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ASSESSMENT OF RISKS ASSOCIATED WITH THE OPERATION OF THE TAILINGS STORAGE FACILITY VELIKI KRIVELJ, BOR (SERBIA)

OCENA RYZYKA ZWIĄZANEGO Z FUNKCJONOWANIEM SKŁADOWISKA ODPADÓW VELIKI KRIVELJ, BOR (SERBIA)

The Tailings Storage Facility Veliki Krivelj was formed by damming the Krivelj River valley, and it constitutes one of the largest industrial waste disposal sites in Serbia. As such, it represents a big challenge for the Bor Copper Mine in terms of stability preservation and environmental protection. Bearing this in mind, it is safe to say that it is of crucial importance to recognize all the risks involved with its operation and management. This paper presents a semi-quantitative assessment of the risks entailed in the management of Tailings Storage Facility Veliki Krivelj, and demonstrates the use of 4×4 risk matrix to estimate the likelihood of potential failure scenarios and consequences and includes the application of the „As Low As Reasonably Practicable" diagram for final risk evaluation. The results show that the management of the Tailings Storage Facility Veliki Krivelj is associated with risks that vary from negligible to high, i.e. from broadly to conditionally acceptable risks and also suggest that the irregularities in hydraulic elements and hydro-technical structures at Tailings Storage Facility are the ones with the greatest impact in increasing the risks.

Keywords: Tailings Storage Facility Veliki Krivelj, risk, failure scenario, consequences, risk matrix

Składowisko odpadów poflotacyjnych Veliki Krivelj powstało w dolinie po przegrodzeniu tamą rzeki Krivelj, w chwili obecnej jest to jedno z największych składowisk odpadów przemysłowych na terenie Serbii. W sowim obecnym kształcie stanowi ono wielkie wyzwanie dla zakładu kopalnictwa miedzi Bor, w zakresie ochrony, zachowania i stabilizacji warunków środowiska naturalnego. Mając powyższe względy na uwadze, stwierdzić należy że kwestią absolutnie kluczową jest rozpoznanie wszelkich rodzajów ryzyka związanego z funkcjonowaniem i utrzymaniem wysypiska. W artykule przedstawiono w pół-ilościową analizę ryzyka związanego z funkcjonowaniem składowiska odpadów poflotacyjnych Veliki Krivelj. Zademonstrowane zastosowanie macierzy ryzyka 4×4 do obliczania prawdopodobieństwa awarii w kilku rozpatrywanych scenariuszach działania oraz towarzyszących im skutków. Przedstawiono także zastosowanie diagramu obliczania ryzyka końcowego według schematu „tak niskie, jak tylko praktycznie wykonalne". Wyniki wskazują, że funkcjonowanie składowiska odpadów poflotacyjnych Veliki Krivelj związane jest

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występowaniem wielu czynników ryzyka, od pomijalnych do bardzo wysokich poziomów, innymi słowy, od ryzyka powszechnie akceptowanego do czynników akceptowanych warunkowo. Wskazano także, że nieregularne działanie elementów hydraulicznych i hydro-technicznych w ramach urządzeń składowiska stanowi czynnik mający największy wpływ na podniesienie poziomu ryzyka.

Słowa kluczowe: składowisko odpadów poflotacyjnych Veliki Krivelj, ryzyko, scenariusz sytuacji awaryjnej, konsekwencje, macierz czynników ryzyka

1. Introduction

Industrial waste disposal facilities are among the largest man-made structures (ICOLD, 2001; Davies, 2002). Disposal site dams are in some cases over 100 m high and interestingly enough the largest dam ever built is made of tailings. The Syncrude Mildred Lake Tailings Dyke in Alberta, Canada, is an embankment dam about 18 km long and to 88 m high (Morgenstern, 2001). Dam failures at industrial waste disposal facilities account for about three-quarters of all major environmental disasters caused by mining activities. There is often a greater likelihood for failure in smaller structures than in larger ones, but they certainly deserve more attention (Bowker & Chambers, 2015).

The data obtained after comparing the parameters for industrial waste disposal facilities indicate that every third of a century their height increases by two times, the area of waste deposits increases by five times, while the volume of waste increases by ten times. If the likelihood of failures is proportional to dump height increase (H) and the consequences are proportional to waste volume increase (V) the potential risk (R) increases to 20 ($H \cdot V = 2 \cdot 10 = 20$) (Robertson, 2011).

The analyses results of 3.500 industrial waste disposal facilities around the world showed that the likelihood of failures is $1 \cdot 10^{-3}$ (Martin et al., 2000). The average costs of failures, which are according to ICOLD characterized as “serious” and “very serious” amount to 509 million euros (Bowker & Chambers, 2015).

If only the flotation tailings from copper mines are taken into account, the calculated failure rate for the 2010-2020 decade amounts to 0.0004 of “very serious” and 0.0005 of “serious” failures per one million ton of copper ore that is 0.00045 on the average. Over the given decade, the copper ore production is expected to be 36.338 million tons in total, which could approximately result in 16 failures at Tailings Storage Facility (TSF) in copper mines, that is 1.6 failures at copper mine TSFs every year (Bowker & Chambers, 2015).

