Contribution to the increase of the hydrological safety of tailings dams

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ABSTRACT

The tailings dams are created by deposition of tailings from the flotation process in the mines. On one hand, the tailings dams fall into the category of civil engineering structures with highest potential risk for the downstream river valley. On the other hand, mining is one of the most important industrial branches worldwide, which means that tailings dams will be present in the future. Tailings dams are complex hydraulic structures that should be checked for the following types of safety: hydrological, seepage, static, seismic, ecological, sociological and economical. The hydrological safety should be provided in the exploitation stage (by using variable reserved storage in the lake) and in the post-exploitation stage (by applying permanent spillway structure). To verify the hydrologic safety a routine approach is not applicable. Instead, the assessment should be adjusted to the tailings dam concept and the flood criterion. The purpose of this paper is to systemize the knowledge gained by researching for an increase of the hydrological safety of the tailings dam Sasa, M. Kamenica, Republic of Macedonia. The specified tailings facility is a cascade system composed of five tailings dams, and the hydrological safety refers to the evacuation of the flood water of Petrova River.

1. BASIC THESIS FOR THE TAILINGS DAMS

The tailings dams are created by deposition of tailings from the flotation process in the ore mines that is being transported by pulp line to the dam site in the appropriate river valley, with sufficient reservoir space. At tailings dam crest, by cycloning of the pulp, the tailings are separated in two fractions. By deposition of the coarser fraction (sand) is created the downstream sand dam. The finer fraction (mixture of water and mud) is discharged in the upstream waste lagoon. In the waste lagoon, during the ore mine service period, a mechanical cleaning is done of the finest particles and chemical treatment of the used reagents, present in the tailings. At one hand, the tailings dams are classified in category of civil engineering structures with highest potential hazard for the downstream river valley. Namely, the eventual tailings dam break would cause rapid and uncontrolled emptying of the waste lagoon, propagation of mud at great distance along the downstream valley, by damaging material goods, endangering of human lives, long-term pollution of the environment and huge losses for the mine industry. On the other hand, the mining is one of the most important industry sectors worldwide as well in Republic of Macedonia.

In Republic of Macedonia there are four active flotation tailings dams, for ore mines Bucim (Radovis), Sasa (M. Kamenica), Zletovo (Probistip) and Toranica (Kr. Palanka) and two passive tailings for the ore mines Lojane (Kumanovo) and Jugohrom (Jegunovce). The importance of the mine industry in Republic of Macedonia can be seen by official data from the State Statistics Institute of Republic of Macedonia. According to the data for gross domestic product (GDP) in 2011, the industry participates with 18% in the total structure of GDP, where the mine sector participated by 1.5%. According to the data for added value from 2010, the participation of the sector "metal production" is 9.34% within the total industrial production. Therefore, it is not hard to predict the tailings dams in the future will be present as active hydraulic structures in Macedonia.

2. MAIN CIVIL ENGINEERING PROPERTIES OF TAILINGS DAM SASA

The grandiosity of the tailings dams as civil engineering structures is most clearly confirmed by the dimensions of the tailings dams Sasa on river Kamenicka or Saska, in the case of ore mine for lead and zinc "Sasa" – M. Kamenica (in service for period 1966-2003 and restarted in 2006).

The tailings dam Sasa is composed of five tailings dams with waste lagoons: (1), (2), (3-1), (3-2) and (4), placed in cascade along the Saska river valley. All tailings dams are constructed by initial dam and downstream method of construction, as most favorable construction method in seismic active areas. According to the actual state of the tailings dam, tailings dam no. 3-2 is in service, created by construction of the sand dam no. 3-2, with designed final crest elevation at 975.0 masl and waste lagoon with maximal operating elevation at 972.0 masl. For deposition of new quantities of tailings in the future service period of the ore mine, apropos upon fulfilment of the capacity of the existing tailings dam no. 3-2, tailings dam no. 4 is to be constructed. The future tailings dam no. 4 that should be in operation in 2017 is located in the valley of Saska River, directly downstream of the sand dam no. 3-2. The elevation of the operation level of waste lagoon no. 4 is adopted at elevation 950.0 masl, and it will be formed by construction of combined tailings dam with crest elevation of 952.0 masl. The evacuation of the flood of tailings dam Sasa is provided by two water conveyors (Figure 1).

