Evaluation of Leakage Potential from Tailing Dam of Sungun Copper Mine Using Hydrogeological Findings and Numerical Modelling

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Abstract

This research predicted the hydraulic behaviour of the Sungun copper mine tailings dam (NW Iran) in the reservoir's final height and introduced the best sealing to prevent downstream leakage. 14 locations upstream and downstream and several boreholes in dam abutments were sampled. PLAXIS numerical modelling predicted the dam's hydraulic behaviour and sealing procedures for various leakage scenarios. For each abutment of the dam, simulation scenarios have been considered, including simulation in the current and final height of the tailings. Suspended injection curtain and full injection curtain in two different positions were studied, as well. Results showed no pollution leakage at the current level of tailings. The PLAXIS model also predicts a reservoir tailings leakage at the final height. Then, the rise in hydraulic head would induce pollution discharge in the downstream areas. With the assumption that the concentration of elements in the effluent from the tailings dam would remain constant, 41 kg per year of heavy elements will flow the downstream waters. It was determined that a full injection curtain with a height of 200 meter, a width of 3 meters and a permeability of 10-8 m/s, near the dam axis had the least amount of leakage (0.13 L/s) in the final level (125 meter) of the left abutment. Then, the PLAXIS model was utilized for the right abutment, which, in the current level, allows leakage (0.06 L/s) and also in the final level (0.18 L/s); thus, the implementation of the injection curtain in the right abutment is not advised.

Keywords: Dam Leakage, Pollution Leakage, PLAXIS Model, Tailings Dam

Introduction

Tailings are waste materials produced during the separation of ores, and have the lowest content of desired components (Hu *et al.* 2021). They consist mainly of insignificant amounts of minerals (metallic and rock forming), process chemicals and water which can be categorized as slurry, paste, filtered or cake, based on the availability of water and solids in it (Munanku *et al.* 2023). Tailings dams are large man-made high-level "debris flow" hazard sources formed by the long-term cycle of hydraulic filling and consolidation. In most cases, they are highly vulnerable due to hydrogeological, geomorphological, and artificial disturbance (Clarkson and Williams 2021). There is also an unavoidable impact on soil and the ecological environment due to storing tailings over long periods (Guimarães *et al.* 2022; Uugwanga and Kgabi 2020). Geotechnical investigations of rock mass permeability coefficient, special applications in groundwater-related issues, such as the quantity of water leakage and estimation of rock mass potential of injection, are on the agenda. Sungun Copper Mine's tailings dam contains semi-solid sediments from Sungun copper mine's concentration process. This is a kind of high-faced dams with a clay core and also the least expensive and simplest type of tailings dams, which must have sufficient strength and unconstrained height. The dam will reach 186 meters, up from 145 meters in 2020. Semi-solid sediments and wastewater will fill the tailings dam reservoir to 270 million cubic meters. A dam leak or failure could harm the environment and local inhabitants. This research predicts the hydraulic behaviour of the tailings dam in the final reservoir height and introduces the best sealing to prevent downstream leakage. PLAXIS numerical modelling is used to design dam components and predict the dam's abutments and body's behaviour before construction. It also predicted the dam's hydraulic behaviour and appropriate sealing procedures for various scenarios of leakage.

Study area

Sungun Copper Mine's tailings dam is located southeast of the mine, upstream of the Zarnekab watershed in northern Iran. The Sungun porphyry deposit, located in East Azerbaijan province, 105 km northeast of Tabriz, Northwest Iran, on the international metallurgical belt known as Alp Himalaya, possesses about one billion tons of sulphide copper ore (Aghili *et al*. 2018; Nasrabadi *et al*. 2009).

