Journal of the Civil Engineering Forum, May 2024, 10(2):187-198
DOI 10.22146/jcef.9520
Available Online at https://jurnal.ugm.ac.id/v3/jcef/issue/archive

# Analysis of Chloride Contaminant Transport in Tailings Storage Facility Dam (Case Study: Gold Mine in Sumatra)

**Devina Pascayulinda*, Budijanto Widjaja, Martin Wijaya**
Department of Civil Engineering, Universitas Katolik Parahyangan, Bandung, INDONESIA
Jalan Ciumbeluit No 94 Bandung
*Corresponding author: devinaaap@gmail.com

**SUBMITTED** 29 August 2023 **REVISED** 9 December 2023 **ACCEPTED** 12 January 2024

**ABSTRACT** In the practice of gold mining industry, hazardous waste known as tailings is produced during the ore extraction process. These tailings are typically stored in a dam structure called a Tailings Storage Facility (TSF). The planning and construction of a TSF are critical considerations, as the failure of a TSF can have substantial environmental impacts, pose risks to human safety, and result in industrial losses. Therefore, strict control is necessary in the development of TSFs to minimize the potential negative consequences. This research focuses on the transport of contaminants within a TSF, specifically examining the concentration of chloride contaminants and conducting particle movement analysis. The study utilizes modeling through the GeoStudio SEEP/W program to simulate groundwater flow profiles and the GeoStudio CTRAN/W program to understand contaminant movement over a 100-year period. GeoStudio modeling employs 10 materials: impermeable clay soil, filter sandy soil, transition gravel rock, three mine waste types (Fine, Rockfill, and Rockfill with fine), hard rock bedrock layer, in-situ soil representing the original layer, landslide with colluvial soil, and the tailings itself. Back analysis is employed to iterate model parameters and ensure modeling accuracy against field data, including comparisons with water quality test results and readings from vibrating wire piezometer (VWP) instrumentation. The contaminant transport is influenced by advection-dispersion processes and tends to concentrate within the TSF boundary toward the dam toe over a 100-year timeframe. The analysis emphasizes the influence of advection in contaminant transport and underscores the importance of particle position relative to the groundwater level, with Particle Tracking Analysis shows significant movement within the groundwater flow area. This research provides crucial insights into the dynamics of contaminant concentration, informing better decision-making in TSF planning and management. The findings underscore the imperative of strict control measures to minimize environmental impacts and human safety risks associated with TSFs, thereby advancing knowledge in gold mining waste management.

**KEYWORDS** Tailings Storage Facility (TSF); Hazardous Materials; Seepage Modeling; Contaminant Transport; Particle Tracking



## 1 INTRODUCTION

Tailings are the waste generated from mining processes typically from the ore processing of gold, silver, and copper, consisting of a mixture of sand, silt, metals, and chemical reagents. This process involves crushing rock into fine particles, often less than 0.1mm, to extract valuable minerals, using water and chemicals. For every ton of ore processed, about 850 kg of solid waste, water, and one kilogram of chemical residue are generated (Jewell, 1998). Tailings typically stored in Tailings Storage Facilities (TSFs), TSFs are vital dam structures meticulously designed to confine this mining waste securely. TSF designs are contingent upon various factors, including the nature of the waste, project economics, water retention, and seismic requirements. TSF failures have wrought significant global consequences, involving loss of life, environmental damage, and contamination of waste. A lack of comprehension regarding tailings behavior, inadequate monitoring, and deficient management are key contributors to TSF failures.

Tailings dams, typical earth-fill embankment dams, are constructed to impound the sludge or refuse resulting from ore extraction processes or other mining activities. Globally, the mining industry annually generates billions of tonnes of this refuse, which is then stored in tailings dams. In 2021, world mining production was estimated at 17.9 billion metric tons, compared to 9.6 billion metric tons in 1985 (Reichl and Schatz, 2023).

Tailings exhibit a slurry-like consistency, comprising fine materials resembling soil. While their behavior aligns with soil mechanics principles, tailings differ fundamentally from natural soils. Initially, ore is extracted through open-pit or underground mining methods, then subjected to crushing and grinding, yielding fine particles akin to sand, silt, and clay. Water and chemicals are introduced to facilitate the separation and retrieval of valuable minerals. To promote water conservation and recycling, a thickening process is implemented via dewatering, resulting in tailings suitable for transfer to Tailings Storage Facilities (TSFs). Refer to Figure 1 for an illustration of the tailings flow process preceding discharge into the TSF.