The idea of geotechnical risk as applied to large structures, such as TSFs, has been around a long time (Caldwell, 2016). Different forms of methodologies has been used in TSFs risk assessment studies. For example, Nelson et al., (1983) prepared a document that appears to have used fault trees to examine the long-term stability of uranium mill tailings facilities. They included consideration of failure due to: erosion, gully formation, river shift, rip rap weathering, and differential settlement. Steffen O., (1987) suggested that well established probability techniques are adequate in providing a reliable measure for dam safety and risk minimisation, although Whitman, (1996) noted that probabilistic methods do not replace traditional tools, but can supplement them. Gordon McPhail, (2015) focused on prediction of geometry of the flow slide that may result from the dam break (flow volume, breach width, rheological characteristics of the tailings…) due to better understanding of TSFs risk. Xin et al., (2011) did detailed study of tailings dam break risk assessment and established the tailings dam stability assessment index system and applied the set pair analysis to assessment the stability of the tailings dam.

As it can be concluded risk assessment of TSFs is very important subject in mining industry. Identified risk can assist engineers in formulating the problems and preventing future failures.

One of the largest TSFs in Serbia is TSF Veliki Krivelj, which is located at about 5 km from Bor (Fig. 1A). This facility was created by damming the Krivelj River valley. It was divided into 2 independent fields. Field 1 was formed by damming the valley with initial embankments, the upstream embankment 1 and the downstream embankment 2. Field 2 was formed by a downstream extension of the TSF and the construction of the downstream embankment 3.

Mining operations commenced in Field 1 and continued from 1982 to 1990. After that the works moved to Field 2 where mining terminated by 2008, at which point Field 1 was reactivated (Fig. 1B).

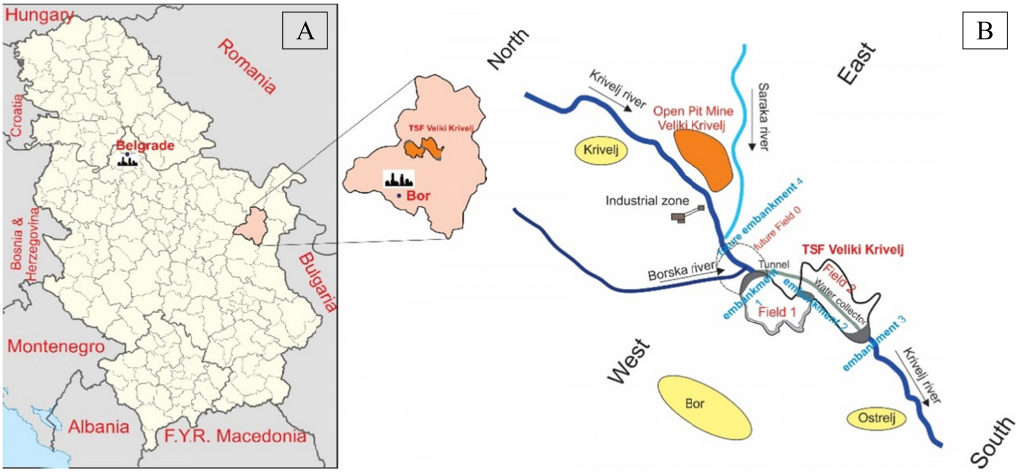

Fig. 1 Map of Serbia with the location of the TSF Veliki Krivelj (A), Layout of TSF Veliki Krivelj (B)

The area of Field 1 is approximately 179 ha, the embankment height presently reaches 120 m, and up to this point, about 137 million tons of tailings have been disposed of in the TSF, occupying a volume of about 101 million m^3. Currently, the available storage capacity in the TSF is about 9.5 million m^3, while the quantity of free water in the tailings settling pond amounts to 2 million m^3.

Bearing all these facts in mind, it is of crucial importance to recognize all the risks involved with its operation and management.

So, the aim of this paper is to:

- Identify all irregularities associated with the operation of the TSF,
- Rank potential risk, and eventually
- Evaluate how tolerable determined risk rank is, as contribution for taking the appropriate measures for mitigation and elimination.

Similar investigation was conducted by Zivkovic et al. (2014) and the risk of TSF Veliki Krivelj was evaluated as insignificant to medium. Also, Lekovski et al., (2013) concluded that TSF Veliki Krivelj is a great threat to surroundings, in general, because of its irregularities such as damaged collector, although risk assessment wasn't the subject of the paper.

The contribution of this paper would be realistic hazard analysis and assessment of risk associated with the operation of the TSF Veliki Krivelj according to updated information about facility condition, since elevation of TSF at Field 1 was done in meantime (MMI Bor, 2016).

2. Risk assessment methodology

The methodology used in this paper in order to simplify and clarify the risk assessment process consists of establishing a hierarchy of hazard control steps, according to the model set by Robertson, (2012):

1. Identification of the most important potential failure scenarios at the TSF and assigning likelihood;
2. Identification of failure consequences and assigning severity;
3. Ranking of risks and assessment of their acceptability;

To be more precised, risk assessment is carried out according to the "Failure Modes and Effects Analysis" (FMEA) method in combination with a risk matrix, which includes a detailed elaboration of potential failure scenarios at the TSF and analysis of consequences that failures can cause, through steps mentioned above.

2.1. Identification of potential failure scenarios

A legitimate method used to predict possible failure scenarios at TSFs is the analysis of historical cases and statistical inference based on available data (Clemente et al., 2013).

An extensive analysis of recorded failures at waste disposal sites (ICOLD, 2001) was used to define three failure scenarios at the TSF Veliki Krivelj:

1. *Seismic hazard scenario,* considers dynamic loading as the failure trigger,
2. *Hydrologic hazard scenario,* considers the inflow of large amounts of atmospheric precipitation as the failure trigger, and
3. *Hydro-technical hazard scenario,* considers that the irregularities in the hydraulic structures built at the TSF represent a failure trigger.