Materials and Methods

Hydrochemistry: The sampling was done in the October of 2019, and the samples were immediately transferred to the laboratory of Tabriz University. The standard sampling procedure was carried out from the downstream side of the potential pollution source (such as a seepage or tailing dam). Surface water samples were taken along the stream beginning at the toe of the dam. Sampling from the tailings dam and the seepage dam was also done in order to establish a more precise correlation between the quality of surface and groundwater and the water contained behind these dams. Water samples were also gathered from nearby springs to examine the quality of the groundwater and any potential implications the tailings dam could have on it. In total, 14 samples were collected, comprising 2 boreholes, 2 tailings dam and seepage dam locations, 5 surface water locations, and 5 groundwater locations. Besides, one borehole in the riverbed and two boreholes in the tailings dam abutments were dug due to a number of factors, such as a more thorough examination of the quality of groundwater to determine whether the tailings dam has any impact on it. Besides, the concentration of heavy elements such as Cu, Fe, Pb and Mn were examined using an atomic absorption machine (Jene_vairo06 analytical model).

Numerical modelling: In this study, a numerical model was employed to predict hydraulic behavior and determine the most effective sealing procedure. The PLAXIS model is capable of modeling and simulating deformation, stability, and analysis of soil

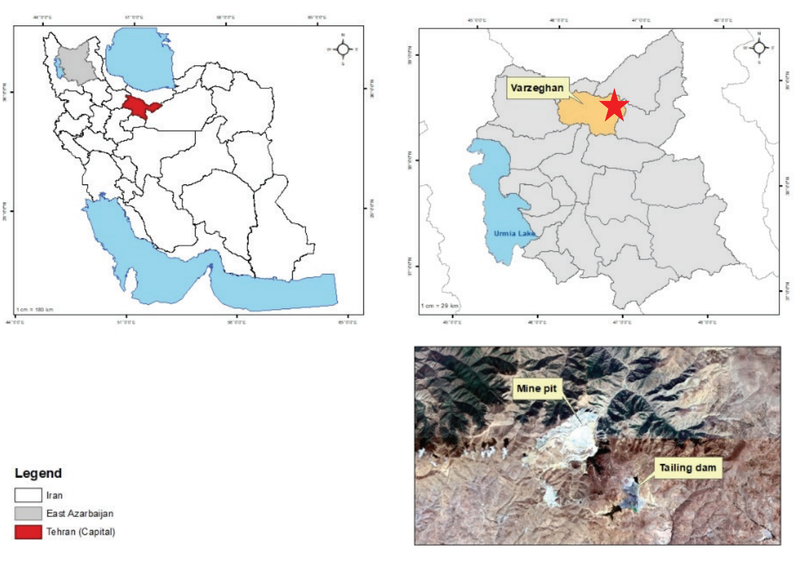

***Figure 1** Location of the study area*

structures using 6- and 15-node triangular elements based on the finite element method. In this model, it is also possible to calculate the flow of water in the dam's abutment, and if there is a pressure difference between the two environments, taking into account all the boundary conditions of the entry and exit of water from one environment into the other, the free surface can be determined. It calculates and draws the current and equipotential lines in the environment using the free surface of the resulting current. For the numerical analysis of contaminant discharge, input information for the PLAXIS model was acquired using data from boreholes drilled during the research and also data from boreholes drilled during the study phase of dam construction. Notably, after conducting the Lugeon test inside the boreholes, permeability data was obtained.

Results and discussion

The majority of the stations were neutral in terms of pH and have a pH above 7 (Fig. 1). Only the station connected to the tailings dam (ST-A-TD) has an extremely low pH because the tailings dam's pH was decreased by the chemicals introduced during the concentration stage. Although a large variation in EC between the tailings dam station (St-A-TD) and other stations was anticipated, the difference between that station and the seepage dam station (ST-A-SD) suggested that the spring waters have been mixed (Fig. 2). On the other hand, the station ST-A-S000, which is located inside the village of Aghababa Sang, displayed anthropogenic impacts such as human and animal waste in this station. Due to the high value of EC in the pollution source (tailings dam and seepage dam), it may be used as a natural tracer to detect the leakage, however the likelihood of leakage is minimal due to the substantial difference in its value in the downstream stations.

