystalline schists in the north, while in the south it rests on quartz conglomerates.

Along the main NNE-SSW fault direction, an underground stream of the Valja Fundata stream was formed in a length of about 750 m, which then flows into the Veliki Pek river. A stream flowed through this valley with a water volume of about 5 l/s of water. The mentioned stream, as well as all storm water from the entire catchment area of Valja Fundata, flowed through the main cave into the Veliki Pek river.

In order to enable the use of the Valja Fundata valley for deposit the flotation tailings and formation of an accumulation lake for return of technological water back to the

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[**] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-47/2023-01/ 200052.*

flotation process, it was necessary to properly close all the karst channels, in order to prevent the outflow of tailings and water, while it was allowed to leachate flows unhindered into the Veliki Pek river.

The area of tailing dump covers an area of about 390 hectares. Around the perimeter, the tailing dump rests partly on the surrounding mountain heights above 545 m altitude, and partly on the sand embankments. The total length of this part of the circumference where the artificial sand embankments are being built is 5.5 km. On the rest of perimeter, the natural terrain is above 545 m altitude in a length of 7 km.

At the "Valja Fundata" flotation tailing dump, the main infrastructure facilities include the following:

- Sand dam "Vančev potok"
- Sand dam "Kaludjerica"
- Sand dam "Prevoj Šaška"
- Sand dam "Pustinjac 1"
- Concrete and sand dam "Pustinjac"
- Pumping station for tailings PS2, pumping station "Kaludjerica", concrete channel between these two pumping stations, floating pumping station for return water.

Figure 1 *Satellite view of the "Valja Fundata" tailing dump with associated facilities, (Source: Google Earth, August 2023)*

2 OBSERVED PROBLEMS AT THE DAM 6 OF THE "VALJA FUNDATA" FLOTATION TAILING DUMP

The investigated field on which the subject flotation tailing dump is located, was the subject of geotechnical and hydrogeological research, when the research goal was to provide the new geotechnical and hydrogeological foundations for the entire area covered by the tailing dump with the surrounding area. The engineering geological mapping was carried out in order to get a better understanding of the actual situation on the subject terrain. A special attention was paid to the state of the external slope of the embankment (Figure 2), terrain zones with the existing deformations, modern exogenous processes, hydrogeological phenomena and terrain stability. On the observed rock outcrops, the thickness of deluvial cover was estimated. Then, the petrological type and rock mass strength were macroscopically defined as well as the presence of fissure discontinuities. The dominant cracks were measured and their orientation, gap size, presence and type of filling, shape and roughness were defined. The results are presented on the basis of observations from the field semi-instrumental mapping and correspondingly obtained geodetic situations [1].

Figure 2 *State of the external slope of the embankment*

Erosion at the "Valja Fundata" flotation tailing dump is an everyday occurrence and can be internal or external. Internal erosion is more dangerous because it is not visible until it appears on the external slope, and then the condition is already critical. It is characterized by the appearance of springs and ponds and removal of material from the flotation tailings dump. External erosion can be caused by the wind and heavy rains, as well as sudden melting of snow. Internal erosion occurs due to the effect of wind and precipitation, as well as the contact of water from the lake and inner leg of the dam. Wind erosion is present on the tailing dump throughout the year with a lower or higher intensity. Due to the harmful effect of wind on the tailing dump, the geometry of all dams on the flotation tailing dump is threatened daily where the crowns of dams suffering the most and less parts of the beaches, because they are partially covered by the dams [3].

Figure 3 shows a part of the dam 6 viewed from direction of the dam 1, where the damage caused by the water and wind erosion on a daily basis at the "Valja Fundata" tailing dump can be seen. Erosion also affects the outer slope of the embankment in the Sector 6 from direction of the PS "Kaluđerica", shown in Figure 5. Erosion caused by the action of both atmospheric water and leachate from the accumulation area of the tailing dump causes the shelling of the outer slope and its collapse. As a result of the leachate action, the sand particles are carried out, as a result of which depressions are formed, and after that, when the stability coefficient falls below the critical level, the parts of the outer slope collapse. Later, as a result of heavier rainfall, larger or smaller ravines are formed along the entire length of the outer slope, which can both locally and generally affect the stability coefficient reduction of endangered dams and embankments [2].

Figure 3 *Effect of water erosion on the outer slope of the Dam 6, August 2023*

Figure 4 *Effect of water erosion on the outer slope of the Dam 6, August 2023*

The stability calculation was done with the Slide v6.0 program from Rocscience. With the Slide program, the stability calculation is performed under conditions of the limit equilibrium. The calculation was made according to the Bishop simplified method for the circular sliding surfaces. The program enables the automatic search of the critical sliding plane with a minimum safety factor. The calculation results show the sliding planes that correspond to the minimum safety factor on each profile. All other sliding planes on each profile have a higher safety factor than shown one (Figures 5 and 6).

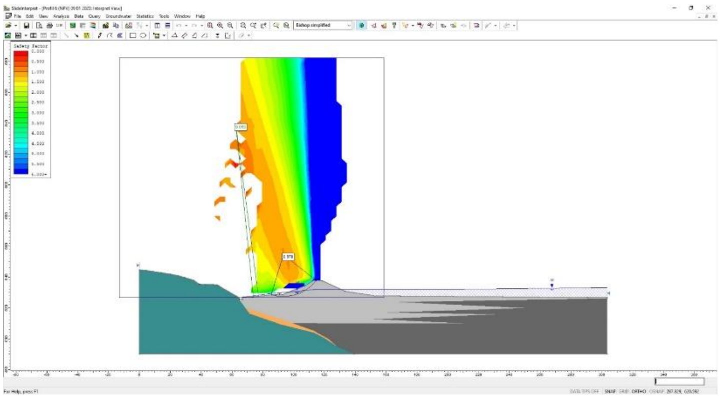

Figure 5 *Static coefficient of safety for profile 6 - 6'*

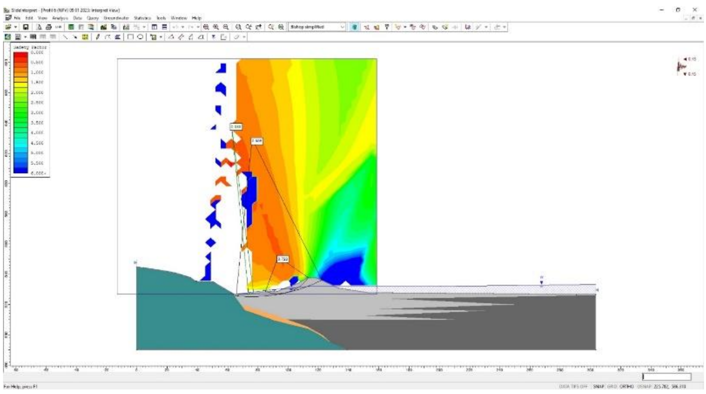

Figure 6 *Dynamic coefficient of safety for profile 6 – 6'*

By comparison the obtained values of the safety coefficients of the flotation tailing dam with the permitted minimum values, prescribed by the technical conditions for the design of embanked dams and hydrotechnical embankments - SRPS U.C5.020, which for the embanked dams over 15 m in height is a minimum of Fs = 1.50 in the case of permanent static loading, i.e., Fs = 1.00 in case of occasional dynamic load for the earthquake occurrence, it can be concluded:

- According to the analysis profile 6 - 6', the value of safety coefficients for static and dynamic loads is below the minimum prescribed value.

Also, the results of performed geotechnical and hydrogeological investigations showed that the future expansion of the flotation tailing dump in the Sector 6 will engage a field with the complex structures and unfavorable geotechnical and hydrogeological properties.

If, during the realization of works on expansion the tailing dump and eventual rehabilitation of the field, the need for additional research and tests should arise and they can be carried out subsequently.

Due to the harmful effect of wind, it is necessary to correct the geometry of the crown of dams several times a year in all places where it is threatened, as well as corrections the external and internal slopes [4].

3 CONCLUSION

On the basis of problems presented in this paper, and in order to enable the expansion and rehabilitation of the tailing dump in the Sector 6, it is necessary to carry out the appropriate preparatory works in the field in order to prevent the water and material seepage through the karst cracks into the surrounding area. This is very important for the reason that it can lead to the pollution of surrounding underground and surface watercourses, as it was the case on two occasions in the past, when the river Veliki Pek and its coastal area were polluted by water and flotation tailings from the "Valja Fundata" tailing dump to its confluence into the Danube River.

In order to prepare the ground surface for further rehabilitation in the Sector 6, it is possible to implement the following actions in order to bring the Dam 6 to a stable state:

- Clearing the entire field in the Sector 6 of vegetation (cutting down trees, removing stumps, bushes and other plant cover) and taking it outside the sector boundary.
- Closing all observed karst cracks and possible sinkholes with the reinforced concrete slabs.
- In order to form a watertight layer and prevent water and material seepage from the extended part of the tailing dump, it is necessary to cover the surface of the Sector with a layer of selected mine overburden, which should be installed by rolling in a layer with a thickness of approximately 2 m.

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 622.79:626.877(045)=111
DOI: 10.5937/mmeb2302023O

Received: 18.09.2023.
Revised: 17.10.2023.
Accepted: 24.10.2023.

Original Scientific Paper
Mining

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INTEGRATED DISPOSAL OF MINING WASTE, AN EXAMPLE OF REHABILITATION THE DAMAGED EMBANKMENT AT THE RTH TAILING DUMP BY THE MINE OVERBURDEN[**]

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Abstract

The RTH flotation tailing dump was created by deposition the flotation tailings in the old open pit of the ore body "H", after which it got its name. The tailings dump is located about 500 m southeast of the Bor flotation facility and has been in continuous operation since 1985. At the beginning of exploitation, the RTH tailing dump, the tailings were only pumped into the open pit without cyclones, after that, when the open pit was filled, two sand dams were built to form the storage area, the dam 1 on the north-western side and the dam 2 on the south-eastern side, which are mutually connected by a peripheral embankment. During 2020 and 2021, due to the reduced production in the Bor pit, the smelter slag was processed more in the flotation plant. Although it has good geotechnical properties, smelting slag is not suitable for the construction of dams and embankments because it does not contain the clay particles that represent a binding agent, so when the wind blows on the built crowns of embankments and dams, the great erosion occurs, which threatens the stability of dams on the complete RTH tailing dump. This paper presents the rehabilitation of a damaged embankment with mining overburden, which represents a good example of integrated disposal of mining waste, where another mine waste (mine overburden) is used for the facility rehabilitation containing tailings of the Bor flotation plant, which reduces the need for the new exploitation and excavation the natural materials, earth and stone.

Keywords: *rehabilitation of dams and embankments, stability, flotation tailing dump, mine overburden, integrated disposal*

1 INTRODUCTION

The flotation tailing dump in the area of the old open pit RTH (the tailing dump got its name after the open pit) has been in operation since 1985. According to the project: Main Mining Desing of the New Flotation Tailing Dump in the Excavated Space "RTH", IBB, June 1984, the tailing dump has the shape of an ellipse with along the approximate direction of the main east-west axis, Figure 1. The Dam 1 is built of hydrocyclone sand and closes the tailing dump from the north-west side, towards the old open pit and the slag dump.

The Dam 1 rests on the high landfill with its left side (viewed downstream through the former Bor river valley), and

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[**] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-47/2023-01/ 200052.*

with its right side on the smelter slag disposal site, from where it passes into the peripheral embankment with which it forms a functional unit.

The waste dump is situated to the southeast of the tailing dump from the old open pit of the ore body "H", which separates the tailing dump from the Oštrelj road and Bor - Zaječar railway. In addition to the open pit overburden that was deposited there (which has an inhomogeneous grain size distribution), this space was also used for disposal of ash, garbage and other waste material.

The Dam 2 was built on this part of the hydrocyclone sand. Looking down the valley of the former Bor river, the Dam 2 extends on its left side towards the high landfill, passing into the peripheral embankment, so that at the point of connection with the landfill, it reached the designed height of K+378 m altitude. From the north, northeast and east sides, the tailing dump is closed with a high landfill with an elevation of over K+400 m altitude. On the south, south-west and west sides there are the main railway line and road that comes in the circle of the RTB facilities, which are protectted from the RTH tailing dump by a perimeter embankment, built of hydrocyclone sand.

Figure 1 *Flotation tailing dump RTH (Google Earth source, April 2021)*

2 OBSERVATION METHODOLOGY OF DAMS AND EMBANKMENTS

Observation of dams and embankments is carried out in accordance with the Serbian standard SRPS U.C5.020, the application of which is mandatory for all dams and embankments with height greater than 15 m, starting from 1980. Observation of high dams in the natural environment requires a multidisciplinary approach, and is achieved through the following aspects:

- visual observation the visible surfaces of the dams and immediate surroundings where the dam is founded, and registration of all changes on those surfaces;
- geodetic observation of benchmarks at the characteristic points of embankment and foundation of the dam;
- measurement of underground water level and piezometric pressures with piezometers with a free level or manometers;
- measuring the quantity and quality of seepage water at collection points - measuring profiles and in drainage systems;
- measurements with special devices for registering the earthquake ground movements;
- measurements with special instruments installed under the surface of the dam body and foundations (measurements of expansions, displacements, total and pore pressures, temperature);
- registration of hydrometeorological parameters (temperature, precipitation, runoff, winds, relative humidity, etc.).

The aforementioned observations have the common goal of providing the necessary insight into behavior of the object, environment in which the object is located and immediate surroundings, from the moment of design, during the object construction, its exploitation and, if necessary, after the end of exploitation and closure of the object.

Based on the observation data, the following is done:

- checking whether the conditions foreseen by the project are fulfilled or not;
- acquiring knowledge about the behavior of the object within the conditions foreseen by the project;
- taking the additional monitoring, rehabilitation or insurance measures (for the threatened area) if some measured values are less favorable than the values provided by the project and if it is determined that this endangers the object or object's surroundings.