The main water conveyor is the diversion tunnel of Saska River in the right abutment of the valley. The entrance structure of the tunnel is in the bank, upstream of the oldest tailings dam (or most-upstream tailings dam no. 1), and the terminal structure (stilling basin and risberm) will be downstream of the downstream toe of the future tailings dam no. 4. The auxiliary water conveyor is the surface channel in the valley left bank that should discharge the flood water of Petrova River. This river is left tributary of Saska River and it inflows in waste lagoon no. 3-2. The great heights of the five sand dams, as well as the five waste lagoons are placed in cascade along the valley of Kamenicka River, by unique water conveyors for outlet of the external and internal water, are indicating that it is a case of most complex multi-dimensional serial hydro system in Republic of Macedonia.

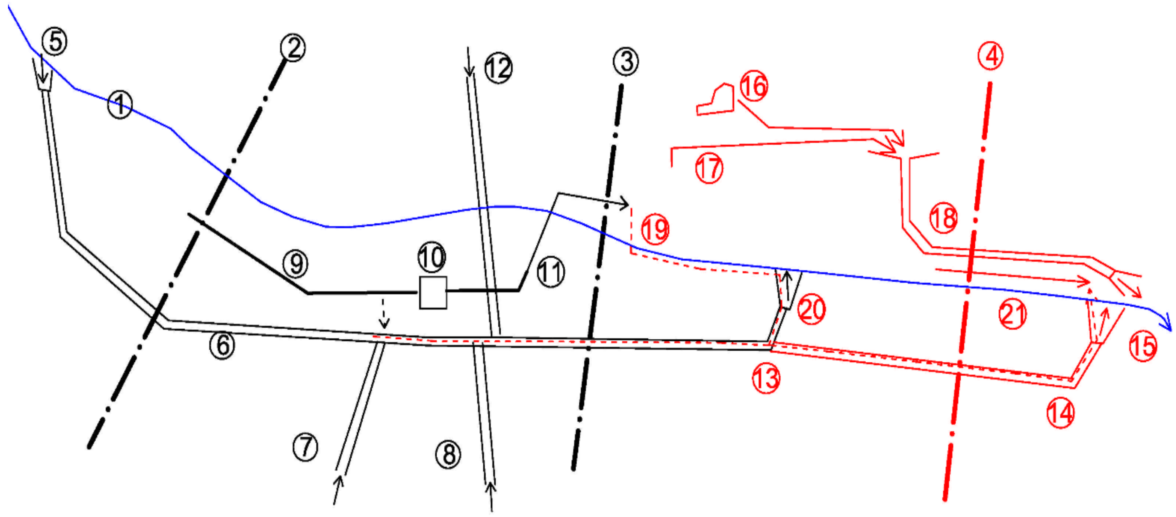

Figure 1. Water conveyors scheme for outlet of the external and internal water from tailings dams no. 3-2 of ore mine Sasa (according to the Basic Design from 2006). (1) Saska river; (2) tailings dam no. 2; (3) tailings dam no. 3-1; (4) tailings dam no. 3-2; (5) entrance structure; (6) diversion tunnel (gallery); (7) spillway collector 5; (8) precipitation collector 6; (9) drainage collector 2; (10) damaged control shaft; (11) drainage collector 3; (12) precipitation collector Velkov Potok; (13) bypass of drainage blanket; (14) section 3-2 from the tunnel; (15) terminal structures of tunnel 3-2; (16) intake on Petrova River; (17) headrace from the lake; (18) precipitation and spillway collector; (19) new section of drainage collector 3; (20) exit from tunnel 3-1; (21) drainage collector

3. SAFETY ASPECTS AT TAILINGS DAMS

The tailings dams are complex engineering structures, composed of initial dam, sand dam, waste lagoon, drainage system, water conveyors for outlet of cleared water and structures for protection in case of external water (averaged or flood water). Due to the great importance of the tailings dams, one of the technical committees within the ICOLD (most influential institution in dam engineering) is the Committee on Tailings Dams and Waste Lagoons. Such committee has issued 11 Bulletins (ICOLD Bulletin 1982, 1989, 1994, 1995, 1996, 2001, 2011, 2013), where are given recommendations on research, designing, construction, maintenance and recultivation of the tailings dams. The tailings dams, due to its purpose and numerous structures of which are composed, should be verified for several types of safety: hydrologic (Brutsaert 2005, Berga & Berga 2015), seepage (Petkovski 2010), static (Petkovski 2006, Petkovski et all 2007), dynamic or seismic (Petkovski & Ilievska 2010, Petkovski & Ilievska 2010, Petkovski et all 2014), operational (Petkovski & Mitovski 2014, Petkovski & Mitovski 2014), environmental (Tanchev 2014), sociologic and economic (Petkovski et all 2014, Petkovski & Mitovski 2015).