Categories of likelihood of every single failure scenario is assigned on the base of objective assessment, like it is suggested in the table 1. Interpretation of likelihood categories is adopted from Xin et al., (2011).

TABLE 1

Categories of likelihood

Likelihood category	Interpretation
High	TSF break at any time
Moderate	Safety facilities exist serious hidden trouble, if not timely treatment will lead to TSF break
Small	TSF meet the basic conditions for safe production
Negligibly small	TSF fully equipped with the conditions for safe production

2.2. Identification of failure consequences

The particularity of this risk assessment is in its deviation from the template, but it is not an unusual recourse in risk assessment to evaluate separately the hazard likelihood and the severity of consequences. In this regard, the severity of consequences was evaluated according to the estimated hazard likelihood. Consequently the hazard scenarios with low likelihood of occurrence may not have high consequence severity, which means that their overall risk cannot be high.

Categories of consequences are slightly modified and adopted from Mill, (2001), like it is shown in the table 2.

This paper analyzes all the potential consequences to: a) local population (human loss, protests, reputation), b) environment (pollution of water, air and soil), and c) infrastructural facilities (damage, destruction, collapse).

TABLE 2

Categories of consequences

Consequences severity	**Interpretation**
High	Considerable damage to traffic route, dam or comparable facility, environmental values or property belonging to others than the dam owner. Potential for loss of human life or serious injury
Moderate	Severe damage on important traffic route, important dam or comparable facility, or to significant environmental values. Major damage to economic values. Small potential for loss of human life or serious injury
Low	Small/negligible potential for damage to traffic route, dam or comparable facility, environmental values or property belonging to others than the dam owner. Negligible potential for loss of human life or serious injury
Negligible	

3.1. Risk ranking

A risk matrix, a tool used in this paper, allows the determination of risk factors obtained as the product of two parameters: the likelihood of risk and the severity of the consequences. By applying matrix 4x4 with weight factors (Table 3), and after a detailed analysis and quantification likelihood of potential failure scenarios, and severity of the consequences that the failures can result in, it is possible to rank risk of every failure scenario separately according to the values given in Table 4.

TABLE 3

The 4×4 Risk Assessment Matrix

		Consequence severity			
		High (4)	**Moderate (3)**	**Low (2)**	**Negligible (1)**
Likelihood	**High (4)**	16	12	8	4
	Moderate (3)	12	9	6	3
	Small (2)	8	6	4	2
	Negligibly small (1)	4	3	2	1

TABLE 4

Risk rank

Total risk factor	Risk rank
0-2	I (Negligible)
3-5	II (Low)
6-8	III (Moderate)
9-12	IV (High)
13-16	V (Extreme)

The idea for risk ranking by obtained risk factors is adopted and set up based on ICOLD model (ICOLD, 2010), whereat assessed risk factors included in hydro-technical failure scenario are summed into one, since it is composed of multiple potential irregularities, unlike seismic and hydrologic failure scenarios.

3. Results and discussion

Due to the fact that active waste disposal sites pose a far greater potential hazard than the inactive ones and that 90 % of all recorded failures at industrial waste disposal sites in Europe and 95% in China occurred during their active, operating lifetime, this paper considers only the risks associated with the currently active Field 1. (Davies et al., 2000; Rico et al., 2008a; Wei et al., 2012; Bowker et al., 2015).

3.1. Identification of Potential Failure Scenarios at the TSF Veliki Krivelj

3.1.1. Seismic hazard scenario

Failures at waste disposal facilities generally occur due to faulty designs, omissions or inadequate management; namely, unexplained circumstances that cause failures do not exist because every event is predictable, except for earthquakes, whose time of occurrence is still not fully predictable (Martin et al., 2002). For this reason, when waste storage facilities are designed it is always necessary to take into account the potential seismic hazard.

According to the seismic hazard maps in Serbia (Radovanovic, n.d.) for the return period of 475 years (Fig. 2), Bor has never been the epicenter of major earthquakes and this region belongs to the macroseismic intensity scale that ranges between VI and VII degree, according to EMS-98. The earthquakes of this intensity are denoted as “Slightly damaging“ to “Damaging“. Possible consequences are referred to as moderate to noticeable damages to buildings creating consternation and fear in exposed individuals (Seismological Survey of Serbia, n.d.).

Bishop and Janbu methods were used to calculate the stability of the TSF (Table 6). Input data are shown in Table 5 and land profiles are shown in Figure 3.

After comparing these results it is possible to infer that the factor of safety obtained for dynamic loading is within the prescribed values, which confirms the stability of the TSF Veliki Krivelj in case of possible earthquake events (Institute for Standardization of Serbia, 1980; MMI Bor, 2016). Therefore, the likelihood of seismic hazard scenario is negligibly small, according to the table 1.