Numerous failure incidents and case studies have


Figure 1 The formation process of tailings from ore extraction (adopted form Jewel (1998))

been documented in recent decades (Rico et al., 2008; Villavicencio et al., 2014; Glotov et al., 2018; Owen et al., 2020; Rana et al., 2021; Piciullo et al., 2022). These studies have primarily focused on identifying the causative factors behind TSF dam failures, their environmental impacts, and the mechanisms of failure. However, these reviews were limited to qualitative and quantitative assessments, lacking experimental or full-scale observations. Cao et al. (2019) conducted a series of experiments to determine the dynamic characteristics of unsaturated copper tailings, aiming to provide a foundation for the safe design of tailings dams. Additionally, Kim et al. (2023) highlighted the critical role of tailings porosity in the failure of dams containing ferrous materials. The failure of a tailings dam often results in the release of toxic or non-toxic tailings, the potential for acid mine drainage, groundwater contamination, and long-term effects on the flora and fauna of the surrounding environment. The stability of TSF is a critical concern in the mining industry, a failure in these dams can have severe consequences, including threats to human lives, substantial industrial losses, and significant environmental impacts. Factors like a lack of understanding of tailings behavior, inadequate monitoring, and poor management are primary contributors to TSF failures. The prolonged environmental and health disaster risks associated with TSF failures, coupled with the extended presence of toxic materials, demand a higher level of care and continued attention, even after mining operations cease. This research is essential due to the high-risk nature of Tailings Storage Facilities (TSFs), which pose extreme environmental and financial threats in the event of failure. Thorough planning is critical to mitigate the potential risks and minimize the severe consequences, such as environmental pollution and significant losses, associated with TSF dam failures. This research is structured to encompass a comprehensive determination of soil parameters based on secondary data, employing modeling using GeoStudio SEEP/W software to analyze groundwater flow profiles and Geostudio CTRAN/W to determine contaminant transport and particle tracking within the TSF, and ultimately comparing the modeling results with field data, including readings from piezometers and water quality tests to validate the model.

The current research on contaminant theory is limited, especially in the context of studies on TSF dams, after mine closure there is currently no ongoing discussion, guarantee, or regulations concerning the long-term impact of TSFs. This is particularly crucial in mineral mines where TSFs dam contain hazardous waste. It is imperative to investigate this to ensure the environmental sustainability and the preservation of undisturbed ecosystems following mine closure. The aim of this research is to ensure that after TSF closure and in the future, there will be no danger or impact from the release of hazardous waste into the environment or the surrounding community.

## 2 METHODS

This study primarily focuses on the transport of contaminants, particularly in the context of TSF dams in gold mining operations in Sumatra, Indonesia. The gold mine employs a gold extraction process involving crushing, grinding, and carbon-in-leach (CIL) methods. The TSF is designed to accommodate 56 million tons of tailings with a peak height of 360 meters above sea level. The topography and hydrogeology surrounding the TSF are significant considerations. Positioned in a formerly river-fed valley, the TSF area comprises 418 hectares, with relatively steep and almost vertical natural slopes. The geological conditions in the TSF area are quite complex, three primary soil categories have been identified: residual soil formed from in-situ weathering, colluvium, and alluvium. These geological conditions play a crucial role in the stability and material interactions within the TSF.

The data collection for this research was conducted through observation and documentation. Observation involved direct on-site monitoring of the Tailings Storage Facility (TSF), while documentation data were obtained from documents and reports. The typical section of the Sumatra TSF is divided into several zones. Zone 1 is the direct contact zone with the tailings at the upstream embankment, composed of low-permeability materials (clay) to restrict seepage from the tailings into the embankment body. Zone 2, the sand filter layer, is designed to collect seepage water passing through Zone 1 and convey it to the base of the embankment for drainage through underdrains. Zone 3 is the structural construction of the embankment and also functions as the area for dumping mine waste from the pit. Zone 4 acts as the foundational layer where tailings meet bedrock, comprising only cleaned natural ground without specific materials and not considered in this modelling. Zone 5, the second filter layer, is designed to separate the sand filter layer from mixing with the mine waste layer or Zone 3, preventing