The similarities between the tailings and fill (embankment) dams (for creation of water reservoirs) have contributed many procedures, approaches and techniques during research, construction and maintenance of the fill dams to be applied in case of tailings dams. However, numerous reports for accidents at tailings dams in the last 3-4 decades worldwide and also domestic, are leading to the conclusion that structural (static and dynamic), seepage, hydrologic and hydraulic safety procedures were not verified with same severity as for fill dams for water reservoirs. Such fact is partially resulting from the long-lasting construction of the tailings dams by the ore mine companies, where as civil engineering material is used sand obtained by separation of the tailings during service period.

Due to the long-lasting construction period, the approach for conventional dams for verification on the proper completion of the dam with the appurtenant structures by the civil engineering company – are full supervision of the construction, inspection of first reservoir filling (testing at terminal stage) and assessment of the proper behaviour of the dam with the applied parameters, through out comparation with monitoring data, most often is not applied in full in case of tailings dams. Unfortunately, such main difference in the “control mechanism” between the conventional and tailings dams, is amplified by the fact that in the case of tailings dams there is no "bottom outlet" apropos there is no possibility for the hydro system to be placed in safe mode.

The aim of this paper is to systemize the gained knowledge from the research of the improvement of the hydrological safety of the tailings dam Sasa for discharge of the flood wave of the water gravitating towards the waste lagoon. Below in the paper will be illustrated with data from research of the hydrological safety of the hydro system composed of 5 tailings dams along the valley of Saska (Kamenicka) River, in case of flood generated in the in-between catchment area from the entrance structure of the diversion tunnel till the dam profile of the most downstream tailings dam, apropos from the catchment area of Petrova River that inflows in the waste lagoon no. 3-2 (Figure 2).