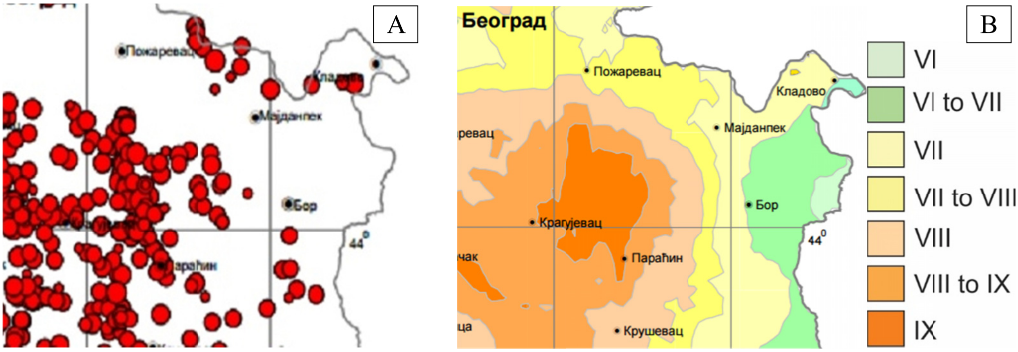

Fig. 2. A: Epicenters of the largest earthquakes in Serbia in the period 1456-2012, B: Seismic hazard in Serbia for the return period of 475 years

TABLE 5

Material parameters adopted for stability calculation

Layers	Cohesion, kN/m^2	Internal friction angle,°	Bulk density, kN/m^3
Sand	0	25	19
Silt	0	23	18
Alluvium	20	30	26
Paleo-relief	150	27	25

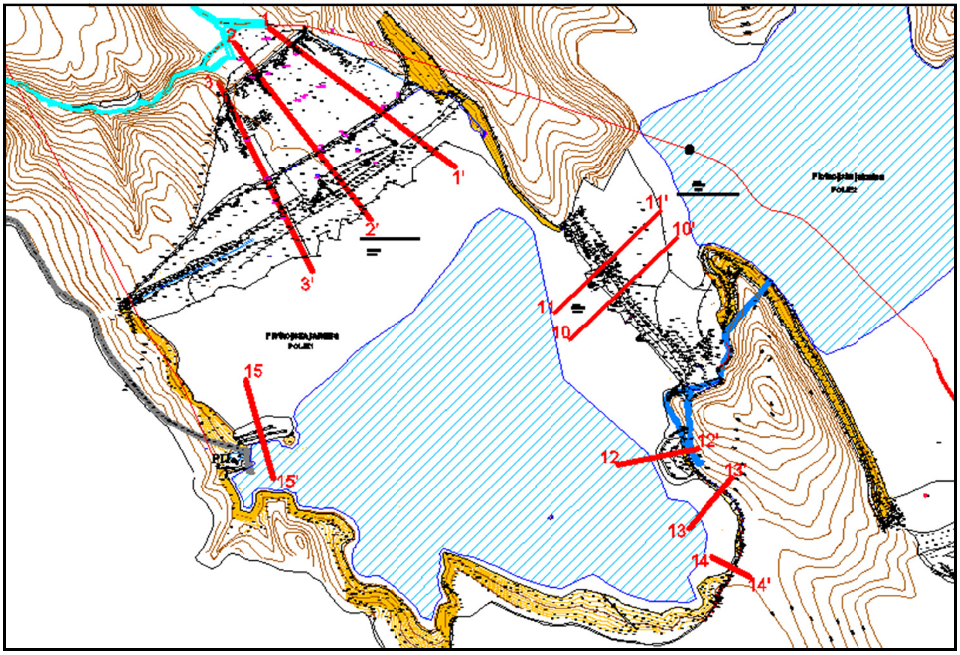

Fig. 3. Field 1 – TSF Veliki Krivelj with land profiles and corresponding stability calculations

TABLE 6

Stability calculation results – dynamic loading

Profile	Fs, acc. to Bishop	Fs, acc. to Janbu	Allowable Fs according to local standard
1-1'	1,226	1,216	>1,0
2-2'	1,203	1,175	
3-3'	1,442	1,421	
10-10'	1,169	1,104	
11-11'	1,152	1,056	

3.1.2. Hydrologic hazard scenario

When it comes to stability of tailings storage facilities, the basic rule is to resolve operations management and water control methods. Water represents potential energy that may, under unfavorable conditions, endanger the stability of the entire structure, instigate its collapse and threaten the environment (Knezevic et al., 2014). According to (ICOLD, 2001) the analysis of more than 200 recorded TSF failures showed that inadequate or insufficient control of water is one of the most common causes of failures often resulting in overtopping dam crests.

The retention space designed for Field 1 has the capacity to intercept extreme precipitation and water from the catchment area with about 7.2 million m^3, and a freeboard height of 5 m.

Table 7 (JCI, 2015) presents different likelihoods of occurrence, the numerical values of maximum daily precipitation at hydrologic stations located in TSF surroundings, which are at approximately the same altitude as the TSF.

TABLE 7

Maximum daily precipitation for different likelihoods of occurrence

Hydrological station	Altitude, m asl	Maximum daily precipitation, mm, for different likelihoods of occurrence		
		0.01%	0.1%	1%
Brestovacka banja	350	265.5	175.6	112.3
Josanica	360	262.3	181.6	120.2
Podgorac	370	156.0	119.3	87.4
Vlaole	400	189.7	142.7	103.5

The watershed of Field 1 occupies an area of 356 ha (MMI Bor, 2016), so in the worst-case scenario, 945.180 m^3 of water would drain into the region contoured as Field 1, which is the case of soil completely saturated with water with no vegetation. If this amount of precipitation is compared with the available retention area of 7.2 million m^3 it can be easily concluded that there is sufficient space to collect all the precipitation from the watershed, even if drainage and free-water evacuation systems are not in operation.