2.1 Visual observations

Visual observation is aimed to a directly observations of occurrences and phenomena related to the exploitation conditions, infiltration regime and tailing dump stability [4]. The obligation of visual observation is daily and is not limited to part of the day, shift, etc. All workers employed at the tailing dump are subject to the obligation of visual observation, including the leading supervisory and technical staff of the copper flotation in Bor. This observation monitors the dynamics of construction the embankments, condition and functionality of piezometers, operation of the drainage system, operation of the hydrocyclone batteries, size of the sedimentation lake, evenness of filling the tailing dump, etc. According to the results in the field and conducted measurements, the MMI Bor prepares the periodic reports.

During the auscultation works, a special attention should be paid to the following phenomena:

- deformations of the basic terrain or external and internal slopes in certain parts of the tailing dump as well as the dam itself and perimeter embankment;
- occurrence of springs, ponds or wet zones;
- occurrence of sufosis phenomenon;
- occurrence of erosion;
- size of the sedimentation lake, its height and position;
- uniformity of filling and reached height of the tailing dump accumulation.

2.1.1 Occurrence of erosion

Erosion at the RTH flotation tailing dump is an everyday phenomenon and can be internal or external. It occurs as a daily phenomenon due to the effect of air currents or atmospheric precipitation on the crown of the dam, as well as on the internal and external slopes of dams and embankments. Internal erosion is more dangerous because it is not visible until it appears on the external slope, and then the condition is already critical. It is characterized by the appearance of springs and ponds and removal of material from the flotation tailing dump. External erosion can be under the effects of wind and heavy rains, as well as a consequence of sudden melting of snow [2]. Internal erosion occurs as a result of the effects of wind and precipitation, as well as water from the storage lake, which in the PPS zone directly rests on the internal slope of the dam.

Wind erosion, as in the previous period, has the most harmful effect on the geometry of dams and embankments. Figure 2 shows the embankment on untreated part of the tailing dump between the PPS and Dam 2, where the damage caused by the wind on a daily basis at the RTH tailing dump is best seen, recorded in 2021. The material is removed from the crown of the dam and stored outside the tailing dump area. This significantly disrupts the designed geometry of the dam and embankment. During the removal of material from the crown of the dam, large depressions up to 3 meters deep are created, what significantly threatens the stability of the dam. The embankment has changed its designed height and cross-section, the crown of the embankment is not of the designed width leading to a decrease in the safety coefficient of that section, because the designed ratio of the embankment height and water in the body of embankment has changed [3].

Figure 2 *Detail of the endangered part of the embankment between PPS and dam 2, flotation tailing dump RTH, 2021*

Figure 3 shows the part of Dam 2 where, due to erosion, the first overflow of water and sludge occurred over dam 2 into the surrounding area on 01/29/2021. year, which could have caused very serious problems at the flotation tailing dump. The quick response of employees at the tailing dump stopped the overflow of sludge, which was quickly localized and stopped. This part of embankment is highly threatened by the wind erosion, and here the urgent interventions are necessary in terms of correcting the geometry of embankment in accordance with the current technological project, in order to prevent the harmful consequences that further erosion of the embankment can cause for the stability of this part of embankment, as well as the entire RTH flotation tailing dump as a unique mining object [5].

In order to rehabilitate the crowns of the dams and embankments at the flotation tailing dump and bring their geometry to the designed geometry, the Investor concluded a contract with MMI Bor for development the SMD for overhanging the flotation tailing dump RTH, within which the Volume II.1 will be prepared under the title: Technical Design of Rehabilitation the Dams and Embankments and Bringing Them to the Designed State According to the Valid Technological Design.

Figure 3 *Completely eroded crown of the Dam 2 where the first serious overflows of water and sludge were observed over the crown and downstream slope, January 29, 2021*

2.2. Conceptual solution for the integrated rehabilitation of endangered dams and embankments by the overburden excavation at the RTH tailing dump

The existing RTH tailing dump in Bor has changed its basic geometry, especially in the crown, due to the weather influences (primarily wind but also the atmospheric precipitation). Considering that this tailing dump is intended to be used in the future, there was a need to bring the existing crown of the tailing dump to the required position and geometry, i.e., it is necessary to rehabilitate it. The planned embankment will be made of earth. The convenience of this solution is that for its construction the deposited mine overburden is used, which is available in large quantities at the location in the immediate vicinity of the RTH tailing dump, the quality of which was checked in the Laboratory for Geomechanics in the MMI Bor, where it was determined that the geomechanical characteristics are of suitable quality for installation into embankment.

In short, the proposed conceptual solution for the rehabilitation of dams and embankments and their restoration to the designed state, according to the current technological design, consists of the following:

- Before the construction of embankment at the RTH flotation tailing dump in Bor, it is necessary to carry out the preparatory works at the tailing dump and borrowing of material - mine overburden, and these preliminary works include the following units:
  - Cleaning and leveling the crown of the existing sand perimeter embankment and leveling the adjacent surfaces on which the mine waste will be incorporated to form a new embankment.
  - Clearing and preparation of borrowed materials for exploitation.
  - Loading, transport and installation of mine overburden in embankments and dams by compaction in layers of a maximum width of up to 50 cm, with checking the compaction of each installed layer, where the compaction of the installed material on the ground should be at least 30 MPa.
- To bring the existing state to the designed state at an elevation of K+378 m altitude, it is necessary to install a total of about **12,550 m^3** of material into embankments and dams in a compacted state with the following geometric characteristics:
  - Embankment length at the base: **Ln=2,191.13 m**
  - Slope of the external and internal slope: **1:2**
  - Width of the embankment crown: **$B_{embankment}$ = 8.0 m**
  - Transverse crown slope: **1.5%**
  - Elevation of the embankment crown: **$K_{embankment}$ = 378.00 m altitude**
- To form the initial volume in the accumulation area of the tailing dump, considering that while the rehabilitation of the crown of the dams and embankments is being carried out at the tailing dump embankment, it is not possible to cyclone and build the embankment from hydrocyclone sand, at the request of the Investor, the crown of the embankments and dams at the RTH tailing dump embankment will be further elevated to a minimum elevations of K+380 m altitude, with the following geometric characteristics:
  - Embankment length at the base: **Ln=2,191.13 m.**
  - Slope of the external and internal slope: **1:2**
  - Width of the embankment crown: **$B_{embankment}$ = 8.0 m**
  - Transverse crown slope: **1.5%**
  - Minimum Elevation of the embankment crown: **$K_{embankment}$ = 380.00 m altitude**
  - Required volume of material for installation in a compacted state: **V=72.300 m^3**

During the summer and autumn of 2021, the rehabilitation works were carried out on the field, after the works on the crown of the dam and geometry of the embankment at the tailing dump, a stable condition was brought in accordance with the valid Technological design. The crowns and embankments after the rehabilitation works are present in Figures 5 and 6.

Figure 5 *Embankment between the Dam 2 and high landfill, October 5, 2021*

2.3. Checking the stability of characteristic profiles at the RTH tailing dump before and after rehabilitation works

The stability calculation of the flotation tailing dump RTH was performed on 4 profiles, but the profile 4 was taken for comparison, where the stability coefficients before the rehabilitation of the embankment were the lowest. Position of the analysis profiles is shown in Figure 6 and Table 1. Table 2 shows the physical and mechanical parameters of flotation tailings and Table 3 the physical and mechanical parameters for disposed mine waste [6].

Table 1 *Position of the analysis profile*

Profile	X1	Y1	X2	Y2
4	7 589 937	4 880 906	7 590 004	4 880 986

Table 2 *Physical and mechanical parameters of the flotation tailing dump*

Profile	Bulk density, kN/m^3	Cohesion, kN/m^2 , (Zone 1/Zone 2)	Internal friction angle, ^{O} (Zone 1/Zone 2)
4	20.45	0/15	25/20

Table 3 *Physical and mechanical parameters for deposited material at the open pit disposal site*

Working environment	Cohesion, kN/m^2	Internal friction angle, °	Bulk density, kN/m^3
Disposed waste	10.00	30.00	20.00

Table 4 *Physical and mechanical parameters of the substrate*

Working environment	Cohesion, kN/m^2	Internal friction angle, °	Bulk density, kN/m^3
Degraded andesite	50	27	20

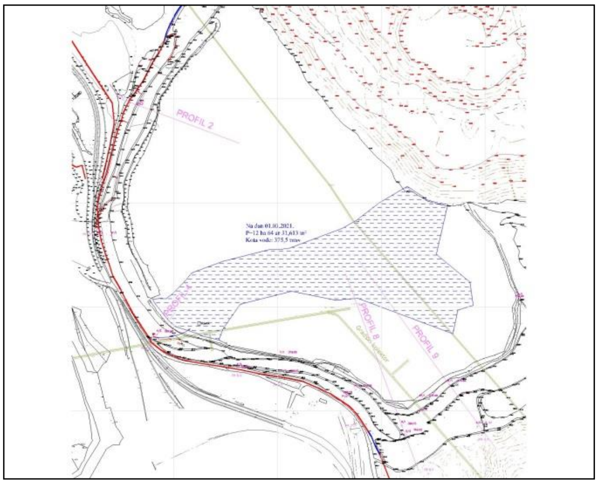

Figure 6 *Position of analysis profiles*

The stability calculation was done with the SLIDE v6.0 program of the company ROCSCIENCE [7]. The stability calculation is carried out under conditions of limit equilibrium, according to the Yanbu method. The impact of groundwater on stability was modeled on the basis of measured water levels in piezometers and level of the water mirror in tailing dump.

The stability calculation, according to the analysis profile for the constant static loads and dynamic loads for the seismicity coefficient KS = 0.13, is shown in Figures 7 and 8 for the profile 4 before rehabilitation [1]. The stability calculation after rehabilitation of the embankment is shown in Figures 9 and 10, while the calculation results are shown in Table 5.

Table 5 *Summary of the stability coefficient of general slopes according to the Yanbu method*

Profile	**F_s static**	**F_s dynamic**
Before rehabilitation		
4	1.036	0.783
After rehabilitation		
4	2.115	1.696

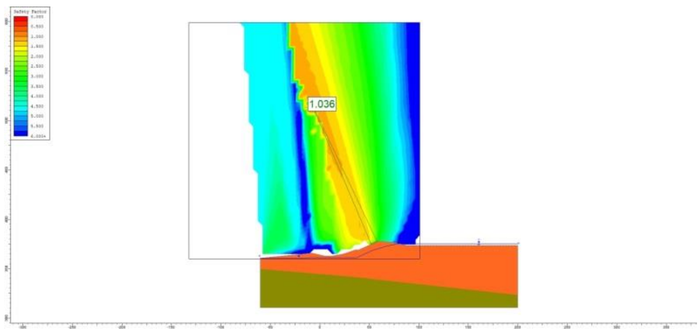

Figure 7 *Stability coefficient according to the profile 4 for static loads, Yanbu method*

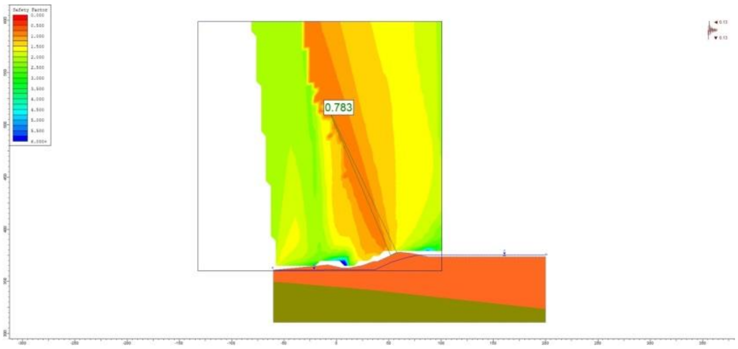

Figure 8 *Stability coefficient according to the profile 4 for dynamic loads, Yanbu method*

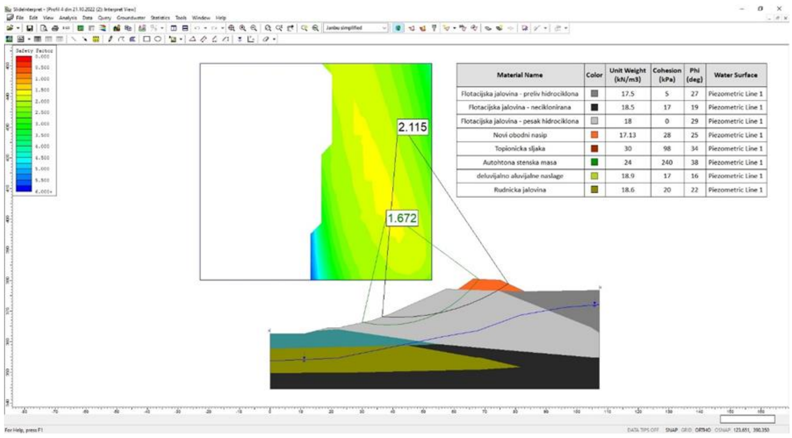

Figure 9 *Stability coefficient according to the profile 4 for dynamic loads, Yanbu method*

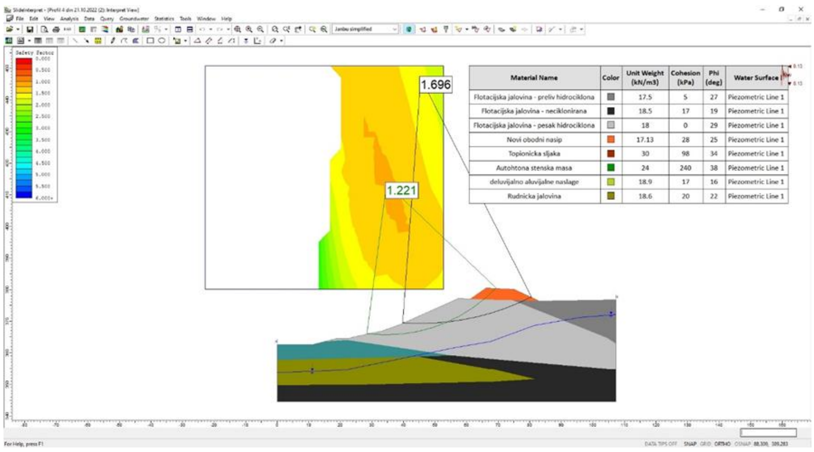

Figure 10 *Stability coefficient according to the profile 4 for dynamic loads after embankment rehabilitation, the Yanbu method*

By comparison the safety coefficients of the flotation tailing dam with permitted minimum coefficients, according to the valid standard for dams (SRPS U.C5.020), which for the embanked dams over 15 m in height is a minimum of Fs = 1.50 in case of permanent static load, i.e., Fs = 1.00 in the case of an occasional dynamic load for the occurrence of an earthquake, it can be concluded that for the profile 4 after rehabilitation, the values for both coefficients (for the static and dynamic loads) are more than doubled, i.e., significantly above the prescribed minimums.