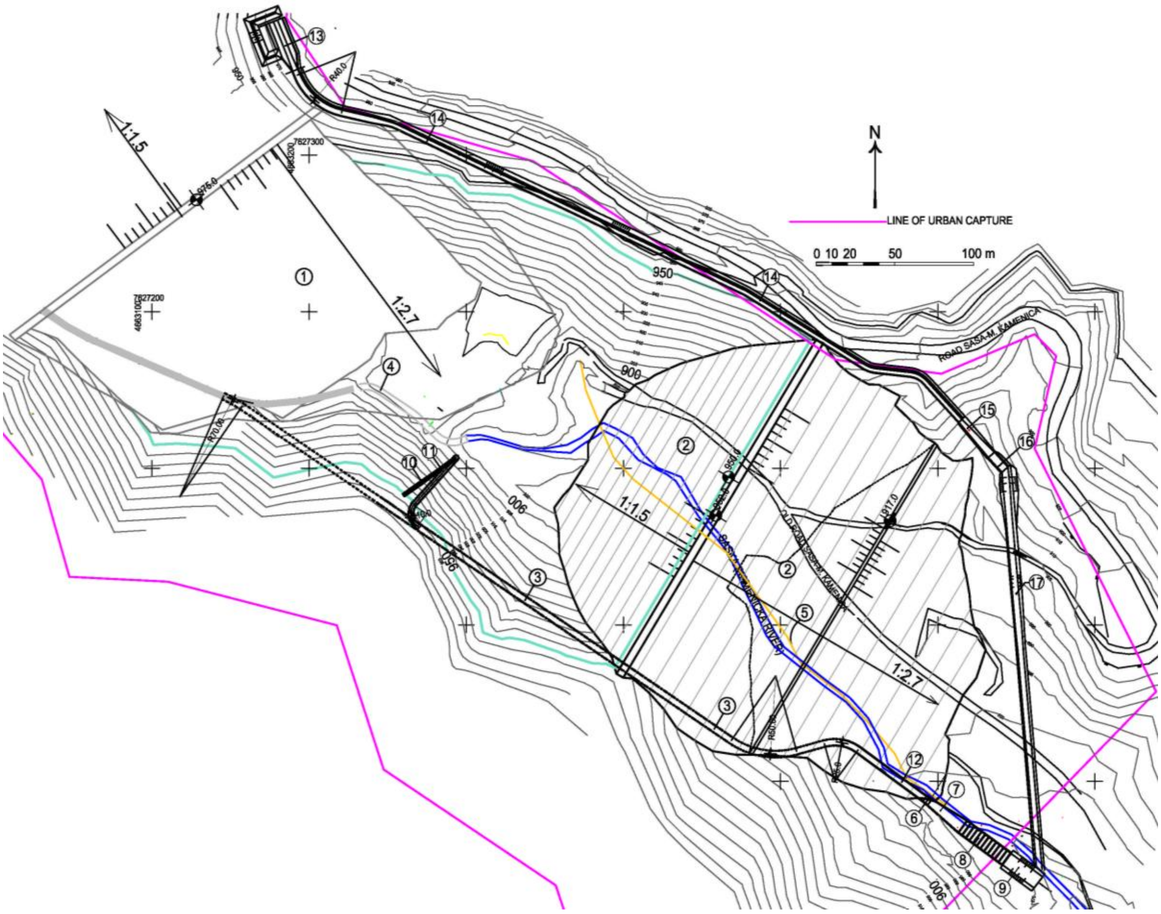

Figure 2. Scheme of the layout of the side channel in tailings dam no. 3-2 and chute downstream of the tailing dam no. 3-2 and no. 4, for discharge of the water from Petrova River. (1) tailings dam no. 3-2; (2) tailings dam no. 4; (3) diversion tunnel for tailings dam no. 3-2; (4) gallery addition for diversion tunnel for tailings dam no. 3-2; (5) drainage collector for tailings dam no. 3-2 and 4; (6) transition of gallery to channel; (7) chute; (8) stilling basin; (9) risberm; (10) collector for cleared water; (11) horizontal tunnel for joint of collector for cleared water with tunnel; (12) gallery addition for diversion tunnel for tailings dam no. 4; (13) side channel of side-channel spillway; (14) chute for Petrova River; (15) roller bucket of chute for Petrova River for tailings dam no. 4; (16) erosion pit; (17) channel downstream of the erosion pit

4. FLOOD PROTECTION IN CASE OF PETROVA RIVER AT TAILINGS DAM NO. 4

The evacuation of the flood water of tailings dam Sasa is provided by two water conveyors. The main water conveyor is diversion tunnel of Saska River in the right bank of the valley, constructed from the entrance structure in front of tailings dam no. 1 up to gallery no. 3-2 apropos only section no. 4 is to be built. The section no. 4 must be built before the commencement of construction of initial dam for tailings dam no. 4 because this tunnel has also the role of diversion tunnel, purposed for diverting of Saska River during construction of tailings dam no. 4. The catchment area gravitating towards the diversion tunnel entrance is 19.7 km^2. The auxiliary water conveyor is the surface channel in the valley left bank that should take away the flood water from Petrova River. Such river is tributary of Saska River with catchment area of 6.7 km^2 and it inflows in waste lagoon no. 3-2. The side channel spillway and the surface channel bypassing the profile no. 3-2 should be built not late before reaching of maximal operation level of lagoon no. 3-2 apropos elevation 972.0 masl. The surface channel used for bypassing of profile no. 4 should be built not late before reaching of maximal operation level of lagoon no. 4 apropos elevation 950.0 masl. The flood water peak is mitigated in the retention area of lagoon no. 3-2 and the spillway discharge is captured by the side channel of the side channel spillway and through out surface channel is discharged downstream of profile no. 4, and in the terminal part is joined with the diversion tunnel stilling basin.