In general, Bor and its surroundings belong to areas where showery precipitations with the outflow of large amounts of water are rare, which is due to the downwind (leeward) position of this area (Lilic, 2015). Therefore, the likelihood of hydraulic hazard scenario is small, according to the table 1.

3.1.3. Hydro-technical hazard scenario

Defects and irregularities of hydraulic elements and structures at TSFs can cause its geotechnical instability, which would necessarily lead to environmental hazard. Many recorded failures and accidents have been the direct result geotechnical deficiencies (Davies, 2002).

When it comes to the TSF Veliki Krivelj, according to recommendations (Knezevic et al., 2014) the following hydro-technical irregularities were analyzed:

1. Freeboard: a) Lower than required – causing embankment instability, b) higher than designed – causing problems with tailings slurry discharge, c) Malfunctioning of hydro-cyclones – causing inadequate separation of silt fractions and hydro-cycloned sand;
2. Damaged drainage system: a) Plugging/blockage – causes embankment damping, b) Sinking– causes embankment damping, c) Physical damage – causes embankment damping;
3. Damaged flow-regulating tunnel: a) Damage caused by the chemical effect of water – leading to breakthrough of flotation tailings, b) Damaged structural elements – resulting in leakage of flotation tailings through cracks, c) Backfilling – endangers the environment and lake formation by interrupting the river flow;
4. Increased amounts and elevated levels of water in the tailings pond: a) Sinking of the mobile barge pumping station – results in an increased level of the tailings pond, b) Pump operating problems – results in an increased level of the tailings pond, c) Inadequate position of the lake in relation to the embankment – causes embankment damping;

In a well-designed and properly managed industrial waste disposal facility, all the previously listed elements entail a low to moderate likelihood of failure occurrence. Only negligence or incompetence in the performance of works is likely to increase the likelihood and therefore the risk (Knezevic et al., 2014).

The analysis and evaluation of the likelihood of failure, according to the table 1, due to each of the above listed potential irregularities at TSF Veliki Krivelj shows the following:

1. The freeboard, i.e. the difference between the height of the dam and the water level in the tailings pond, is adequate, so the likelihood of failure is low.
2. A total of 20 hydrocyclone batteries operate at embankments 1 and 2, that is, 10 batteries at each embankment. It has been noticed that some batteries provide a lower solids content in hydrocyclone sand than required (65%). The grain-size of hydro-cycloned material is not always satisfactory. This anomaly, if not prevented on time can eventually lead to embankment instability. The likelihood of failure occurrence due to hydrocyclone malfunction or faulty operation is low.
3. At embankment 1 there are 2 drainage systems, and the lower drainage system was noticed to function poorly, while the upper drainage system is out of operation and it is practically impossible to restore it. This situation causes the elevation of seepage water levels, erosion on the outer slope and therefore embankment instability (Fig. 5). The likelihood of failure due to drainage system malfunctioning is high.
4. The tunnel that conducts the flow of Krivelj River alongside Field 1 has been repaired and presently it is in a relatively good condition. In continuation, passing directly through Field 2, the tunnel conducts the river flow through a water collector that has been repaired repeatedly, but it is still in poor condition and represents the weakest point in TSF surroundings. A rather serious failure of the collector would provoke the sinking of the tunnel section and of the retention area upstream of the tunnel. This would not have

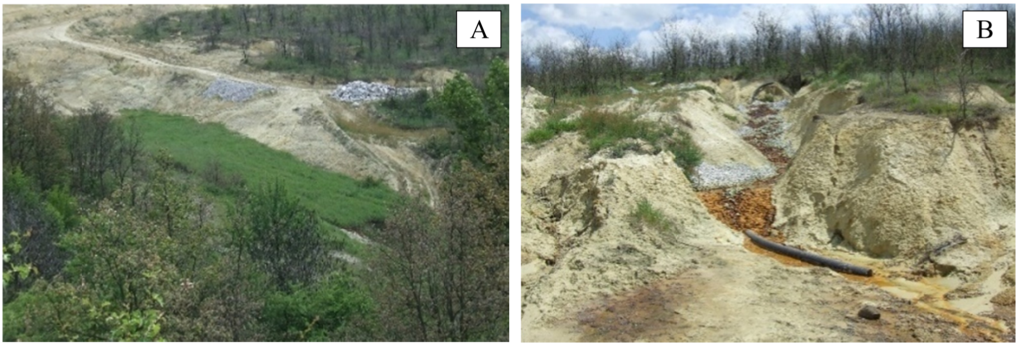

Fig. 5. A specific phenomenon occurring at the outer embankment slope 1: (A) lush grass in the humid zone, (B) gully formed by water discharged due to non-functional drainage

a direct impact on the functioning of Field 1, but since it would jeopardize and disrupt the operations at the open pit mine it would pose an indirect threat to Field 1. The likelihood of failure occurrence is moderate.

5. In the tailings pond at Field 1, there is generally an excess of water jeopardizing the stability of the embankment 1, due to elevated levels of seepage water (MMI Bor, 2016). This anomaly is attributed to poor functioning of the drainage system and frequent breakdowns of the pumping system. The likelihood of failure occurrence is moderate.

Taking into account the highest estimated likelihood of failure due to the above listed irregularities, it is possible to conclude that, as per the hydro-technical hazard scenario, the overall likelihood of failure is moderate to high and compared to the other two scenarios this is the least favorable.

3.2. Identification of failure consequences at the TSF Veliki Krivelj

Before we analyze the consequences, in order to assess more realistically their scope and significance, it was necessary to predict the quantity of tailings slurry that would be discharged by overflow and the slurry travel distance.