Anomalies in the concentrations of Fe at various stations suggested that they come from the ground (local igneous rocks), as some stations upstream of the dam had concentrations of Fe that were even greater than those in the reservoir sample (Fig. 3).

Pb was present in the highest concentration at the tailings dam station, but its low concentration at other sample sites that were around the source of the pollution suggested that there is no leakage of pollutants

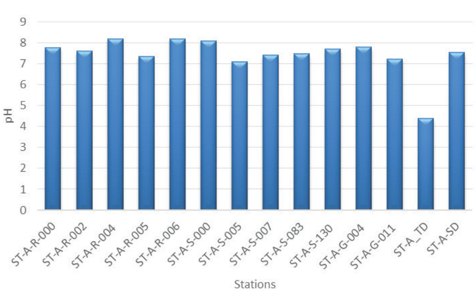

Figure 2 *pH in sampling stations*

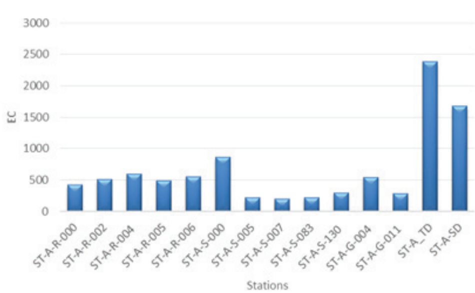

Figure 3 *EC in sampling stations*

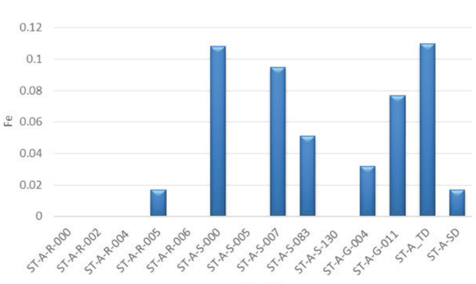

Figure 4 *Concentration of Fe in sampling stations*

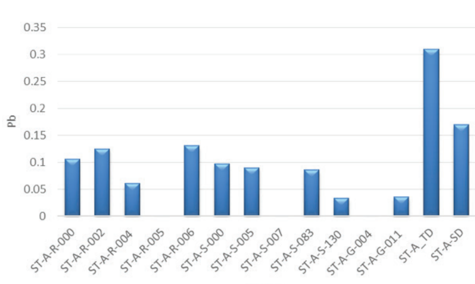

Figure 5 *Concentration of Pb in sampling stations*

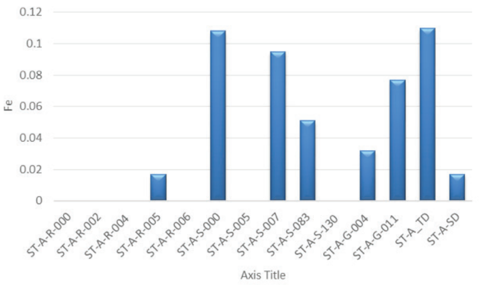

Figure 6 *Concentration of Cu in sampling stations*

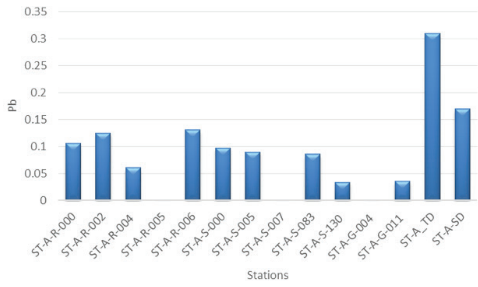

Figure 7 *Concentration of Mn in sampling stations*

at the present time (Fig. 4). As anticipated, due to the processing of various sulphide ores, particularly copper ores, the concentration of Cu was highest in the tailings dam reservoir, whereas the very low concentration of this element at other stations indicated that the reservoir was devoid of water (Fig. 5). In fact, Cu concentration changes in comparison to the seepage dam indicated blending with spring water and natural attenuation. Mn concentration was high in the tailings dam reservoir and seepage dam, and its concentration can increase as the level of the dam storage rises, followed by an increase in the concentration of other elements, causing numerous environmental problems (Fig 6). Similar to Pb, Mn can be utilized as a natural tracer to examine leakage at higher concentrations.