The hydrologic criteria for dimensioning of the spillway structure of tailings dam Sasa, that must be identical for the both water conveyors, in the previous designs was adopted for return period T=1,000 years (Srebrenovic 1986). Such criteria, during designing of tailings dam no. 3-2 up to elevation 960.0 masl was adopted/inherited in accordance with the technical documentation dating from 1980. At present is actualized eventual upgrading of the spillway structure, in order to achieve improved hydrologic safety of the tailings dam apropos for return period T=10,000 years. The basic aim of the innovated analysis is to determine feasible technical solution for the spillway structure that will provide improved hydrologic safety for outlet of Petrova River (tailings dams no. 3-2 and no. 4) and in same time to estimate preliminary costs for eventual upgrading of the hydraulic structures. Such parameters are required for decision making on the increase of hydrologic safety threshold in case of tailings dam Sasa for discharge of the flood water from Petrova River.

In accordance with the Soil Conservation Service, USA (SCS 1971, SCS 1986) the formulation of the Synthetic Hydrograph Method, on determination of the flood water, the initial loss (humidity deficit) equals to:

$$I = 5.08 \cdot \left(\frac{1000}{CN} - 10 \right) \cdots\cdots [mm]$$

The cumulative surface discharge (or effective rainfalls) R(t) for time t, in dependence of the total cumulative rainfalls P(t), equals to:

$$R(t) = \frac{(P(t) - I)^2}{P(t) + 4 \cdot I} \cdots\cdots [mm]$$

So that, all until the cumulative sum of rainfalls is less than the initial loss, apropos $R(t) < I$, it means that the total rainfalls are being infiltrated and surface discharge does not occur apropos $R(t) = 0$. The incremental effective rainfalls r(dt) [mm], for period dt (Figure 3), can be estimated by the series of the cumulative effective rainfalls:

$$r(dt) = R(t) - R(t-dt)$$

The incremental effective rainfalls r(dt) [mm], if approximated in incremental triangle hydrographs for second discharge Q [m^3/s], by time lasting TB [h], in that case for catchment area A [km^2], the peak discharge is Qp [m^3/s]:

$$Q_p = \frac{2}{3.6} \cdot \frac{A}{T_B} \cdot r(dt) \cdots\cdots [m^3/s]$$

By interferential of the incremental hydrographs for the surface discharge is estimated the summary hydrograph for the surface discharge (Figure 4).

The values of the intensive rainfalls (for different time lasting) are taken over from meteorological station Kriva Palanka that is closest station for pluviometry measuring (Shkoklevski & Todorovski 1993). The time lasting of the hydrograph increase Tp, is adopted from chart, matching the regional analysis for catchment area of river Vardar. So, for the left side catchment area of tailings dam no. 3-2, with surface A=6.7 km^2 is adopted Tp(A)=0.7 h Below in the text a calculation is given of the hydrograph of flood water for the catchment area gravitating towards profile no. 3-2, for A=6.7 km^2, Tp(A) = 0.7 h, for rainfalls with return period T=10,000 years.

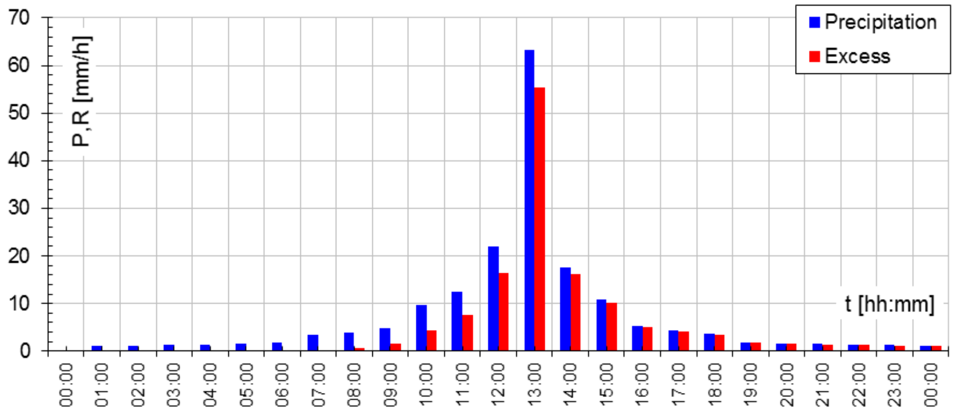

Figure 3. Distribution of the total and effective rainfalls, for time step dt = 1.0 h, for catchment area A = 6.7 km^2, for return period T = 10,000 years