3 CONCLUSION

Based on the above mentioned, the conclusion is that the integrated rehabilitation works on the embankments and dams of the RTH tailing dump showed the excellent results on the ground, so that the tailing dump can be further be elevated and exploited in safe and stable conditions, up to the designed height of K+390 m altitude. What is particularly important, both from an economic and ecological point of view, is that during the integrated remediation, only the existing mine waste was used, i.e., already disposed the mine overburden, without the need to form a new land loan and natural materials to be excavated and transported from another location what prevented the harmful effects of the new mining works on the environment for the needs of embankment rehabilitation.

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 622.79(045)=111
DOI: 10.5937/mmeb2302033T

Received: 04.09.2023.
Revised: 27.10.2023.
Accepted: 30.10.2023.

Original Scientific Paper
Geotectonics

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HYDROGEOLOGICAL ANALYSIS OF THE EXISTING STATE OF DRAINAGE WITH A NEW SYSTEM OF WELLS FOR LOWERING THE GROUNDWATER LEVEL OF THE RTH FLOTATION TAILING DUMP IN BOR[**]

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Abstract

After conducting the geotechnical and hydrogeological explorations of the RTH flotation tailing dump and determining the stability of slopes for the overhanging purposes, the zone with the observed instability, an elevated and unfavorable gradient of the groundwater level, was determined and located. Due to these reasons, further design of the groundwater level regulation system was started. The hydrodynamic analysis of the task determined that in order to achieve the effects of lowering and regulating the level of underground water, it is necessary to construct fourteen wells.

Keywords: *flotation tailing dump, groundwater level, hydrodynamic analysis*

1 INTRODUCTION

The RTH tailings dump was built from materials of anthropogenic origin, at the location where the Bor River used to flow before the formation of the open pit. After the artificial diversion of the river, the mining activities were started, where on one side, the mineral raw materials were excavated and mine waste was disposed so that after completion, the excavated area would be used for disposal of flotation material. Before the actual disposal of flotation material and during disposal, a higher overhang was carried out by forming the dams and embankments, in order to prevent it from protruding outside the land fill. The last applied geotechnical explorations were carried out in 2022. As part of them, the hydrogeological investigations of the location in question were carried out. Since there was a need to define a technical solution for lowering and regulating the level of underground water in a pre-defined area of the tailing dump, the continuation of numerical interpretation of the collected and presented exploration results with the analysis of various technical solutions was started. This paper presents the basic concept and technical solution of groundwater level regulation and expected effects of the system operation.

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[**] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Contract No. 451-03-47/2023-01/ 200052.*

2 PRESENTATION OF RESEARCH RESULTS PERFORMED EXPLORATION RESULTS

The geological foundations of the field, planned for overhang the tailing dump, were obtained on the basis of results of the existing and supplementary explorations [1]. A total of 20 wells were drilled on the field, and piezometer structures were installed in 19. After washing, they are included in observation the groundwater level regime. Geotechnical and hydrogeological mapping was performed on the extracted core. Determination of the layers, defined by the origin and period of origin, was carried out as follows:

- Parent rock,
- Parent rock (deluvium),
- Mine waste - landfills,
- Smelter slag,
- Flotation tailings - dust and sludge,
- Flotation tailings - sand,
- Embankments of heterogeneous composition,
- New perimeter embankment.

In addition to mapping the core and defining the lithological composition and belonging to a specific (determined) formation, the samples were taken for the grain-size analysis on a certain number of samples. Based on the results of the grain-size analyses, and for the purposes of defining the hydrogeological function of individual lithological members, the filtration coefficient was calculated according to the empirical patterns. The affiliation of formations was defined by synthesis of all results according to the hydrogeological function. The hydro-geological function of individual lithological members by wells is shown in Figure 1.

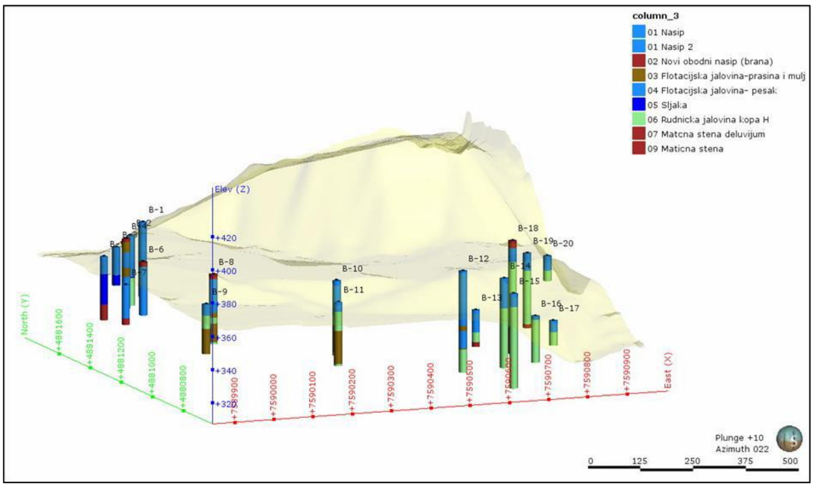

Figure 1 *3D view of wells with hydrogeological interpretation of the well core*

Based on the presented results of exploratory drilling, installation of the piezometer construction and backfilling of the piezometer, observation of the underground water level and mapping of the field, and as a part of the very complex hydrogeological conditions of formation, it can be stated that an outcrop with a free level is formed on the entire area, where it can be classified according to the type of porosity in the following way:

- compact type of outcrop with good water permeability,
- compact type of outcrop with lower water permeability,
- complex type of porosity with lower water permeability,
- conditionally dry part of the field.

By synthesis all the results from exploratory drilling, installation of piezometers, groundwater level measurement to the field mapping, a hydrogeological map of the RTH flotation tailing dump, shown in Figure 2, was made.

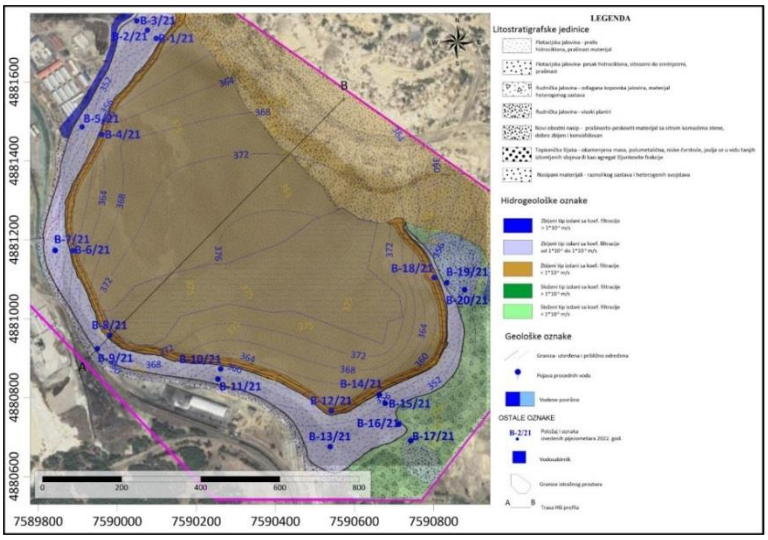

Figure 2 *Hydrogeological map of the RTH flotation tailing dump*

3 DEVELOPMENT OF A HYDRODYNAMIC (MATHEMATICAL) MODEL

To define the concept of groundwater level regulation, a mathematical model of the flotation tailing dump was developed. For the purposes of development a hydrodynamic (mathematical) model [2], the finite difference method (MODFLOW) was used.

Regarding the model layers as well as the filtration characteristics, it was used that the model layer 1 is flotation sand and the model layer 2 is flotation sludge. Other hydrogeological members that have a subvertical transition are defined by the filtration coefficient within the limits of their distribution. The base of the model consists of the parent rock, which is assumed to have no groundwater flow and does not affect the groundwater balance within the RTH tailing dump body.

The external and internal boundary conditions were used as the boundary conditions of the hydrodynamic model of the RTH tailing dump. The external boundary conditions define the current domain. A DRN (Drain) type condition was used, where a special attention was paid to the character and manner of lateral outflow from the model. As an internal boundary condition, the boundary type CHD was used, which reflects the elevation of vertical recharge of the tailing dump.

During realization of the applied geotechnical explorations, fifteen horizontal drains were made, namely six drains near Dam 1 and nine drains near Dam 2, whose effect is incorporated into the model. What is known is the position of the drain beginning and length of its installation. It was assumed in the model that direction is assumed and drain is completely horizontal.

Using the MODFLOW package, that is, the GMG solver. The modeling results are shown on the map in Figure 3, where the hydroisohypses, obtained by the mathematical model and residual difference between the calculated groundwater level and measured groundwater level on the piezometers, are shown.

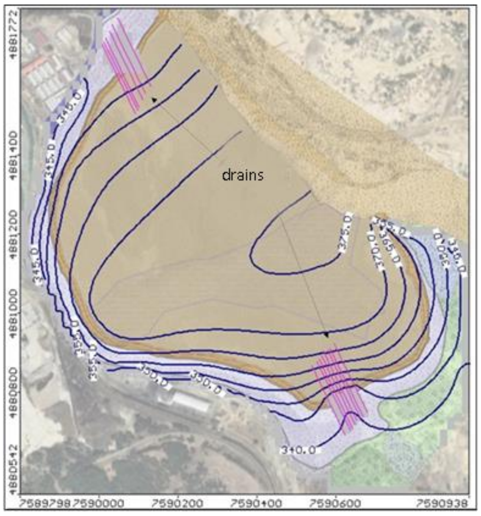

Figure 3 *Hydrodynamic model of the RTH tailing dump*

The model calculates the amount of water that flows out of horizontal drains was calculated on a model. At Dam 1, Q = 46,018 m^3/day = 0.53 l/s; while at Dam 2 Q = 182.36 m^3/day = 2.11 l/s. It was concluded that the effect was achieved by creating the horizontal drains, lowering the groundwater level by about 2 m.

4 DEFINING THE CONCEPT OF THE GROUNDWATER LEVEL REGULATION SYSTEM

In order for local instability to be regulated, it is necessary to lower the groundwater level by 4-5 m in the subject area. For the need to dimension the level lowering system, the presented hydrodynamic model will be used.

What is important to note, and for the purposes of dimensioning the technical solution for lowering and regulating the level of underground water, is the fact that there is flotation sand in the area of interest, from the surface of the terrain. It has a relatively homogeneous granulometric composition, with a filtration coefficient of $1x10^{-6}$ m/s. The mine waste is in the foothills with extremely heterogeneous filtration characteristics, and filtration coefficients from $1x10^{-5}$ to $1x10^{-7}$ m/s.

Since it was not possible to define the boundary of the mine waste, based on the filtration characteristics on the basis of the exploratory wells, the filtration characteristics must be monitored indirectly during well drilling [3].

The values of filtration coefficients mostly range from $1x10^{-6}$ to $1x10^{-5}$ m/s and more. This indicates that the underground water moves freely (gravitationally from higher to the lower potential), i.e., vertical wells of small diameter are an adequate method for lowering and regulating the level.

The individual capacity of the well, depending on the filtration coefficient, and for the conditions of the underground water regime, according to the various criteria, ranges in the interval as shown in Table 1[4].

Table 1 *Permissible speeds of water reaching the well under different criteria*

Different criteria	**Filtration coefficients (m/s)**		
	1.00E-07	**1.00E-06**	**1.00E-05**
Zihart criterion	Vd = 2.11E-05	Vd = 6.67E-05	Vd = 2.11E-04
Modified Zihard criterion	Vd = 1.05E-05	Vd = 3.33E-05	Vd = 1.05E-04
Abramov criterion	Vd = 1.55E-04	Vd = 3.33E-04	Vd = 7.18E-04
Kovac criterion	Vd = 4.22E-05	Vd = 9.09E-05	Vd = 1.96E-04
Kovac critical speed	Vkr = 1.61E-05	Vkr = 3.66E-05	Vkr = 8.30E-05
Q (l/s)	**0.43**	**1.36**	**3.39**

Under the most unfavorable conditions, and assuming that the well is well constructed, the smallest

expected capacity of each well is 0.43 l/s. Using the hydrodynamic model, in order to lower the level of 4-5 m in the analyzed area, it is necessary to build fourteen wells. Their effect in depth and in terms of the radius of effect of the group of wells is shown in Figure 4.