Development of PLAXIS model for the abutments

To create the model, first the geometry of the model was defined based on its scale for the both abutments, then based on the results of Lugeon test and its changes at various depths based on the permeability, 17 layers for the left abutments and 15 layers for the right abutments was outlined on the geometry of the model. Then parameters such as horizontal permeability (Kx), vertical permeability (Ky), saturated weight (Ψsat), unsaturated weight (Ψunsat), adhesion (C), internal friction angle (Φ), Poisson's ratio, modulus of elasticity (Young Modulo) and shear modulus (G) were examined and entered to the model. The permeability was estimated at $2 * 10^{-5}$ (m/day) by analyzing the excavations conducted within coring process. In order to grid the model in the left abutment, the number of elements was 679 and their average size was 13.11 meters in an arrangement with triangular cells, which finally created 5611 nodes and 8148 stress points in the grid. In the right abutment, the number of model elements was 877, the number of nodes was 7203, the number of stress points was 10524, and the average distance between elements was 12.15 meters. For each abutment of the dam, simulation scenarios have been considered, including simulation in the current and final height of the tailings. Various scenarios including suspended injection curtain and full injection curtain in two different positions were studied, as well.

Development of PLAXIS model for left abutment

The first scenario is a simulation of the reservoir's current water level, which is approximately 95 meters above the bottom of the valley. In addition, to improve the precision of the calculations, the iterative procedure is manually defined for the model, and the acceptable error tolerance was set at 0.001. The second scenario of the simulation is related to the time when the water level behind the dam is at its highest level after the completion of the tailings dam promotion. In this scenario, the final water level will be 125 meters (Fig. 8). Considering the leakage rate of the left abutment at the final level (171 m^3/day) means that 62415 cubic meters of pollutants will enter the surface and ground waters downstream every year. The leakage amount of the elements with the concentrations in the summer of 2019 has been calculated according to the leakage rate at the final level in this abutment. Finally, it was determined that the tailings dam will release 41 kg of heavy elements per year into the waters downstream. With the assumption that the concentration of elements in the effluent of the tailings dam will remain at the current level, and taking into account the irreversible environmental effects of heavy elements and other toxic elements, sealing techniques are required to prevent pollutant leakage. This injection curtain was suspended in the model with a width of 3 meters and a permeability of 10^{-8} m/S.

Suspended/full injection curtain in the final level (position A)

In order to prevent pollutant leakage in the final level, the application of the injection curtain in the left abutment was investigated. The depth of the suspended injection curtain and full injection curtain are 136 and 200, respectively. The total discharge and extreme velocity in these scenarios are shown in Figure 9. According to the results, the performance of the full injection curtain is more effective than the suspended injection curtain. According to the nature of the materials stored behind the dam, the amount of discharge per year if this plan is implemented is 4,259,550 liters (0.13 L/S), which reduces the risk of contamination of the downstream areas even less than the previous scenario. Therefore, another scenario was investigated in order to reduce as much as possible the amount of pollutant leakage in the left abutment and also the best place to implement the injection curtain.