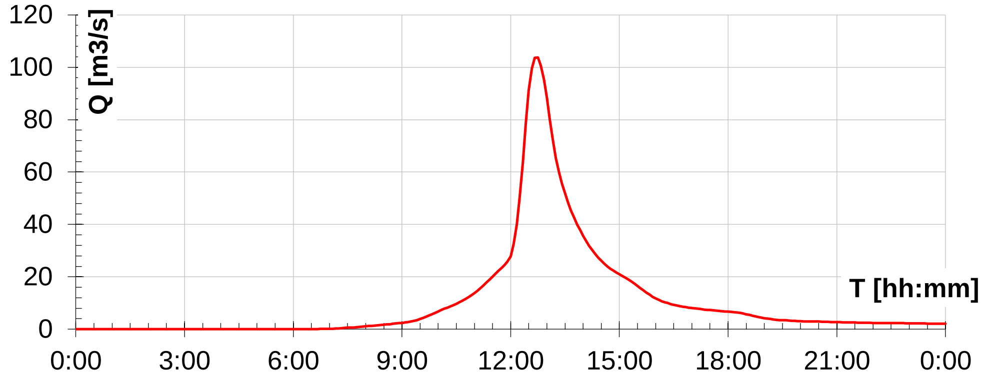

Figure 4. Flow wave with calculation time step dt = 5 min, for catchment area A=6.7 km^2, for return period T = 10,000 years, Qpeak = 103.7 m^3/s, V = 890,200 m^3

The values of the maximal discharges for flood waves with other probabilities of occurrence are presented on Figure 5. To determine the reserved volume in the waste lagoon of the new tailings dam no. 4, it is also required to know the water volume of the flood waves with different probability of occurrence. The flood water volume in case of Petrova River is V = V(T).

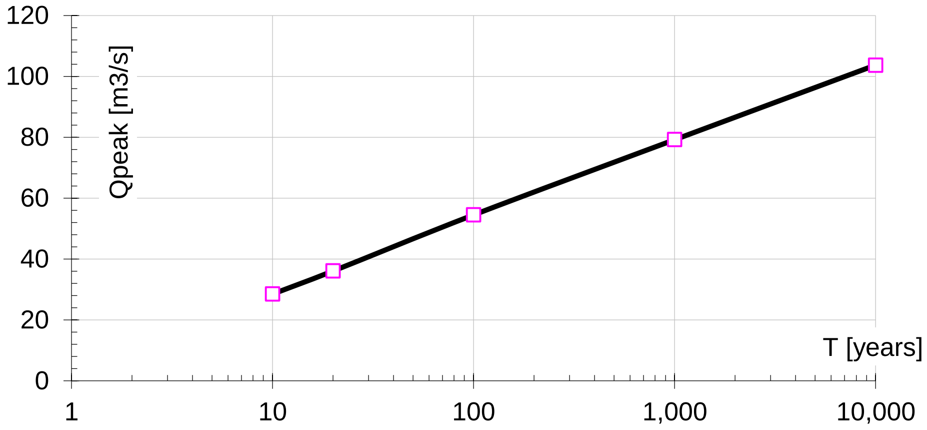

Figure 5. Maximal values of flood water in catchment area of Petrova River with A=6.7 km^2, according to the Synthetic Hydrograph Method

During service of waste lagoon no. 4 the protection in case of flood of Petrova River is possible by the reserved volume for capturing of the flood wave. Here below follows the calculation of the required elevation of the sand dam crest ZPB [masl] – in dependence of the achieved elevation in the waste lagoon ZTE [masl]. In such calculation is adopted reserved freeboard of 1 m above the maximal operating level of the water. Such elevation of the sand dam is obtained by acceptation of the flood wave volume V = V(T), for adequate return period "T", that is kept in the reserved volume of the waste lagoon VR (Figure 6).