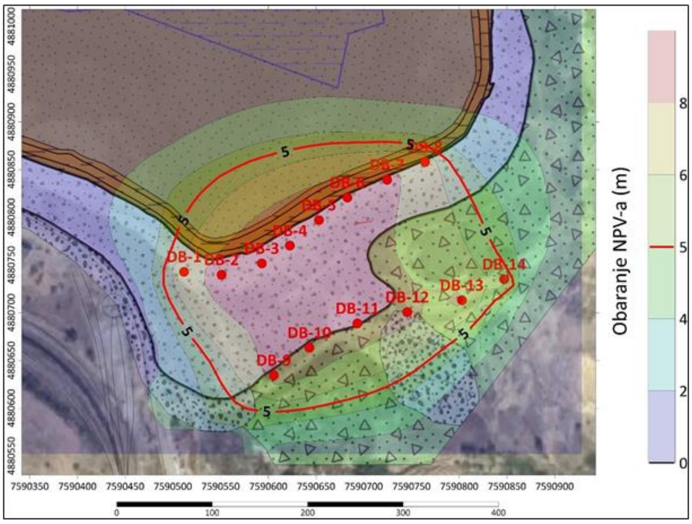

Figure 4 *Expected effect of operation of fourteen wells with the position shown*

The designed position and expected depth of the well is shown in Table 2.

Table 2 *Designed wells*

Well label	Y	X	Prognostic depth (m)
DB-1	7590512	4880743	50
DB-2	7590551	4880740	50
DB-3	7590593	4880752	50
DB-4	7590622	4880770	50
DB-5	7590653	4880797	60
DB-6	7590683	4880821	60
DB-7	7590724	4880839	50
DB-8	7590764	4880858	50
DB-9	7590606	4880635	50
DB-10	7590643	4880664	40
DB-11	7590693	4880689	40
DB-12	7590746	4880701	50
DB-13	7590803	4880713	50
DB-14	7590847	4880735	50

CONLUSION

Based on the results of the conducted hydrogeological and geotechnical explorations of the RTH flotation tailing dump in Bor, a hydrodynamic model of the tailing dump was created. In order to achieve the necessary lowering of the underground water level at the Dam 2 of the landfill, for the purpose of stabilization and rehabilitation the facility, it was necessary to find an adequate technical solution. Through hydrodynamic analysis, it was determined that fourteen wells must be constructed in order to achieve the effects of lowering and regulating the level of underground water. Their position and achieved effects of their installation were modeled and determined.

After completion of the field works on installation the well structures, and based on the report on the construction and testing the wells, it is necessary to purchase and equip the well with the well pumps, electrical and mechanical equipment, as well as a suitable drainage system to the receiver that is not in hydraulic connection with the underground water at microlocation. Based on the pumping test, determine the actual exploitation capacity of the well and put the system into operation. Since there is a piezometer network at the location where the wells in question are being drilled, it will be possible to determine the actual effects of the system operation directly in the field. After six months of the system operation and continuous monitoring of exploitation on wells and level measurements on piezometers, it is necessary to recalibrate the hydrodynamic model and give an assessment of the achieved effects in relation to the designed one.

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 614.715:622(045)=111
DOI: 10.5937/mmeb2302039P

Received: 28.07.2023.
Revised: 14.09.2023.
Accepted: 03.10.2023.

Original Scientific Paper
Environmental protection engineering

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AMBIENT AIR QUALITY AT THE PISKANJA BORON MINERAL DEPOSIT NEAR BALJEVAC ON THE IBAR RIVER

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Abstract

This paper presents the results of the ambient air quality in the area of Piskanja boron mineral deposits, located in the eastern part of the Jarandol Tertiary Basin, on the right bank of the Ibar River. The analysis included samples from four measuring points, sampled during the summer and winter months of 2018-2019. The total atmospheric deposition, pH value, and heavy metal content (Pb, Cd, Zn, As) in the total atmospheric deposition were measured at all four measuring points. In addition, sulfur dioxide, nitrogen dioxide, soot, and PM_{10} particulate matter were analyzed at two measuring points. Considering the obtained results and applicable legal regulations, the tested air samples were found to be within the prescribed limit values by the analyzed parameters, except for the measured PM_{10} concentrations (particulate matter less than 10 µm). The obtained test results should contribute to determining the direct impact of future exploitation of boron minerals on air quality.

Keywords: *ambient air, boron minerals, Piskanja deposit, Jarandol basin*

1 INTRODUCTION

The Piskanja boron mineral deposit is located on the right bank of the Ibar River, in the eastern part of the Jarandol Basin in the immediate vicinity of the Baljevac settlement, municipality of Raška. The Jarandol Tertiary Basin is divided by the Ibar River into two parts: eastern - Piskanja, encompassing the Piskanja boron deposit, and western - Jarandol, with the Bela stena and Borovak magnesite deposits, Jarando coal deposit, boron mineral deposit in Pobrđe and boron mineralization occurrences in Raspopovići. In genetic terms, the Piskanja deposit was formed in the Neogene, sedimentary series of the Jarandol Basin, in the immediate vicinity of which there are larger massifs of volcanic andesitic, dacite and phenodacite rocks. Given the sedimentary series covered with the alluvial formations and humus, these rocks are mostly inaccessible to a direct observation in surface terrain [1, 2].

The beginning of boron mineral research in this deposit dates back to 1987 when the "Ibarski rudnici" company drilled a 3.5 m thick layer of boron minerals at a depth of 306.7 to 310.2 m. Ever since, a detailed geological exploration has been carried out on several occasions to define the quantity and quality of the useful component. Based on the obtained results, the potential borate reserves in the Piskanja deposit are estimated at over 7,500,000 tons of quality boron minerals (colemanite, ulexite, probertite), with the average content of useful component of about 36% B_2O_3 [3]. Due to the high useful component content, the deposit exploitation is planned. In order

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to determine the direct impact of the future mine on the quality of the main environmental parameters, the environment was "as is" tested in the deposit area [4].

As a part of these tests, the ambient air quality was analyzed from four different locations in the subject deposit area. The results of these tests are presented in this paper. Figure 1 shows the sampling site location.

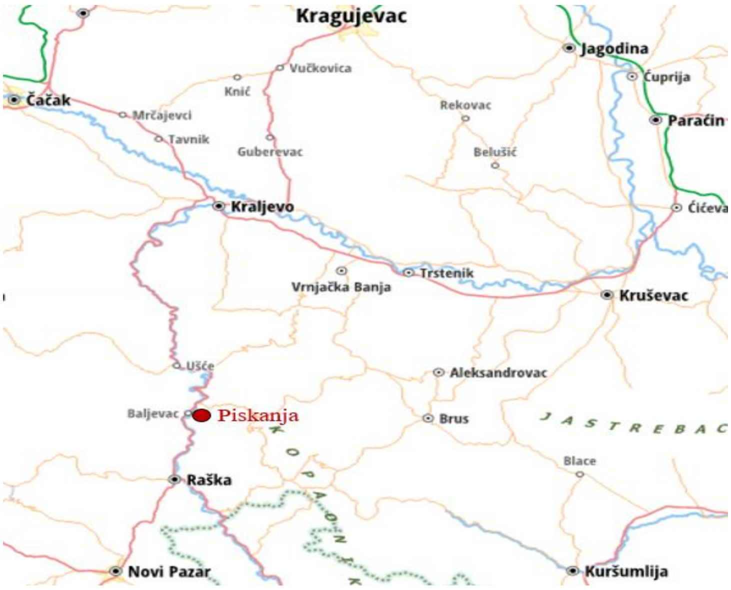

Figure 1 *Location of sampling*

2 TEST MATERIAL AND METHODS

The ambient air quality in the Piskanja boron mineral deposit area was tested in the summer (June 4, 2018 - July 4, 2018) and winter (January 17, 2019 - February 16, 2019) periods.

Sampling was performed at four measuring points, taking into account the population and the spatial coverage of the deposit area (Table 1).

Table 1 *Description and coordinates of sampling point*

Marking of measuring/sampling points	Sampling point	Coordinates	
		N	E
MM6	Family house of Milinka Mihajlović	43 23 14.50	20 39 00.37
MM7	Family house of Zvezdan Jovanović	43 22 52.50	20 38 55.80
MM8	Family house of Milica Todorović	43 22 44.90	20 39 16.90
MM9	Family house of Vidosava Radosavljević	43 22 42.57	20 38 38.25

At all four measuring points, the total atmospheric deposition and pH values were measured by monthly sampling. In addition, the heavy metal content (Pb, Cd, Zn, As) was determined in the total atmospheric deposition. During the testing period, at two measuring points (MM6, MM7), sulfur dioxide, nitrogen dioxide, and soot were analyzed by the 24-hour sampling, while PM_{10} particulate matter was measured 15 days a month.

Locating, sampling and measuring parameters in the field and laboratory conditions were performed by the Belgrade Mining Institute. Heavy metal content in sediments was determined by the Institute Mol d.o.o. Stara Pazova. The air samples were analyzed according to the standards and using the accredited methods.

Following laws and bylaws regulate the protection of air from pollution in Serbia: the Air Protection Act [5] and Decree on Conditions for the Air Quality Monitoring and Requirements [6] which defines, among other things, the measurement conditions and concentration limits of pollutants harmonized with the EU requirements. In the particulate matter limit values guidelines, the World Health Organization (WHO) did not prescribe a lower particulate matter concentration threshold below which there is no impact on human health, but gave the certain guidelines and recommendations. The guidelines offer the recommended levels of exposure to PM_{10} and $PM_{2.5}$, ozone, nitrogen dioxide, and sulfur dioxide, as well as measures to encourage a progressive improvement in the air quality and reduce the impact of pollution on health [7, 8].

3 RESULTS AND DISCUSSION

Figures 2–8 show the results of measuring the tested parameters for the summer and winter seasons, while the statistical indicators are given in Tables 2–5. In the same tables, GV (limit values) are given for comparison purposes, the concentrations of which are defined by the Decree on Conditions for Air Quality Monitoring and Requirements [6].

The average daily concentrations of sulfur dioxide at the MM6 and MM7 measuring points do not exceed the limit values, and no extremely high concentrations were recorded, see Figures 2 and 3.

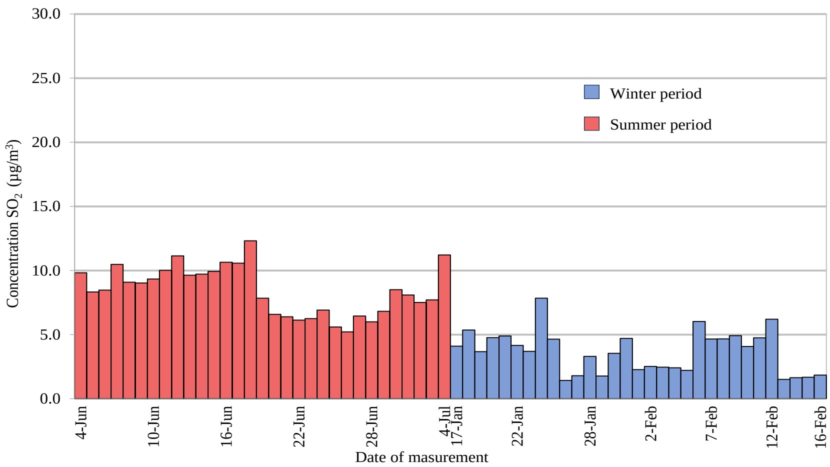

Figure 2 *Average daily concentrations of SO_2 at the MM6 measuring point i n summer and winter periods*

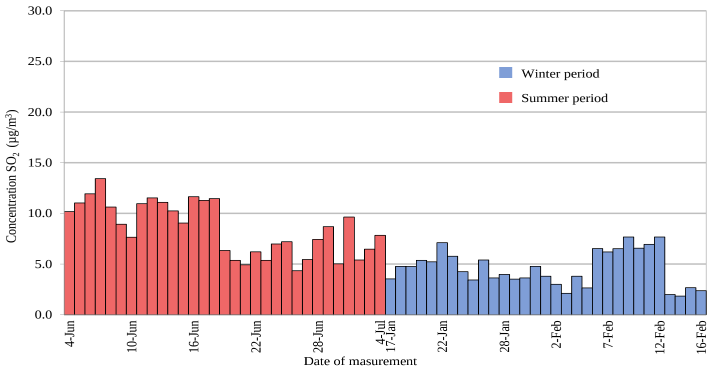

Figure 3 *Average daily concentrations of SO_2 at the MM7 measuring point in summer and winter periods*

Table 2 *Statistical indicators of SO_2 at the MM6 and MM7 measuring points in summer and winter periods*

Marking of measuring/ sampling points	Summer period			Winter period		
	C_{av}	C_{min}	C_{max}	C_{sr}	C_{min}	C_{max}
MM6	< 10.0	< 10.0	12.3	< 10.0	< 10.0	< 10.0
MM7	< 10.0	< 10.0	13.4	< 10.0	< 10.0	< 10.0
LV(C_{24}) = 85 µg/m^3						

Analyzing the obtained results, it can be concluded that the maximum values of SO_2 concentration were measured in the summer period. The maximum daily concentrations of 13.4 µg/m^3 and 12.3 µg/m^3 were recorded at MM7 and MM6 measuring points, respectively. The elevated concentrations in the summer period are associated with polluter located near the subject deposit. This primarily refer to the coal separation in Baljevac and landfill of small, waste coal containing about 42% of ash [9].

During the entire measuring period, the average daily concentrations of nitrogen dioxide were significantly below the limit values prescribed by the Decree [6].