Suspended/full injection curtain in the final level (position B)

The injection curtain was applied in the vicinity of the valley (location of leakage) where the hydraulic head difference is high, with a depth of 110 m and 140 m for the suspended injection curtain and full injection curtain, respectively (Fig. 10). The extreme velocity ($90.82*10^{-3}$ meters per day) and the total discharge (45.5 m3/d) in suspended injection curtain scenario showed a relatively large change compared to the scenario of the suspended injection curtain in position A, and this indicates a lower efficiency. The injection curtain suspended in position A was aimed at reducing the amount of pollutant leakage, so the use of the full injection curtain in this position was investigated in the next scenario. In full injection curtain scenario, the amount of discharge does not show a significant reduction compared to the scenario of the suspended injection curtain at this point, and in comparison with the full injection curtain applied in position A (adjacent to the dam axis), it shows a much lower efficiency, so that the leakage flow has increased by 27% (40 m^3/d). With the current discharge rate, the input amount of heavy elements in the final level and taking into account the full injection curtain in the left abutment in position B, a total of 9.68 kg per year will be released from the dam (Tab. 2). Therefore, with the water level reaching its maximum, it is felt necessary to implement sealing techniques to prevent any pollution from leaking downstream.

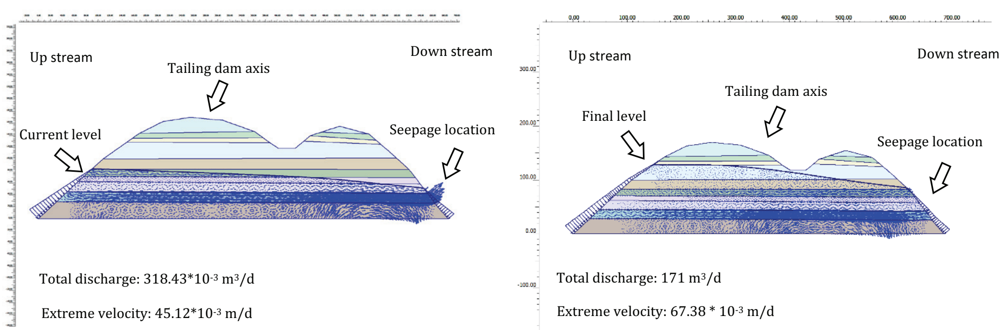

***Figure 8** Development of PLAXIS model for the left abutment in the first and second scenarios.*

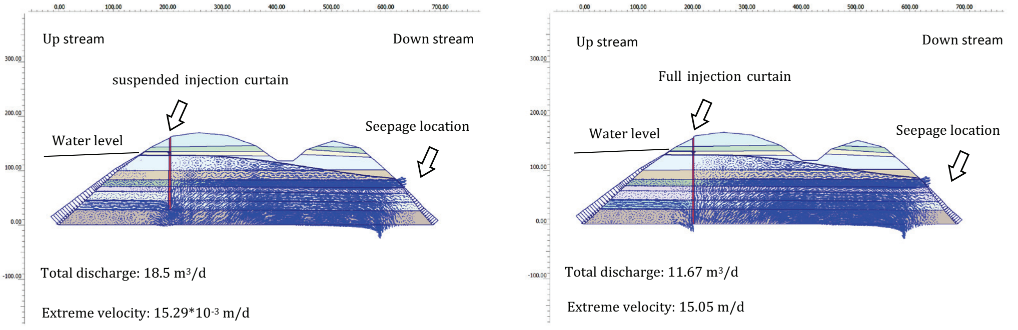

Figure 9 *Suspended/ full injection curtain in the final level (position A)*

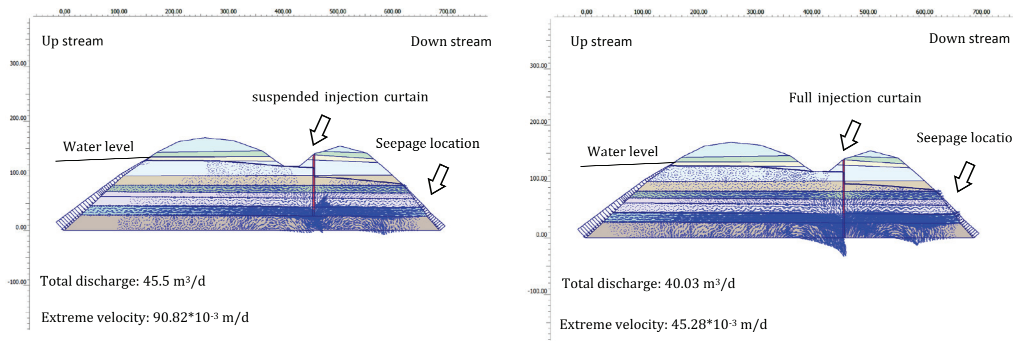

Figure 10 *Suspended/ full injection curtain in the final level (position B)*

Table 1 *Total discharge and the amount of heavy elements leakage (per year)*

Scenarios	Suspended injection curtain (position A)	Suspended injection curtain (position B)	Full injection curtain (position A)	Full injection curtain (position B)
(m^3/d) Total discharge	18.5	45.5	11.67	40.03
Heavy elements leakage (per year)	4.44	10.77	2.8	9.6

Development of PLAXIS model for right abutment