Unlike water storage dams, in which in the event of dam break, almost the entire amount of water is discharged, when it comes to embankment failures at industrial waste dumps, almost the entire quantity of solid material remains in the storage space, due to the viscous nature of waste, the travel distance is shorter, but the flood waves can be up to 6 m higher (Rourke & Luppnow, 2015; Jovanovic, 1997).

There are numerous data bases and analyses of recorded accidents and failures at industrial waste dumps in Europe and the world (ICOLD, 2001; Wise Uranium Project, 2014; Rico et al., 2008a; Rico et al., 2008b; Jeyapalan et al., 1981; Lucia et al., 1981; USCOLD, 1994; Azam & Li, 2010). Based on all these analyses, on the average, the amounts of discharged tailings slurry range from 20 to 40% of total deposited amounts (Azam & Li, 2010; Lucia, 1981; Jeyapalan et al., 1981), while the range of discharged amounts slurry of goes from 1 to 100% (ICOLD, 2001; Wise Uranium Project, 2014).

If one takes into account the most commonly quoted approximation (Rico et al., 2008b) asserting that at embankment failures, about 30% of total deposited waste spills out, this means that in case of the TSF Veliki Krivelj even 30.6 million m^3 of tailings slurry could be discharged.

A total amount of 137 million tons of (dry) tailings is deposited in the TSF. The bulk density of tailings being deposited is 1.35 t/m^3, and the average porosity reaches 50%, which gives the total amount 50.7 million m^3 of water trapped in the pores. The solid to liquid phase ratio within the storage area is 102:53 or 1.94:1, which means that the average density of materials in the TSF is approximately 66% solids (by volume). It is obvious that slurry of this concentration cannot flow freely. Clearly, the water trapped in pores cannot drain out, so if we adopt the worst-case scenario implying that this is all free water from the tailings pond (about 2 million m^3) and 1/3 of trapped water, it makes about 18.9 million m^3. For assessment Rico et al. (2008b) it remains 11.7 m^3 of solid tailings, which gives the solid-to-liquid ratio of 11.7: 18.9 = 0.62: 1, i.e. the volume percentage of solid phase would be about 37.5%. This density is high for the free flow of tailings slurry, but this is only the average density value. At first, water, with a small percentage of solid phase, will start flowing, followed by the suction effect and a constant increase of inclination towards the exit, and so the discharge of 30.6 million m^3 of water and tailings is considered as the worst-case scenario.

With regard to tailings slurry travel distance after discharge it is very difficult to determine how far it will "advance" in the event of failure. For this purpose, we used a simple qualitative assessment method called Zone of Influence. The Zone of Influence is the area that could be affected by the slurry flood wave. The limits of this zone for TSF shall be determined as follows (Blight, 2009):

- Upstream from any point of embankment perimeter, up to the distance of 5 × H from embankment toe (where H is the total planned height of the embankment), *i.e. about 0.6 km*,
- Within the plane parallel to ground slope – a distance of 10 x H from embankment toe, *i.e. about 1.2 km,*
- Downstream from the lowest point of embankment perimeter, distance greater than 100 × H, *i.e. 12 km,*
- 2 × the steepest ground slope (%) measured 200 m from the lowest embankment point, multiplied by the height of the embankment, where the minimum distance is 0.5 km, and the maximum is 6 km, *i.e. 0.96 km.*

Figure 4 presents the so-determined Zone of Influence at the TSF. Based on formerly defined rules for the determination of boundaries, and in accordance with the altitudes of the surrounding terrain it is possible to anticipate the flood wave route. These considerations also take into account the possibility of uncontrolled release/spill of slurry over embankment crests.

In the event of breach or slurry spillage over the crest of embankment 1, the flood wave would practically take on the one-dimensional model of movement and would necessarily reach the Open Pit Mine Veliki Krivelj. Since the mine site is located at a lower altitude than the TSF (Fig. 5), and considering the low resistance of the land relief, across which the flood wave is moving, the wave would eventually flow into the mine site.

The mine currently employs 554 workers organized in three shifts, of which 300 employees work in the first shift. This number includes workers engaged in drilling, blasting, mining and transport operations, as well as the workers who are not directly exposed to risk, such as those who are employed in the dispatch center and in equipment maintenance. According to Graham's