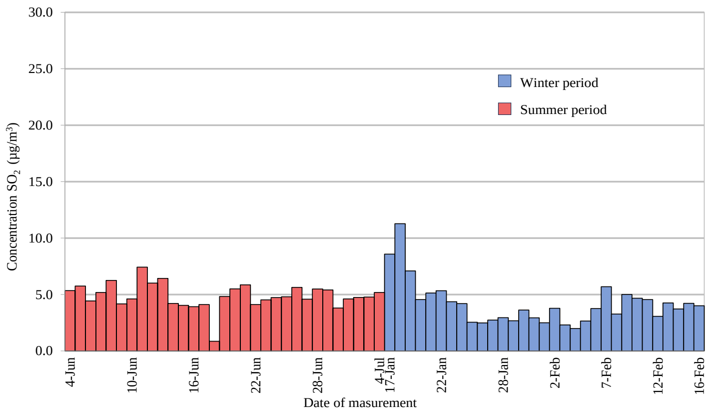

Figure 4 *Average daily concentrations of NO_2 at the MM6 measuring point in summer and winter periods*

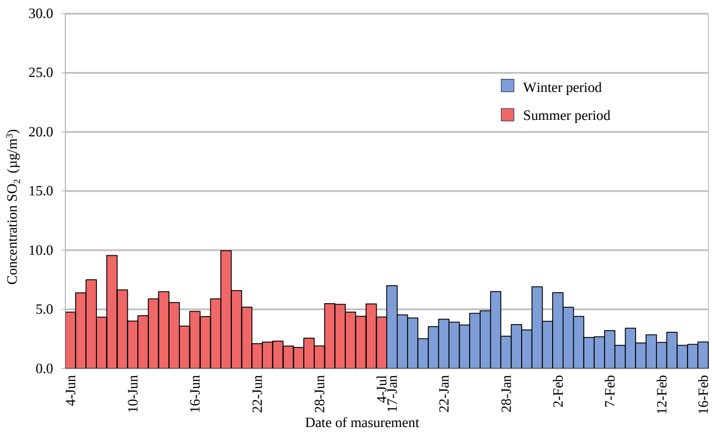

Figure 5 *Average daily concentrations of NO_2 at the MM7 measuring point in summer and winter periods*

Table 3 *Statistical indicators of NO_2 at the MM6 and MM7 measuring points in summer and winter periods*

Marking of measuring/ sampling points	Summer period			Winter period		
	C_{av}	C_{min}	C_{max}	C_{sr}	C_{min}	C_{max}
MM6	4.9	< 3.0	7.4	4.2	< 3.0	11.3
MM7	4.9	< 3.0	10.0	3.8	< 3.0	7.0
LV(C_{24}) = 85 µg/m^3						

The maximum average daily concentration was measured at the MM6 measuring point as 11.3 µg/m^3 in winter and 10.0 µg/m^3 in summer, while the other values were significantly lower.

The average daily concentrations of soot at the MM6 and MM7 measuring points do not exceed the maximum allowed concentrations in any measuring period, see Figures 6 and 7.

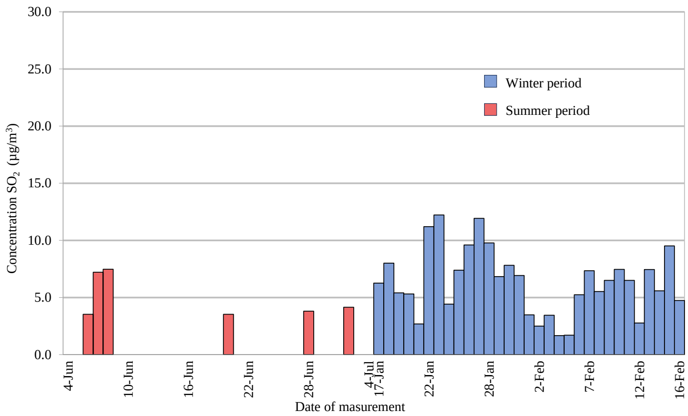

Figure 6 *Average daily concentrations of soot at the MM6 measuring point in summer and winter periods*

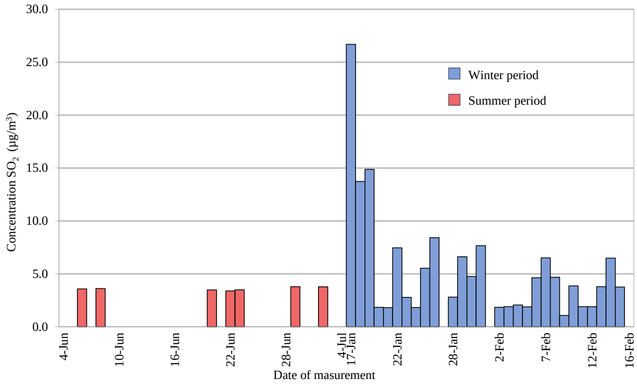

Figure 7 *Average daily concentrations of soot at the MM7 measuring point in summer and winter periods*

Table 4 *Statistical indicators of soot at the MM6 and MM7 measuring points in summer and winter periods*

Marking of measuring/ sampling points	**Summer period**			**Winter period**		
	C_{av}	C_{min}	C_{max}	C_{sr}	C_{min}	C_{max}
MM6	< 2.0	< 2.0	7.5	< 2.0	< 2.0	12.2
MM7	< 2.0	< 2.0	3.8	4.9	< 2.0	26.7
MAC **(C_{24}) = 50µg/m^3**						

The maximum daily concentration of 26.7 µg/m^3 was recorded in winter at the MM7 measuring point, which is still within the permitted values. It can also be concluded that significantly higher soot concentrations were recorded in winter that is explained by the combustion of organic matter in individual furnaces.

Concentrations of PM_{10} during the summer period, at both measuring points, were below the prescribed limit values. The analysis of the results showed that during the winter period the daily limit value of PM_{10} was exceeded for three days at the MM6 measuring point and six days at the MM7 measuring point, see Figures 8, 9. The maximum concentration was measured at MM7 measuring point and was 85.3 µg/m^3.

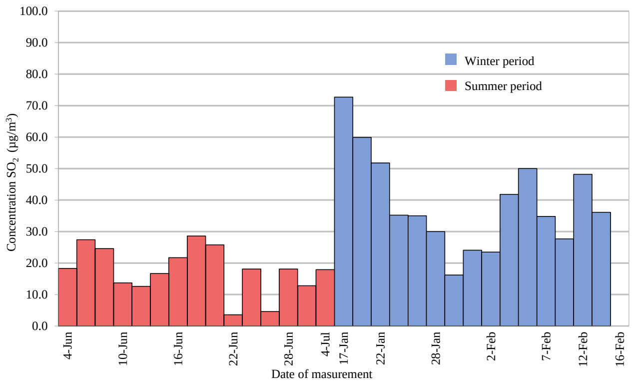

Figure 8 *Average daily concentrations of PM_{10}, at the MM6 measuring point in summer and winter period*

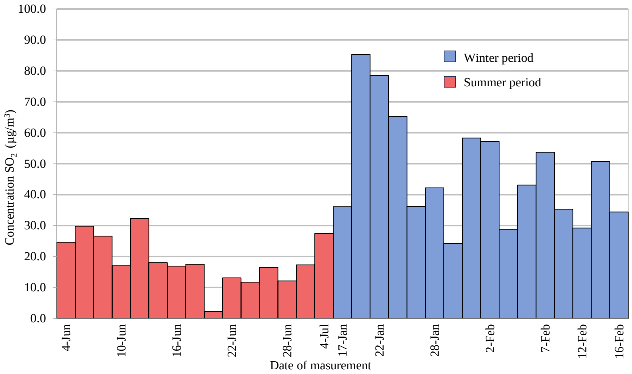

Figure 9 *Average daily concentrations of PM_{10} at the MM7 measuring point in summer and winter period*

The elevated measured values of PM_{10} in the winter period at this location are mostly precipitated from the ashes of individual household furnaces. Therefore, they are directly related to the combustion of organic fuels in households. The value of PM_{10} emission also depends on air currents, i.e., wind speed [10].

Table 5 *Statistical indicators for particulate matter at the MM6 and MM7 measuring points in summer and winter periods*

Marking of measuring/ sampling points	Summer period			Winter period		
	C_{av}	C_{min}	C_{max}	C_{sr}	C_{min}	C_{max}
MM6	17.6	3.6	28.6	39.1	16.2	72.7
MM7	19.9	2.2	36.1	48.2	24.2	85.3
GV **(C_{24}) = 50µg/m^3**						

Table 6 shows the measurement results at all four measuring points of the following parameters: pH value, total atmospheric deposition (TAD), heavy metal content (Zn, Pb, Cd, As) in the total atmospheric deposition. Within the same table, the maximum allowable concentrations (MAC) for the total atmospheric deposition are given.

Table 6 *Results of pH, TAD and heavy metal in the TAD measurements*

Marking of meas-uring/ sampling points	Summer period						Winter period					
	pH	TAD	Zn	Pb	Cd	As	pH	TAD	Zn	Pb	Cd	As
MM6	7.47	94.1	14.64	3.44	<0.07	0.92	6.12	61.3	8.56	4.43	<0.07	0.92
MM7	7.03	85.5	10.68	6.63	<0.07	0.77	5.98	51.1	12.99	5.42	<0.07	0.77
MM8	5.93	153.4	7.73	5.03	<0.07	1.59	5.18	49.0	4.38	3.48	<0.07	1.59
MM9	5.61	107.1	5.60	1.59	<0.07	0.82	5.4	42.0	8.41	2.44	<0.07	0.82
MAC (1 month) = 450 mg/m^{2}day												

The value of the total atmospheric deposition in the subject area was within the limits prescribed by the Decree on Conditions for Air Quality Monitoring and Requirements [6]. During the measurement period, at all four measuring points, the concentration of atmo-spheric deposition ranged from 42.0 - 61.3 mg/m^2 per day in winter and 85.5 - 153.4 mg/m^2 per day in summer. The Decree on Conditions for Air

Quality Monitoring and Requirements does not prescribe the maximum allowable quantity of these metals in the total atmospheric deposition [6]. The obtained values can be used to monitor the impact of future exploitation on the area air quality.

4 CONCLUSION

To manage the air quality in an area, it is necessary to monitor the concentrations of pollutants, characteristic of the sources of pollution in that area. The environmental impact of a project cannot be determined without study the environment quality before the start of the project. Due to this reason, the air quality was tested in the area of the Piskanja boron mineral deposit before exploitation. Sampling was performed during the summer and winter seasons with four measuring points arranged so as to cover the entire deposit area. The analysis included the following parameters: sulfur dioxide, nitrogen dioxide, soot, PM_{10} and total atmospheric deposition. The content of Zn, Pb, Cd and As heavy metals was also determined in the total atmospheric deposition.

The test results showed that the ambient air of subject area was not burdened with excessive concentrations of the measured parameters in the examined period. Except for the measured PM_{10} concentration, the analyzed parameters do not exceed the limit values prescribed by the Decree on Conditions for Air Quality Monitoring and Requirements. The elevated PM_{10} content for several days during the winter period, at both measuring points, is associated with the combustion of organic fuel in the individual furnaces. The measurements carried out are aimed to be used in monitoring the impact of future exploitation of boron minerals at the Piskanja deposit on the air quality to prevent or minimize the adverse effects of exploitation.

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 614.715(045)=111
DOI: 10.5937/mmeb2302047T

Received: 01.08.2023.
Revised: 10.10.2023.
Accepted: 12.10.2023.

Original Scientific Paper
Environmental protection engineering

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SUSPENDED PARTICLES CONCENTRATIONS IN THE SECONDARY SCHOOLS IN BOR (SERBIA) IN HEATING SEASON[***]

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Abstract

This paper presents the results of measurements the suspended particles of the PM_{10} and $PM_{2.5}$ fractions in two high schools in Bor (School of Mechanical and Electrical Engineering - MS and Grammar School - GM). The measurements were conducted in two heating seasons for a duration of seven days (five weekdays, and two weekend days). Periods during the weekdays when there were classes and weekend days when there were no classes at school were analyzed separately. The measurement results show that the average concentrations of suspended particles PM_{10} during the class period were 1.7 (GM) and 2.4 (MS) times higher than in the period without classes. The average concentrations of suspended particles $PM_{2.5}$ in both schools during the class period were 1.5 times higher than in the period without classes. In MS the average PM_{10} and $PM_{2.5}$ concentrations during classes were above daily limit values for 3 of 5 working days. In contrast, there was no exceeding of the average daily limit values for concentrations of suspended particles during classes in GM. The results of measurements indicate that more attention should be paid to the way classrooms are cleaned to reduce the possibility of particles resuspension due to the movement of pupils during the teaching period.

Keywords: *classroom, real-time monitoring, particulate matter, air pollution*

1 INTRODUCTION

The most studied and most frequently mentioned environmental pollution is the air pollution. Long-term exposure to the low concentrations of pollutants is a particular problem, which is the most common case [1-3]. The difficulty in study the effects of air pollution on health is the presence of a mixture of pollutants in the air, which is almost always the case making it difficult to single out the individual impacts. EU and national legislation have prescribed the monitoring of two fractions of particles present in the air, particles smaller than 2.5 μm in diameter, and coarse particles that are 2.5-10 μm in diameter [4]. The introduction of limit values for pollutant concentrations in the ambient air, especially those related to the suspended particles, contributes to improving the population health.

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[***] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Grant No. 451-03-47/2023-01/ 200052.*

The urban air quality is thought to have a more significant impact on population health than the other environmental factors, and the ambient air pollutants are one of the most significant causes of health problems in general. According to the WHO (World Health Organization), over 4 million deaths occur annually in the world due to the air pollution [5]. Many of the adverse health effects come from the inhalation of increased concentration of particulates from the ambient air. A very important impact on human health has particles with a diameter of less than 2.5 µm. The consequences of a large uptake of these particles into the lungs are usually respiratory infections and, in extreme cases, death. People suffering from asthma, heart or lung disease are most vulnerable to particulate pollution [6 -9].

It is very important to determine the impact of indoor PM concentrations on human health because people spend most of their lives indoors [10]. In the indoor environment, both indoor and outdoor sources contribute to PM levels. The PM in indoor air originates from outdoor infiltration and additional indoor sources such as cooking and heating devices, tobacco smoking, building materials, etc. Indoor air quality in educational buildings is of great importance since children and students spend a large part of their time in classrooms. Unfortunately, there are almost no systematic monitoring programs dealing with the indoor air quality in educational buildings in the Republic of Serbia. This work presents the result of an ongoing study on student's and teacher's exposure to the suspended parti-cles PM_{10} and $PM_{2.5}$ in two secondary schools (School of Mechanical and Electrical Engineering - MS and Grammar School - GM) in Bor, Serbia.