Unlike the left abutment, which is not covered with mineral waste, in this abutment, the waste itself prevents the penetration of more and more pollutants and acts as a waterproof layer. The total discharge in this case is 5300 L/d (0.06 L/S), which will be 1934 m^3 per year, that is much less compared to the discharge of the left abutment. In fact, mineral tailings in the right abutment acts as the injection curtain in the left abutment, and it has greatly reduced the amount of leakage and decrease it down to almost zero. The second scenario was run for the maximum level of tailings and water in order to simulate the behavior of the tailings dam and to estimate the amount of possible discharge. In this scenario, the total discharge was not significantly different from the current level due to the increase in tailings level, and only the velocity has increased, which is the possible reason for the increase in hydraulic head as a result of raising the reservoir level. The discharge rate will be 15.5 m^3/d (0.18 liters per second). Therefore, it is not necessary to implement sealing procedures such as injection curtains.

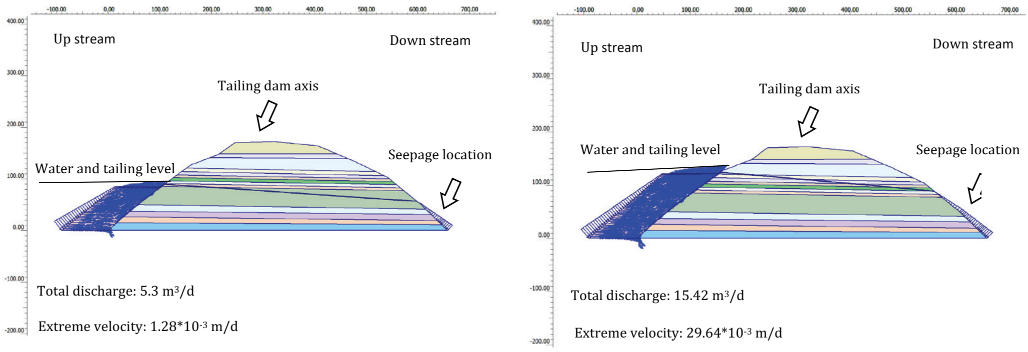

***Figure 11** Development of PLAXIS model for the right abutment in the first and second scenarios.*

Conclusion

There was no pollutant leakage at the current level of tailings or its concentration is not detectable due to natural attenuation. Alternatively, based on the results of the PLAXIS model a leak can be probable in the final height of the tailings in the reservoir. Then, the rise in hydraulic head would induce pollution leakage in the downstream areas, which will enhance its environmental and social warning due to the existence of dam storage and agricultural fields. With the assumption that the concentration of elements in the effluent from the tailings dam would remain constant, 41 kg per year of heavy elements will flow the downstream waters. It was determined that a full injection curtain with a height of 200 meter, a width of 3 meters and a permeability of 10^{-8} m/s, near the dam axis had the least amount of leakage (0.13 L/s) in the final level of the left abutment. PLAXIS model implementation for the right abutment, showed that due to low leakage amount of 0.06 L/s in the current level and 0.18 L/s in the final level, utilizing the injection curtain in the right abutment is not advised.

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