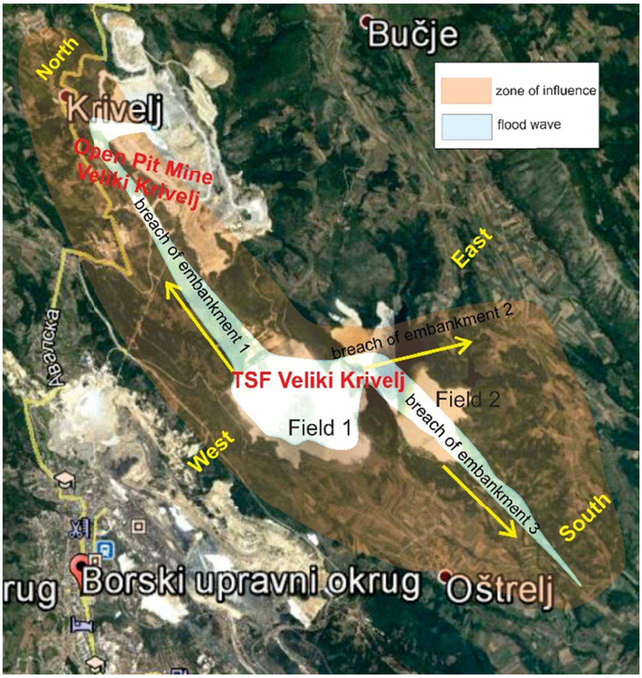

Fig. 4. The Zone of Influence at the TSF Veliki Krivelj

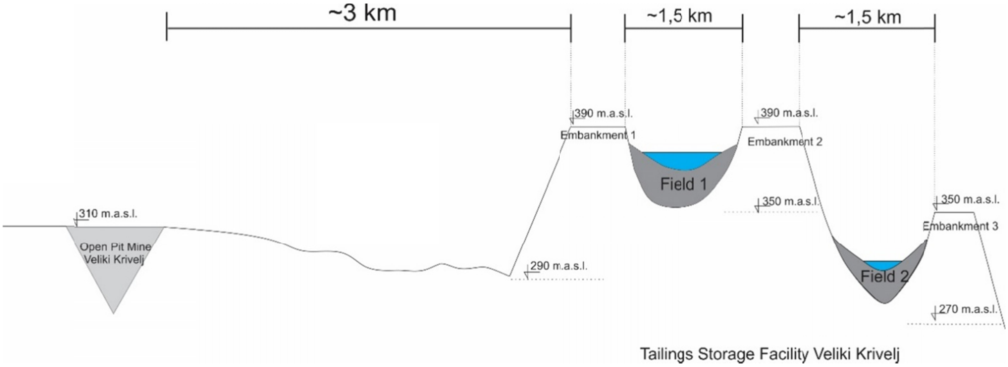

Fig. 5. Position of the TSF Veliki Krivelj relative to the Open Pit Mine Veliki Krivelj (not to scale)

method (Graham, 1999), if we adopt that the severity of the flood wave is low, that the warning to the people exposed is issued on time (15 to 60 min), and that the severity of the flood wave is fully understood the mortality rate ranges from 0-0.004. This means that if the slurry flood wave flows into the open pit mine, in the worst-case scenario there would be one human casualty. The time indicated for warning is sufficient to evacuate small machinery from the mine, but damage will be caused to heavy machinery, since the time for its evacuation is over 60 minutes, like for example for excavators, but only if they are located at the lowest benches. In any case, mining operations at the open pit would be temporarily suspended, which implies certain material losses for the entire company.

In the event of such a disaster, particular problem would be the creation of a high flood wave composed of tailings from the Field 1 (Jovanovic, 1997), in which case, only water with some traces of tailings would flow into the mine, and most of the tailings would remain close to the embankment, constantly threatening to block the entrance to the Krivelj River Tunnel or to provoke the plugging of the tunnel/or collectors. In this case the mine would be particularly endangered, since it would be continuously flooded with water from the river.

In the event of breach or slurry spillage over the crest of embankment 2, the flood way can be analyzed by considering two different cases. In the first case, the damage would be small because of the short travel distance of the flood wave, which would flow into the inactive Field 2, with enough capacity to take it in completely. The impact of this scenario is negligible and there are practically no environmental consequences since the wave would be immobilized. In the second case, the Field 2 would not be able to take in the entire quantity of discharged tailings slurry, or the strength of the flood wave would be so great as to cause breach or spillage over the crest of embankment 3, which contours downstream the TSF. In any of these cases the wave would not affect residential areas but it could cause some environmental damage.

Generally speaking, the quality of soil in this area is very poor, which is the consequence of air pollution generated by copper ore processing plants and dust emissions from the mine, overburden disposal sites and tailings storage facilities, which mainly affect its surface layers (Faculty of Mining and Geology, 2010). The agricultural areas that surround the TSF from the south are in fact damaged clay soil, the use of which is possible only after implementing land amelioration measures (Antonovic et al., 1974).

Potential air pollution from tailings slurry discharge is mainly set off by dispersion of waste fines from dry, crusty surfaces under the influence of wind. The effects will not be apparent immediately after the discharge of tailings slurry, but after some time, when the material starts to dry, it is very likely that under certain conditions the fines will be dispersed to great distances, far from the point of discharge. The effects of this type of pollution are limited.

The Krivelj River is an endangered perennial stream. If its tunnel or collectors were damaged during TFS failure, this could have an adverse impact on surrounding watercourses. Considering that water is the biggest transport medium all the local impacts could become regional. According to (Lekovski et al., 2013), the concentration of tailings pollutants in Krivelj River immediately following the breach would amount to 64.62%. The water quality of this river has not been categorized, but in practice, it is safe to assume that it corresponds to Class III water quality standards. The results of chemical analyses of water samples from Krivelj River indicate its current pollution level (Faculty of Mining and Geology, 2010). This river belongs to the Black Sea watershed and indirectly it affects the Danube River. However, bearing in mind the negative impact of a decades-long mining in this district and considering that the water quality of the permanently polluted stream Saraka that flows into the Krivelj River is practically equal to acid mine water (Bogdanovic et al., 2013), it is clear that the already existing damage to this aquatic ecosystem would be only slightly increased.

In this area there are no protected natural resources or immovable cultural heritage. Therefore, damage would be caused to the local roads used for mining machinery.

This type of failure would certainly give rise to protests and create general fear among the local population, undoubtedly compromising the reputation of the Bor Mining and Smelting Company.