2 METHODOLOGY

Both schools (MS and GM) are located in the Bor town residential area, about 2 km southwest of the copper smelter facilities, as shown in Figure 1. The indoor measurements of suspended particles at each school were conducted at one selected classroom located on the second floor. Both classrooms have a floor space of approximately 60 m^2 and volumes of 240 m^3. The floor is covered with the worn wooden parquet. There is no air conditioning system in the classrooms. The window areas in both classrooms are about 8 m^2. The classrooms are occupied by 15-30 pupils during teaching hours. During the measurements campaign (heating season), the schools were heated regularly using the remote district heating system.

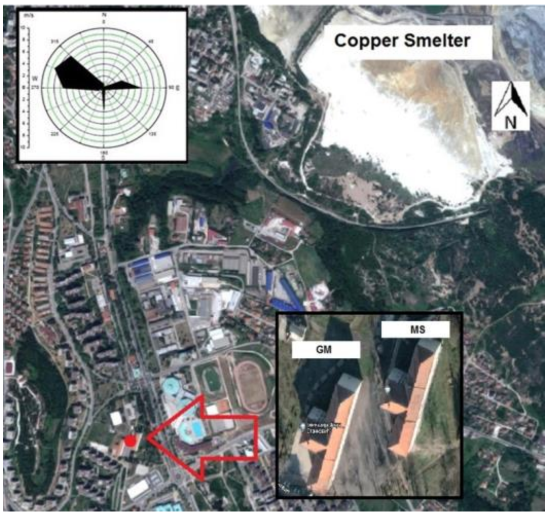

Figure 1 *The position of MS and GM schools on the Bor town map*

The measurements of suspended particulate matter, PM_{10} and $PM_{2.5}$ fractions, were carried out simultaneously in the classroom and outdoor air, for five consecutive working days (Monday - Friday) and two non-working days (Saturday-Sunday). The measurement of indoor PM concentrations was carried out with a Turnkey Osiris real-time PM monitor [11]. The results of measurements were analyzed separately for the teaching hours (PP - pupils present), from 7 AM - 3 PM, and no teaching hours (PA - pupils absent), from 3 PM to 7 AM in the morning of following day. The measurement of outdoor PM concentrations were carried out with a Grimm EDM180 PM monitor at the National Air Quality Monitoring Station (NAQMS) Bor Town Park (TP) (44º04 33''N, 22º05'58''E).

3 RESULTS AND DISCUSSION

The average PM_{10} levels measured in the classrooms at MS and GM are shown in Table 1. According to data shown in Table 1, the average daily concentration of PM_{10} in the classroom at MS was 31.5 μg/m^3. At the same time, the average daily concentration of PM_{10} in the ambient air was 25.5 μg/m^3. Also, the average concentration of PM_{10} in the classroom at MS during the teaching period was 46.2 μg/m^3. This is 1.7 times higher PM_{10} concentration compared with the PM_{10} concentration recorded in the no teaching period (27.2 μg/m^3). In MS the average PM_{10} concentrations during classes were above daily limit values for 3 of 5 working days.

Table 1 *Average PM10 levels and I/O ratios measured in the classrooms at MS and GM (PP - pupils present, PA - pupils absent)*

MS working days						
Date	PM_{10} IN 24h	PM_{10} OUT 24h	PM_{10} IN/OUT 24h	PM_{10} IN PP	PM_{10} IN PA	PM_{10} IN PP/PA
	μg/m^3	μg/m^3		μg/m^3	μg/m^3	
21/01/19	25.6	27.5	0.9	21.6	26.1	0.8
22/01/19	41.8	28.2	1.5	54.2	32.3	1.7
23/01/19	31.5	30.7	1.0	57.8	28.8	2.0
24/01/19	31.2	21.0	1.5	50.3	26.7	1.9
25/01/19	28.9	20.3	1.4	46.9	23.3	2.0
Average	31.5	25.5	1.3	46.2	27.2	1.7
MS weekend days						
27/01/19	5.3	32.5	0.2	6.0	5.5	1.1
28/01/19	11.3	26.3	0.4	12.1	12.7	1.0
Average	8.3	29.4	0.3	9.1	9.1	1.0
GM working days						
Date	PM_{10} IN 24h	PM_{10} OUT 24h	PM_{10} IN/OUT 24h	PM_{10} IN PP	PM_{10} IN PA	PM_{10} IN PP/PA
	μg/m^3	μg/m^3		μg/m^3	μg/m^3	
13/03/23	6.8	22.3	0.3	9.1	4.9	1.9
14/03/23	7.2	36.2	0.2	11.1	5.3	2.1
15/03/23	17.2	28.1	0.6	30.8	11.8	2.6
16/03/23	17.4	11.8	1.5	33.2	13.0	2.6
17/03/23	16.8	12.0	1.4	30.9	13.1	2.4
Average	13.1	22.1	0.8	23.0	9.6	2.3
GM weekend days						
18/03/23	9.4	32.8	0.3	9.7	5.8	1.7
19/03/23	5.1	22.8	0.2	4.5	10.1	0.4
Average	7.3	27.8	0.3	7.1	8.0	1.1

The average PM_{10} levels measured in the classroom at GM was 13.1 μg/m^3. At the same time, the average daily concentration of PM_{10} in the ambient air was 22.1 μg/m^3. Also, the average concentration of PM_{10} in the classroom at GM during the teaching period was 23.0 μg/m^3. This is 2.3 times higher average PM_{10} concentration compared with the PM_{10} concentration recorded in the no teaching period (9.6 μg/m^3).

It can be seen from the presented data that even though in the observed periods, the average daily concentration of PM_{10} in the outdoor air was approximately the same, the average daily concentration of PM_{10} in MS was significantly higher compared to the average daily concentration of PM_{10} in GM. We believe that the different practices of aeration and cleaning, as well as the long presence and large number of students in the classroom in MS compared to the GM, caused such results. This can be confirmed on the basis of changes in PM_{10} concentrations, shown in Figures 2 and 3.

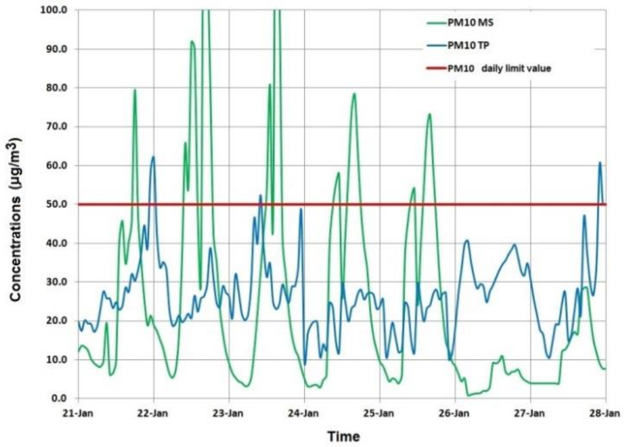

Figure 2 *Line diagram of PM_{10} measured in MS and outdoor air at TP*

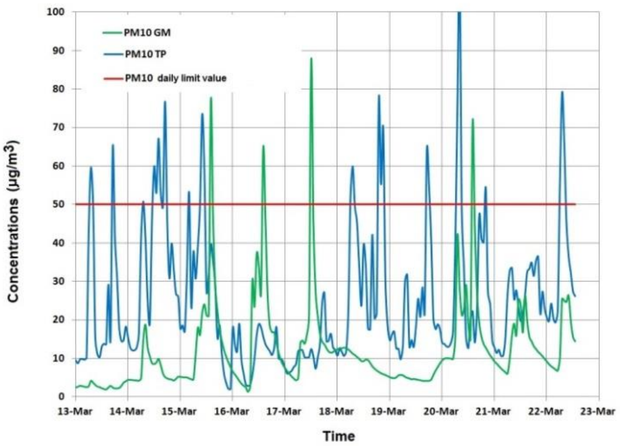

Figure 3 *Line diagram of PM_{10} measured in GM and outdoor air at TP*

The average $PM_{2.5}$ levels, measured in the classroom at MS, are shown in Table 2. According to data shown in Table 2, the average daily concentration of $PM_{2.5}$ in the classroom at MS was 17.6 μg/m^3. At the same time, the average daily concentration of $PM_{2.5}$ in the ambient air was 21.1 μg/m^3. Also, the average concentration of $PM_{2.5}$ in the classroom at MS during the teaching period was 22.1 μg/m^3. This is 1.5 times higher $PM_{2.5}$ concentration compared to the average $PM_{2.5}$ concentration, recorded in the no-teaching period (14.8 μg/m^3). In MS, the average PM_{10} concentrations during classes were above daily limit values for 3 of 5 working days.

Table 2 *Average $PM_{2.5}$ levels and I/O ratios measured in the classrooms at MS and GM (PP - pupils present, PA - pupils absent)*

MS working days						
Date	$PM_{2.5}$ IN 24h	$PM_{2.5}$ OUT 24h	$PM_{2.5}$ IN/OUT 24h	$PM_{2.5}$ IN PP	$PM_{2.5}$ IN PA	$PM_{2.5}$ IN PP/PA
	μg/m^3	μg/m^3		μg/m^3	μg/m^3	
21/01/19	15.5	22.2	0.7	15.5	16.1	1.0
22/01/19	24.5	22.6	1.1	28.7	16.3	1.8
23/01/19	17.2	26.5	0.6	28.5	12.9	2.2
24/01/19	18.8	19.8	1.0	25.3	17.9	1.4
25/01/19	12.0	14.6	0.8	12.7	10.7	1.2
Average	17.6	21.1	0.8	22.1	14.8	1.5
MS weekend days						
27/01/19	5.1	22.3	0.2	4.1	4.2	1.0
28/01/19	8.1	24.7	0.3	5.0	5.7	0.9
Average	6.6	23.5	0.3	4.5	5.0	0.9
GM working days						
Date	$PM_{2.5}$ IN 24h	$PM_{2.5}$ OUT 24h	$PM_{2.5}$ IN/OUT 24h	$PM_{2.5}$ IN PP	$PM_{2.5}$ IN PA	$PM_{2.5}$ IN PP/PA
	μg/m^3	μg/m^3		μg/m^3	μg/m^3	
13/03/23	4.0	12.8	0.3	3.9	3.0	1.3
14/03/23	4.7	19.7	0.2	6.6	3.8	1.7
15/03/23	8.5	18.1	0.5	12.5	6.1	2.0
16/03/23	8.3	8.6	1.0	11.7	7.7	1.5
17/03/23	7.6	9.1	0.8	8.7	9.3	0.9
Average	13.1	22.1	0.6	8.9	6.0	1.5
GM weekend days						
18/03/23	7.8	16.3	0.5	8.1	4.9	1.7
19/03/23	4.1	15.8	0.3	3.7	7.4	0.5
Average	6.0	16.0	0.4	5.9	6.1	1.1

The average $PM_{2.5}$ levels measured in the classroom at GM was 13.1 μg/m^3. At the same time, the average daily concentration of $PM_{2.5}$ in the ambient air was 22.1 μg/m^3. Also, the average concentration of $PM_{2.5}$ in the classroom during the teaching period was 8.9 μg/m^3. This is 1.5 times higher average $PM_{2.5}$ concentration compared with the $PM_{2.5}$ concentration recorded in the no-teaching period (6.0 μg/m^3). Changes in $PM_{2.5}$ concentrations in the observed classrooms are shown in Figures 4 and 5.

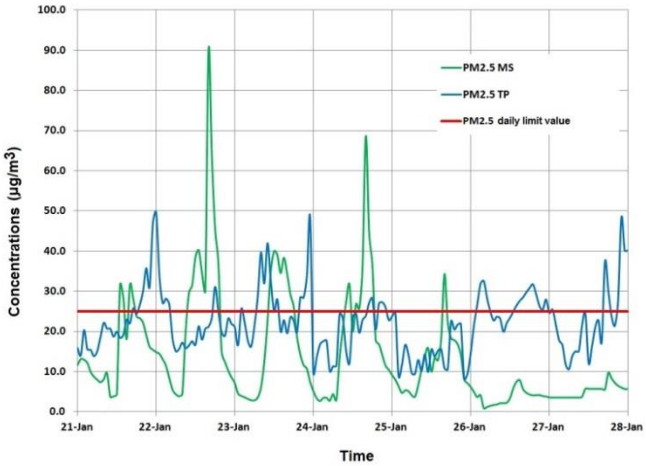

Figure 4 *Line diagram of $PM_{2.5}$ measured in MS and in the outdoor air at TP*

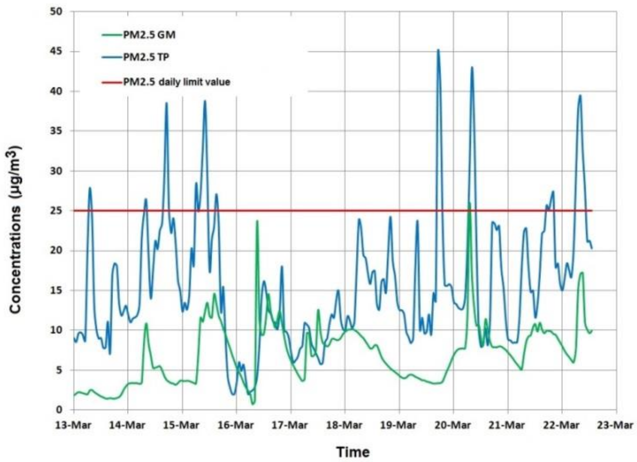

Figure 5 *Line diagram of $PM_{2.5}$ measured in GM and in the outdoor air at TP*

The PM_{10} levels measured in the MS and GM classrooms are comparable with previously reported PM_{10} levels, measured in schools in the Republic of Serbia and EU [12-15]. For example, the average PM_{10} levels in the classrooms in Thessaloniki was 118 µg/m^3, and in the range of 75 - 203 µg/m^3 in the classrooms in Athens [12]. As reported in [13], the PM10 levels measured in schools in Aveiro, Portugal, were 49.2 and 79.8 µg/m^3. The same paper states that the average PM_{10} I/O ratio was 2.4 and 1.84, which is comparable to our results. The average daily PM_{10} level measured in the city of Niš, at the Faculty of Occupational Safety in Nis, was 47.0 µg/m^3, and at the primary school, Vožd Karađorđe in Niš was 54.6 µg/m^3 [14]. Also, the average PM_{10} levels in two primary schools in Bor and Zlot in the heating season were 44.2 µg/m^3 and 49.5 µg/m^3, respectively [15].