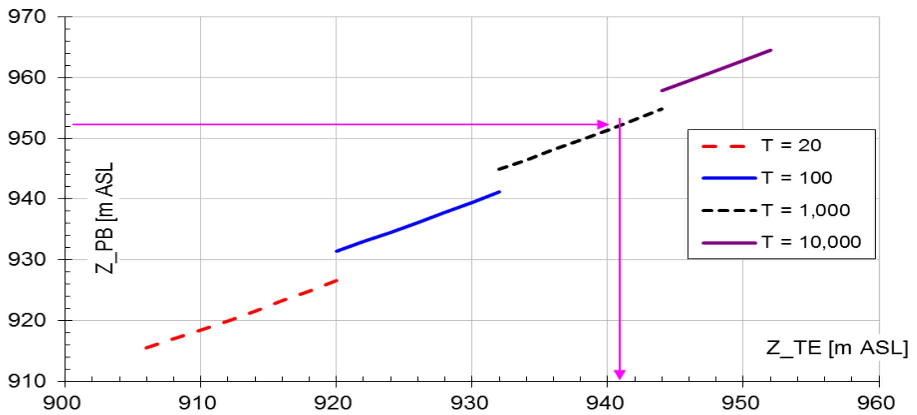

Figure 6. Dependence ZPB = Z(ZTE), by estimation that the flood wave volume V(T) is kept in full within the reserved volume VR, and afterwards is discharged through the openings of the spillway collector for cleared water

By this analysis for various heights of the waste lagoon are adopted various occurrence probabilities for flood water, that in case of different time lasting and damage potential (at eventual break of the downstream dam due to overflow) are providing acceptable hydrologic risk for certain stages of tailings dam exploitation. Before waste lagoon exploitation, by construction of the initial dam at crest 906.0 masl a space is provided for acceptance of the flood wave with return period T= 10 years, as acceptable hydrologic risk for construction of the drainage system below the tailings dam. For first stage, at waste lagoon elevation till 920.0 masl (with included initial dam), is adopted reserved volume in the lagoon to equal the flood wave volume for return period T=20 years. In the second stage, for elevations of the waste lagoon from 920.0 to 932.0 masl (where damages in the downstream valley are greater in case of eventual dam break), is adopted that the reserved volume of the lagoon to equal the flood wave volume with return period T=100 years. In the third stage, for elevations of the waste lagoon from 932.0 to 944.0 masl is adopted that the reserved volume of the lagoon to equal the flood wave volume with return period T=1,000 years. And in In the fourth (final) stage, for elevations in the waste lagoon higher then 944.0 masl (where damages in the downstream valley are greatest in case of eventual dam break), is adopted that the reserved volume of the lagoon to equal the flood wave volume with return period T=10,000 years.,

In the post-service period for tailings dam no. 4 the protection in case of flood water from Petrova River is possible by permanent spillway structure, with included retention capacity of the lagoon. In the analysis of the retention capacity of the waste lagoon for final stage is applied hydrological model – by water balance of the reservoir. By such model is treated the equation of continuity, with neglecting of the dynamic effects of the flow, according to the following equation in discrete shape:

$$Vi+1 = Vi + (Xi + Xi+1)*dt/2 - (Yi + Yi+1)*dt/2$$

In the above equation for two successive time steps i and i+1, for increment dt, where: V is the volume, X is inflow and Y is outflow (spillway and eventual outlet), unknown are values: Vi+1 and Yi+1. Therefore, the equation is transformed in implicit shape, expressed through one variable Hp – spillway height and is being solved by numerical method by acceptable accuracy.

The required spillway length (Lp) of the collection channel of the side channel spillway is adopted to be defined by use of the following two criteria: (a) spillway height (Hp) to be less then 2.0 m and (b) the initial fill in the lagoon (Z1) to be less then 0.5 m in regard of the normal level Zn=Zp=972.0 masl apropos elevation of collector overflow for discharge of the cleared water in the post-service period to be less then Zk=971.5 masl. Namely, during creation of the “beach” in final stage of the tailings dam no. 3-2, it is estimated that the slope of the deposited silt in the lagoon will reach elevation 972.0 masl (in near by of the crest) and it will not go beyond elevation 971.5 masl in near by of the spillway collector. By application of the above specified criteria are obtained results, displayed on Figure 7. The calculated spillway length is Lp=9.2 m, and authoritative discharge for dimensioning of the spillway structure is QmaxPR=51.7 m^3/s, thus obtaining spillway height Hp=2.0 m.