If likelihood categories are taken into account, concequences severities are, according to the table 2, adopted as follows:

- Seismic hazard scenario – Negligible consequences;
- Hydrologic hazard scenario – Small consequences;
- Hydro-technical:
  - Freeboard – Negligible consequences,
  - Malfunctioning hydrocyclones – Negligible consequences,
  - Malfunctioning drainage system – Small consequences,
  - Tunnel sinking – Negligible consequences,
  - Excess water in the tailings pond – Negligible consequences.

3.3. Risk ranking

Since risk is the product of the likelihood of occurrence of an event and the consequences arising from that event (Robertson, 2012), the risk factors needed for ranking are obtained by multiplying the numerical values adopted for likelihood and consequence categories qualitatively described in the matrix, table 3. After that risk is ranked according to the values given in Table 4.

The obtained risk factors for every failure scenario at TSF Veliki Krivelj by methodology described earlier, are shown in Table 8.

We can acknowledge that there is always a risk involved, but its acceptability is changeable and adaptable. If we analyze the acceptability of risk according to the modified "As Low As Reasonably Practicable" (ALARP) diagram the seismic hazard scenario at the TSF Veliki Krivelj can be classified as a broadly acceptable risk (Fig. 6), which respectively results in a negligible risk ranked with 1. As for the hydrologic hazard scenario the risk is slightly higher, and with factor 4 and rank 2, it belongs to conditionally acceptable risks.

TABLE 8

Risk quantification

Hazard scenario		**Quantification**		**Risk factors (L x C)**		**Risk rank (according to table 4)**
		Likelihood (L)	**Consequences (C)**			
Seismic		1	1	1		I (Negligible)
Hydrologic		2	2	4		II (Low)
Hydro-technical	Freeboard	1	1	1	12	IV (High)
	Malfunctioning hydrocyclones	1	1	1		
	Malfunctioning drainage system	3	2	6		
	Tunnel sinking	2	1	2		
	Excess water in the tailings pond	2	1	2		

As previously established the hydro-technical hazard scenario is the least favorable, with the highest risk factor (12) it was ranked as high, conditionally acceptable risk (4). The risk with such ranking can easily pass into the category of unacceptable risks, if adequate measures are

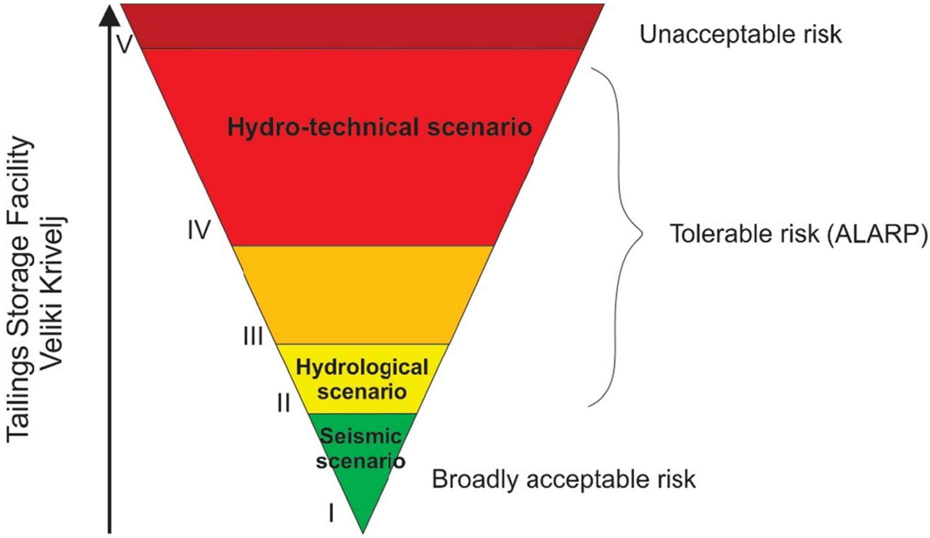

Fig. 6. ALARP diagram (David & Wilkinson, 2009)

not taken. More specifically, the hydro-technical hazard scenario, due to which the operations at the TSF may seem unacceptable, is the result of the poor functioning of the drainage system at embankment 1. This situation can cause the increase of seepage water levels and consequently the instability or ultimately embankment failure or break.

It is important to emphasize that only usual kind of irregularities as source of failure are considered in this paper. This paper is limited to the assessment of the liquefaction because of the lack of relevant information and complexity of that kind of study.

4. Conclusion

The assessment of risks associated with the operation of the Tailings Storage Facility Veliki Krivelj is crucial to ensure the preservation of all aspects of safety and environmental protection. In order to assess the risks as realistically as possible, three potential hazard scenarios are analyzed: seismic, hydrologic and hydro-technical. After determining the potential quantity of discharged tailings slurry and its travel distance it was possible to evaluate the hazard consequences.

Once the likelihood of failure and the severity of consequences are identified according to the table 1 and 2, it is estimated that the operation of the TSF Veliki Krivelj has a negligible risk in terms of seismic hazards, when it comes to hydrologic hazards the risk was estimated as low, but according to the hydro-technical hazard scenario the risk was evaluated as high. Analyzing which aspects of its operation carry the highest risk and can easily pass into the category of unacceptable risks, according to ALARP diagram, it can be concluded that malfunctioning of the drainage system at embankment 1 plays the most important role in this. Risk assessment represents a good method to draw attention in a transparent way to any deficiencies in the TSF Veliki Krivelj, with a view to taking adequate protective measures against all environmental hazards.

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