4 CONCLUSION

This work presents the results of measurements the mass concentration of PM_{10} and $PM_{2.5}$ in the indoor air of two secondary schools in Bor during the heating period. The measurement results show that the average concentrations of suspended particles PM_{10} during the class period were 1.7 (GM) and 2.4 (MS) times higher than in the period without classes. The average concentrations of suspended particles $PM_{2.5}$ in both schools during the class period were 1.5 times higher than in the period without classes. In MS, the average PM_{10} and $PM_{2.5}$ concentrations during classes were above daily limit values for 3 of 5 working days. Limited ventilation in classrooms during the heating period and resuspension of particles are reasons that caused the high indoor PM concentrations during the teaching period in comparison to the PM concentrations in the no-teaching period. Thus, the appropriate measures should be prescribed to provide better air quality inside the schools, such as different cleaning and ventilation practice. Further study should be continued in the no-heating period to determine whether there are seasonal differences in levels of PM in the classrooms in comparison to the outdoor PM levels.

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 621.51(045)=111
DOI: 10.5937/mmeb2302055R

Received: 31.07.2023.
Revised: 09.10.2023.
Accepted: 11.10.2023.

Original Scientific Paper
Mechanical Engineering

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OPERATION OF THE COMPRESSED AIR PRODUCTION INSTALLATION WITH VARIABLE AIR CONSUMPTION[**]

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Abstract

This paper presents an analysis of operation the compressed air production installation under the given operating conditions on an example of conceptual solution for the process air supply to a filter press of the Filtration Facility in the Copper Mine Majdanpek. Calculation was made using an analytical method for the installation operation with variable air consumption. Also, this paper presents a layout of technological scheme of the process air supply to the filter press, as well as the technical characteristics of compressed air production installation.

Keywords: *compressed air, filter press, technical characteristics*

1 INTRODUCTION

Purchase of a new filter press of type VPA 1540-24 was envisaged for the needs of reconstruction the Filtration Facility in the Copper Mine Majdanpek in 2017. It is necessary to provide the process and instrument compressed air for the filter press operation. The parameters of process and instrument compressed air are defined by the supplier of the filter press-Metso Company. This paper gives an analysis of operation the installation producing process air for the filter press operation. The required process air quality is 2.7.1 according to ISO 8573-1. The pressure and flow rate of process air are variable during the working cycle of the filter press and their values are given in Table 3.

2 TECHNICAL DESCRIPTIONS

The compressor station operation is analyzed in this paper for the filter press operation with the following equipment:

1. Compressor unit GA75+; made by Atlas Copco [1], [2]
2. Air receiver 10 RVH 15; made by MIP Process equipment [3]

The compressor unit is a stable oil injected rotary screw one-stage air-cooled compressor with electromotor drive GA75+ – 10 with integrated refrigerant dryer IFD and heat recovery unit ER. Technical characteristics of the compressor unit are given in Table 1.

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[**] *This work was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Grant No. 451-03-47/2023-01/ 200052.*

Table 1 *Technical characteristics of the compressor unit*

Manufacturer	Atlas Copco
Type	GA75+ – 10 WorkPlace Full-Feature (with ER unit)
Installed motor power	75 kW
Maximum working pressure	9.75 bars
Nominal working pressure	9.5 bars
Capacity FAD (1 bar; 20°C)	12.6 m^3/min
Noise level	68 db(A)
Compressed air outlet	G 2 ½ “
Dimensions (L x W x H)	2290x1080x1962 mm
Weight	1680 kg

The air receiver is made of a carbon steel sheet, as horizontal. The air receiver is equipped with all the necessary connections for compressed air inlet and outlet for the safety valve, pressure gauge, command air, condensate drainage and revision.

The air receiver is equipped with the following fittings: safety valve, manometer and shut-off valve for condensate drainage. Technical characteristics of the air receiver are given in Table 2.

Table 2 *Technical characteristics of the air receiver*

Manufacturer	MIP Process equipment
Type	10 RVH 15
Volume	15 m^3
Maximum working pressure allowed	10 bars
Length	6250 mm
Height	2145 mm
Diameter	Ø1800 mm
Compressed air connections	DN150
Weight	2900 kg

The refrigerant dryer IFD, integrated into a compressor unit, produces the pressure dew point of the compressed air of +3°C. The heat recovery unit ER enables the subsequent utilization of the waste heat of compressor that can be used for heating in the winter regime. To ensure the required compressed air quality between the compressor unit and air receiver, two lines with filters for compressed air DD+, PD+ and QD+ are provided, one of which is in operation and the other in reserve. An electronic water drain EWD is used for condensate removal. The compressed air is delivered from the air receiver, placed outside next to the compressor station, in the Filtration Facility by a steel pipeline Ø139.7x4 mm. Technological scheme of the process air supply for filter press is shown in Figure 1.

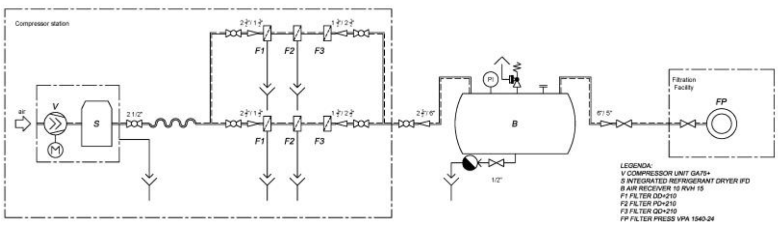

Figure 1 *Technological scheme of the process air supply for filter press*

3 CALCULATIONS

Calculation of the installation for compressed air production has for a purpose determination the process air parameters during the working cycle of a filter press and in particular the quantity of produced compressed air per unit of time defined by loaded and unloaded periods of compressor operation as well as the working pressure values in the compressed air installation. The calculation was done for the following operating conditions adopted:

1. Compressor in operation i.e., loaded ("switched on") compressor produces constant quantity of air per unit of time of $\dot{V}_c = 12{,}6\left[\frac{m^3}{min}\right]$. This quantity of air per unit of time represents the volumetric flow rate for free air delivery conditions (FAD) and it corresponds to the mass air flow rate of $\dot{m}_c = 15{,}12\left[\frac{kg}{min}\right]$ (for the air density of $\rho = 1{,}2\left[\frac{kg}{m^3}\right]$).

2. When pressure in the air receiver rises up to the set value of the unloading pressure compressor switches to the mode of operation when it is unloaded ("switched off") and then there is no air output. The unloading pressure amounts $p_{isklj} = 9{,}2[bar]$.

3. When pressure in the air receiver drops down to the set value of the loading pressure compressor switches to the mode of operation when it is loaded ("switched on"). The loading pressure amounts $p_{uklj} = 8{,}2[bar]$.

4. Maximum pressure in the net is $p_{max} = 10[bar]$.

5. Minimum pressure during the working cycle in the net is $p_{min} = 7[bar]$.

6. Air temperature in the net is constant and amounts $t = 20[°C]$.

7. Volume of the pipeline is neglected, i.e., the volume of installation is equal to the volume of air receiver and amounts $V = 15[m^3]$.

8. All losses due to system leaks are ignored.

In Table 3, the required parameters of process air are given by the stages of one working cycle of the filter press according to [4] and [5].

Table 3 *Required parameters of process air*

Number	Stage of the cycle	Duration of the stage of the cycle	Air pressure at filter press downstream of the control valve	Minimum air volumetric flow rate	Maximum air volumetric flow rate	Average air volumetric flow rate	Air volume consumed in the stage of the cycle
	-	min	bars	Nm^3/min	Nm^3/min	Nm^3/min	Nm^3
1.	Filtration	1.90	-	0	0	0	0
2.	Compression	0.50	8	2	2	2	1
3.	Air blow	4.03	7	6	22	14	58
4.	Top blow (technical time -first part)	0.083	4	60	60	60	5
5.	Washing (technical time - second part)	0.083	-	0	0	0	0
6.	Top blow (technical time - third part)	0.083	4	60	60	60	5
7.	Technical time - fourth part	3.05	-	0	0	0	0

According to [4] the normal working conditions refer to the temperature of $t = 20[°C]$ and pressure of $p = 1{,}013[bar]$.

The following calculation formulas were used in the calculation:

1. $\rho_1 = \frac{p_{1aps}}{R_g \cdot T_1}\left[\frac{kg}{m^3}\right]$- air density at the beginning of respective stage of compressor operation

where:

$p_{1aps}[Pa]$- absolute air pressure at the beginning of respective stage of compressor operation

$R_g = 287\left[\frac{J}{kg \cdot K}\right]$- individual gas constant for air

$T_1 = 293[K]$- absolute air temperature at the beginning of respective stage of compressor operation

2. $m_c = \dot{m}_c \cdot \tau_T[kg]$- air mass produced during the respective stage of compressor operation

where:

$\dot{m}_c = 15.12\left[\frac{kg}{min}\right]$- air mass produced per unit of time during the respective stage of compressor operation

$\tau_T[min]$-duration of the respective stage of compressor operation

3. $m_p = \int_{\tau_1}^{\tau_2} \dot{m}_p d\tau\ [kg]$- air mass consumed during the respective stage of compressor operation

where:

$\dot{m}_p = \dot{m}_p(\tau)\left[\frac{kg}{min}\right]$-air mass consumed per unit of time during the respective stage of compressor operation

$\tau_1[min], \tau_2[min]$-time of the beginning and the end of the respective stage of compressor operation

4. $\Delta m = m_c - m_p[kg]$- difference between produced and consumed mass of air during the respective stage of compressor operation

5. $\rho_2 = \frac{\rho_1 \cdot V + \Delta m}{V}\left[\frac{kg}{m^3}\right]$-air density at the end of the respective stage of compressor operation

where:

$V = 15[m^3]$-volume of the air receiver

6. $p_{2aps} = \rho_2 \cdot R_g \cdot T_2[Pa]$- absolute air pressure at the end of respective stage of compressor operation

where:

$T_2 = 293[K]$-absolute air temperature at the end of the respective stage of compressor operation

Using the formulas from 1. to 6. and taking into account the compressor loading and unloading pressures, a compressed air production diagram can be determined, i.e., the periods of loaded and unloaded compressor operation as well as the working pressures in the installation during one working cycle of the filter press.

The results of analysis are given on diagrams in Figure 2.

4 DISCUSSIONS OF CALCULATION

When sizing a compressor to work with variable air consumption, there is an option of selecting a compressor with a lower capacity than the maximum air consumption, since in periods when air consumption is higher than production, the required amount of air is provided from the air receiver. If the air consumption in relation to time is known it is possible to determine both the required compressor capacity and required air receiver volume meeting the required air parameters during the working cycle.

In this example, the consumption of process air as well as the required process air pressure during the working cycle are determined by the technological requirements (see Table 3). During the first stage of the working cycle (filtration) there is no air consumption, the pressure in the installation is equal to the unloading pressure of 9.2 bar and the compressor is switched off. During the second stage of the working cycle (compression) the air consumption is constant and amounts 2.4 kg/min and pressure at the filter press is 8 bar.