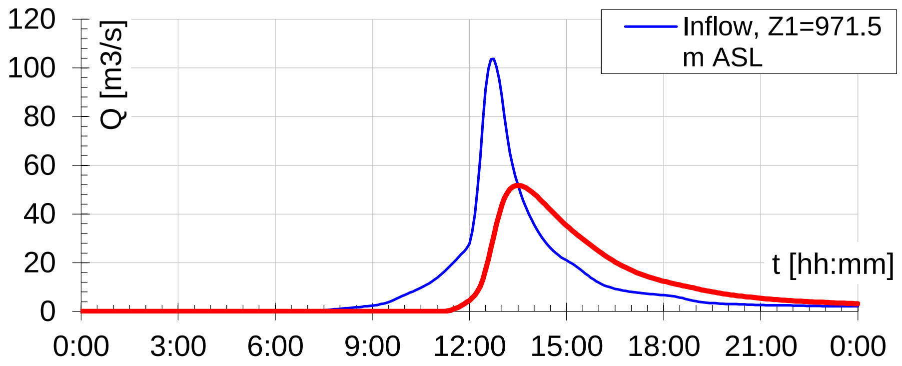

Figure 7. Input and output discharge hydrograph, for spillway length Lp = 9.2 m, for initial elevation fill Z1=971.5 masl, and Qmax=51.7 m^3/s

5. CONLUDING REMARKS ON FLOOD PROTECTION IN CASE OF PETROVA RIVER OF TAILINGS DAM SASA

For protection of tailings dam Sasa in case of flood water from Petrova River, two stages should be treated. The first stage is service period of the tailings dam no. 4, when in case that spillway structure is not completed, then the protection is provided by variable reserved volume of lagoon no. 4. The second stage is the post-service period of tailings dam no. 4, where the spillway structure is completed in full, and the flood water peak is mitigated by the retention capacity of lagoon no. 3-2.

For mitigation of the flood wave from Petrova River, with return period T=10,000 years and peak discharge Qmax=103.7 m^3/s, at dam profile no. 3-2 is adopted reserved and retention space in the lagoon. The reserved volume of 0.071 millions m^3 lies between elevation of spillway collector for cleared water in the post service period Z1=971.5 masl (that is initial lagoon fill at flood occurrence) and normal level in the lagoon or spillway elevation Zp=972.0 masl. The retention volume of 0.292 millions m^3 is from spillway elevation Zp=972.0 masl to maximal level in the lagoon Zmax=974.0 masl. The freeboard above maximal level till the crest of tailings dam no. 3-2, at elevation Zkr=975.0 masl is hn=1.0 m. Such freeboard meets the design codes, having in consideration that is a case of waste lagoon with negligible water depth and lowered possibility for creation of high waves at action of wind.

By analysis of the lagoon capacity for mitigation of the flood wave (with reserved and retention volume) the discharge peak of Qmax=103.7 m^3/s, for initial fill at Z1=971.5 masl, the authoritative discharge for dimensioning of the spillway structure is decreased to QmaxPR=51.7 m^3/s, for spillway length Lp=9.2 m. Taking into consideration the hydrologic, topographic and geologic conditions of the dam site, as well and dam type, for evacuation of the natural flood wave in service period is adopted spillway structure in the left bank of the river valley, composed of: (1) side channel spillway with side channel, (2) chute and (3) terminal part.

By the innovated hydrologic-hydraulic analysis is confirmed that alternative no. 2 for spillway structure for discharge of the flood water from Petrova River, for return period T2=10,000 years, is feasible solution regarding the technical aspect. The cost difference of the spillway structure alternatives for tailings dam no. 3-2 and no. 4, for flood water from Petrova River, obtained for various hydrologic safety, expressed with return period of flood for T1=1,000 and T2=10,000 years, is relatively small and it accounts dC=C2-C1= 2,756,694 - 2,341,828 = 414,866 €. The increment of the hydrologic safety in case of alternative no. 2, expressed by return periods is significant T2/T1 = 10,000 / 1,000 = 10 or 900% higher, while the increment in cost for alternative no. 2 is negligible C2/C1 = 2,756,694 / 2,341,828 = 1.177 or only 17.7%. Taking into consideration that such simplified comparison of alternatives no. 1 and no. 2, from hydrologic and investment aspect, we conclude that alternative no. 2 should be adopted, with return period T2 = 10,000 years.

6. ACKNOWLEDGEMENTS

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