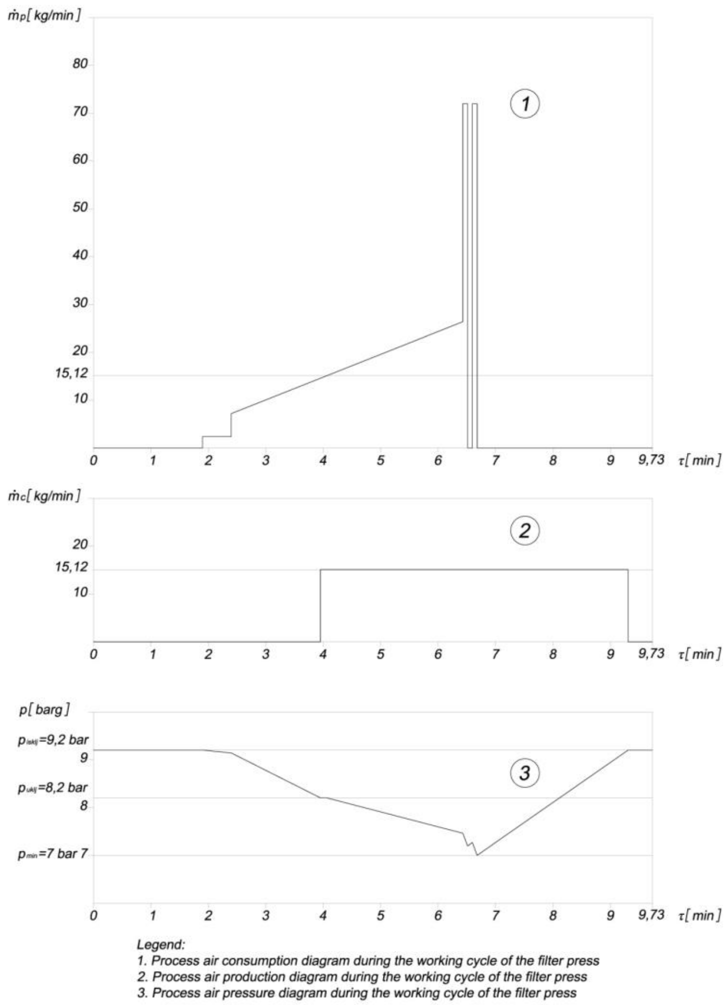

Figure 2 *Process air parameters during the working cycle of filter press*

At the same time the compressor is switched off so the pressure in the installation drops to 9.14 bar. During the third stage (air blow) air consumption changes from the minimum which amounts 7.2 kg/min to the maximum which amounts 26.4 kg/min and pressure at the filter press is 7 bars. At this stage, during the 93.1 sec time with the compressor switched off, the pressure drops to 8.2 bar. After that, with the compressor switched on for a period of 6.6 sec the pressure remains approximately the same since the air production is approximately equal to the consumption. Finally, at the end of the third stage for a period of 142.1 sec with compressor switched on, the pressure drops to 7.46 bar due to the fact that the air consumption is higher than production. The remaining working cycle time is technical time. During the first part of the technical time for a period of 5 sec top blow is carried out with the air consumption of 72 kg/min and pressure at the filter press is 4 bar. The pressure drops to 7.197 bar. At the second part of the technical time, for 5 seconds, washing is performed and there is no air consumption, so the pressure increases to 7.266 bar as the compressor is switched on. The third part of the technical time has the same parameters as the first part of the technical time and, at the end of it, the pressure drops to 7 bar. At the fourth part of the technical time, there is no air consumption, so that at first for a period of 157.6 sec the pressure rises to the unloading pressure of 9.2 bar, and pressure remains the same. The compressor is switched on 55% of working cycle duration of the filter press. The total cycle time of the filter press is 9.73 min. At no time, the pressure in the installation does not fall below the minimum pressure value for the respective stage in the working cycle of filter press. The scenario analyzed here is the most unfavorable case i.e., the case when the lowest pressure in installation is achieved, because at the moment when the system goes into a part of diagram where the consumption is higher than production (243.7 sec from the beginning of cycle) the pressure in the installation is equal to the loading pressure of 8.2 bar. In the next part of the cycle, the pressure can only fall because the air production is less than consumption and at one point it reaches a minimum value. The minimum value of the pressure in installation for the entire working cycle is at the end of stage 6 according to Table 3 (top blow - the third part of the technical time). However, after that begins the stage when there is no air consumption and when there is enough time for pressure in installation to rise to the unloading pressure of compressor before beginning the next stage when the cycle repeats.

5 CONCLUSION

The exposed methodology of calculating the operation of installation for compressed air production with variable air consumption represents an analytical method for determining the operating parameters of compressed air under given operating conditions. When choosing a compressor beside the capacity, the other parameters are taken into account, such as the loaded and unloaded period of compressor operation, achievement of the required air quality, possibility of cooling and utilization of waste heat. When determining the capacity, the addition for losses, reserve for additional consumers and addition due to the calculation errors, are also taken into consideration [6]. In this case, the air receiver is selected according to the requirement that system works without unallowable pressure drops during the consumption spikes, realizing all the other functions that an air receiver has in the compressed air installations. The most optimum solution is found analyzing various variants from which one variant is represented in this paper. Compressor and air receiver are important but not the only equipment in the compressor station. More detailed considerations of the design of compressor stations in Flotation plants are given in the paper [7].

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MINING AND METALLURGY INSTITUTE BOR
UDK: 622

ISSN: 2334-8836 (Štampano izdanje)
ISSN: 2406-1395 (Online)

UDK: 621.65:622.79(045)=111
DOI: 10.5937/mmeb2302061M

Received: 27.09.2023.
Revised: 30.10.2023.
Accepted: 01.11.2023.

Original Scientific Paper
Mechanical engineering

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DRAINAGE PUMP STATION OF THE DAM 4-1 – VELIKI KRIVELJ[**]

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Abstract

The paper presents the hydraulic calculation of pipelines and selection the pumping units for hydrotransport of drainage water of the Dam 4-1 from the planned well on the dam to the tailing dump.

Keywords: *hydraulic calculation, pumping station, borehole pump*

1 INTRODUCTION

The Veliki Krivelj tailing dump is a valley-type tailing dump and occupies space in the former bed of the Kriveljska river. The village Oštrelj is downstream from the tailing dump, and upstream is a conveyor system for waste transport from the Krivelj mine to the old open pit Bor and Veliki Krivelj open pit mine.

From the beginning of its work in 1982 until 1989, the Veliki Krivelj Flotation Plant disposed tailings in the old tailing dump - Field 1. The Field 1 was created by closing the valley of the Kriveljska river with two barrier sand dams, upstream the Dam 1 and downstream the Dam 2. In order to evacuate the water of the Kriveljske river, a tunnel was constructed through the original terrain, from the left bank of the river. The length of the Ø3 m diameter tunnel is 1414 m.

In 1990, the tailing dump was expanded downstream, occupying the additional space in the bed of the Kriveljska river – the new tailing dump or Field 2. To contour the new tailing dump, it was enough to build only one dam – the Dam 3. A collector with a diameter of 3 m and length of 2075 m was constructed at the bottom of the Kriveljska river bed for water drainage waters of the Kriveljska river, which is a continuation of the existing tunnel. Due to the problems with the collector itself, its rehabilitation was carried out on a length of 621 m initia-

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[**] *The research presented in this paper was done with the financial support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, within the funding of the scientific research work at the Mining and Metallurgy Institute Bor, Grant No. 451-03-47/2023-01/200052*

lly, which was extended to a total of 700 m during 2010 and 2011. The repaired part of the collector is located under the body of the Dam 3 and starts about 200 m from the outlet of the collector. The rehabilitation was carried out by installing a reinforced concrete ring with a thickness of 40 cm. The light opening on the repaired part of the collector has been reduced to 2.2 m. The other main facilities of the tailing dump are: Dam 1, Dam 2, Dam 3, Dam 4-1, facilities for diversion of the Kriveljska river, safety overflow body in the Field 2, Revision Well in the Field 0, tailings supply system to the tailing dump and return water system from the tailing dump to the pool above the Old Flotation Plant and pool above the New Flotation Plant.

Figure 1 *Layout of the tailing dump of the Flotation Plant Veliki Krivelj*

Due to a lack of free storage space in the Field 1 and its filling over the designed height by more than 3 m, the exploitation of the new Field 0 began in the spring of 2021 and then the drainage system of the Dam 4-1 begins to function in full with the well with borehole pumps.

In order to drain the Dam 4-1, the construction of a drainage system is planned, which includes the construction of a well in which two borehole pumps will be installed, one as the working pump and the other as a reserve. The pumping station is designed for a flow of 30 l/s. A steel pipeline with flanges is placed inside the well, and connection with the plastic HDPE pipeline is made outside the well, after the steel pipe joint, as shown in Figure 1.

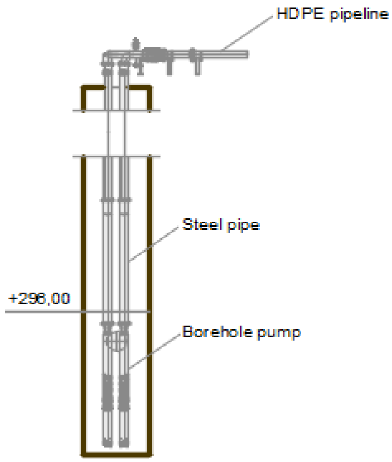

Figure 2 *Cross section of the well*

The pipeline is laid along the edge of the dam, then over the crown of the dam to the place where it flows into the lake at a distance from the dam. It is planned to lay the pipeline in a trench measuring 400x600 mm and then cover with material to protect it from the external effects. In this way, the water will be prevented from freezing in the pipes in case the pumps are out of operation in a period of extremely low temperatures. In the Phase I, the HDPE pipeline crosses the dam at an elevation of +340 and is 900 m long and, in the Phase II, it should cross the dam at an elevation of +393 and is 950 m long.

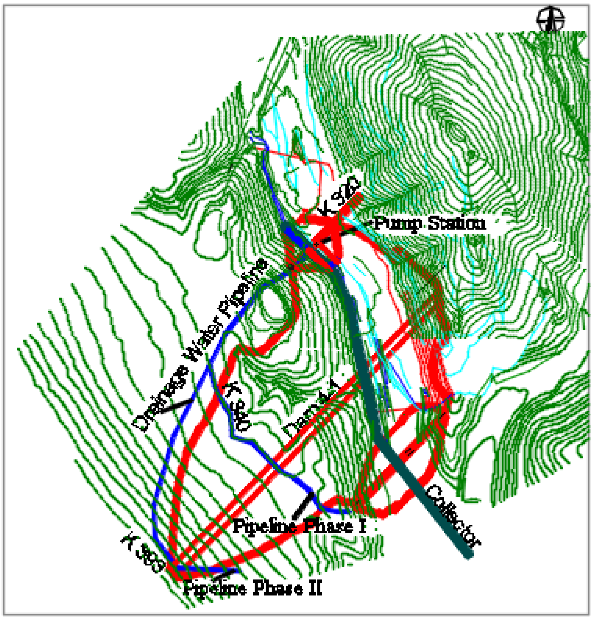

Figure 3 *Layout of the Dam 4-1*

2 CALCULATION

Dam drainage water pump in the station 4-1 (elevation of the pipeline crossing over the crown of the dam + 393)

Initial data:

- Amount of drainage water:
- Q_v=108 [m^3/h]
- Elevation of water level in the drainage well K+296 [m]
- Elevation of outflow of drainage water into tailings: K+393 [m]
- Pipeline length in the Phase II: L2=950 [m]

HDPE pipeline DN 180 (L=950m):

Fluid transport speed:

- $Q_v = 108$ [m^3/h]	Fluid flow
- D=0.1472 [m]	Internal diameter of the pipeline
- $\upsilon = \frac{4 \cdot Q_v}{3600 \cdot D^2 \cdot \pi} = 1.763\ [\frac{m}{s}]$	Fluid speed
- $L = 950$ [m]	Pipeline length
- $C = 130$	Coef. of conditions of the inner surface of pipe
- $i_f = (\frac{Q_v}{3600 \cdot 0.27854 \cdot C \cdot D^{2.63}})^{\frac{1}{0.54}} = 0.02\ [\frac{m}{m}]$	Hazen-Wiliams [3]
- $\sum h_i$ =19.2 [m]	Line losses

Total head loss:

H_1=393	Elevation of the dam pass
H2=296	Elevation of the water level in the drainage well

$H_{g=}$393 – 296=97 [m]

$H_{man} = H_g + \sum hi = 116.2$ [m]

The total pressure [2] drop is:

ρ =1000 [kg/m^3]	Water density
g= 9.81 [m/s^2]	Gravitational acceleration

$\Delta P = \rho \cdot g \cdot H_{man} = 11{,}4 \cdot 10^5$ [Pa]

The total power of the motor to drive the pump: [2]

$$P_{em} = \frac{Q_v \cdot \Delta P_2}{1000 \cdot \mu_p \cdot \mu_m \cdot 3600} = 45.4\ [kW]$$

$\mu p = 0.81$	Efficiency of the pump
$\mu m = 0.93$	Efficiency of the electric-motor

Borehole pump with 52 kW electric-motor (similar to LOWARA Z8 125 7- L8W)

Water Hammer [1]:

- Fluid flow — Qv=108 — [m^3/h]
- Static head — Hg=97 — [m]
- Internal diameter of pipe — Dn=147.2 — [mm]
- Wall thickness of pipe — δ=16.4 — [mm]
- Elasticity modulus of water — E_w=20700 — [daN/cm^2]
- Elasticity mo0dulus of pipe — Ep=11· 10^3 — [daN/cm^2]

Fluid density: $\rho = \frac{\gamma}{g} = \frac{0{,}001}{9{,}81}$ dN/ s^2/ cm^4

Celerity of pressure wave: [1]

$$a = \sqrt{\frac{Ew}{\rho\cdot(\frac{Dn}{\delta}\cdot\frac{Ew}{E\check{c}}+1)}} = \sqrt{\frac{20700}{\frac{0{,}001}{981}\cdot(\frac{147.2}{16.4}\cdot\frac{20700}{11\cdot10^3}+1)}} = 336.9 \text{ [m/s]}$$

The propagation time of water hammer:

$$T = \frac{2\cdot L}{a} = \frac{2\cdot950}{336{,}9} = 5.64 \text{ [s]}$$

When stopping the pump, there is a change in speed from v_1 = 1.76 [m/s] to v_0 = 0 [m/s], so $\Delta v = 1.76$ [m/s] which creates the water hammer:

$$\max P_1 = \pm(v_1 - v_0)\cdot\frac{\gamma\cdot a_{sr}}{g} = \pm 1.76\cdot\frac{0.001\cdot336.9\cdot10^5}{9.81} = \pm\ 6.05 \text{ [bar]}$$

The initial hydrostatic pressure is 97 [m], so the pressure at the pumping station is:

$$abs_{max} = \frac{H_g}{10} + maxP_1 = 9.7 + 6.054 = 15.75\ [bar]$$

$$abs_{min} = \frac{H_g}{10} - maxP_1 = 9.7 - 6.054 = 3.65\ [bar]$$

Based on these values, the armature was dimensioned for the nominal pressure value of 16 bar.

Polyethylene pipeline HDPE 100 DN 180 SDR 11 for the working pressure of 16 bar is adopted.

3 CONCLUSION

Based on the proposed solution, a drainage system was built and put into operation in 2019.

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[3] www: http://www.vanguard.edu/psychology/apa.pdf (for web document)

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We are thankful for all authors on cooperation

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Народна библиотека Србије, Београд

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MINING and Metallurgy Engineering Bor / editor-in-chief Milenko Ljubojev. - 2013, no. 2- . - Bor : Mining and Metallurgy Institute Bor, 2013- (Bor : Grafomedtrade). - 24 cm

Tromesečno. - Je nastavak: Rudarski radovi = ISSN 1451-0162
ISSN 2334-8836 = Mining and Metallurgy Engineering Bor
COBISS.SR-ID 201387788