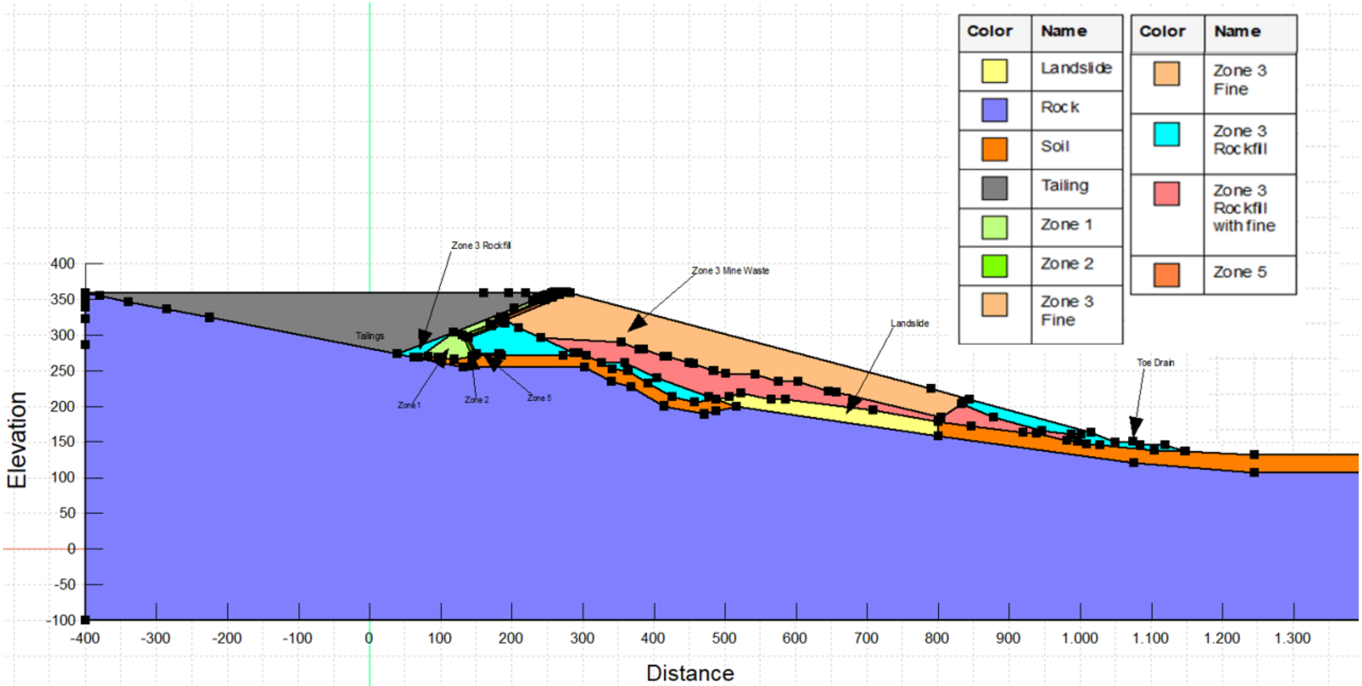


Figure 2 Typical section TSF modeling in GeoStudio program

sand from migrating into Zone 3. The modeling was conducted in 2D using the Geostudio 2022.1 software and was achieved by creating cross-sections based on the topography layout and the as-built design of the TSF dam. To fulfill the objectives of this research, two analyses were performed, covering the conditions when the TSF dam reaches its full capacity and when the TSF dam reaches 100 years of age. Figure 2 above illustrates the GeoStudio modeling process for the Tailings Storage Facility (TSF).

Soil consists of air, water, and the framework whose changes in mass depend on water content. SEEP/W in GeoStudio calculates fluid movement within soil pores, and the calculations are based on the theory (Domenico and Schwartz, 1998). Mass change over time, $M_{st}$, and the difference between inflow ($m_{st}$) and outflow ($m_{out}$), as well as mass changes within the soil framework, $M_s$. The calculation continuation regarding this can be seen in Equation 1 and Equation 2.

$$M_{st} = \frac{dM_{st}}{dt} = m_{st} - m_{out} + M_s \quad (1)$$

$M_{st}$ can be divided into mass of liquid, $M_w$, and mass of water vapor, $M_v$, as follows:

$$M_{st} = M_w + M_v \quad (2)$$

When soils dry out, the surface of the soils becomes unsaturated, and changes in matric suction are simulated in the model. Matric suction is related to volumetric water content and hydraulic conductivity. If the model is used as 'saturated only,' the assumption is that water content remains unchanged over time (GEOSLOPE International Ltd., 2018).

Bulk motion of contaminants involves three aspects: diffusion, advection, and mechanical dispersion. Diffusion is the movement of contaminants from areas of high concentration to areas of low concentration. Advection describes how contaminants travel with the fluid. Mechanical dispersion accounts for the paths created by soil particles, influenced by pore size differences. Generally, diffusion has a smaller impact on contaminant transport, with soil particle hindrance playing a more significant role (Bear, 1972). Hydrodynamic dispersion is influenced by flow path length, spatial variations in pore size, and friction between fluid and soil particles. Hydrodynamic dispersion, $D$, can be described as a combination of mechanical dispersion, $D'$, and diffusion, $D^*$ (Bear, 1972), further calculations regarding this matter can be observed in Equation 3, 4, 5, and 6:

$$D = D' + D* \quad (3)$$

$$D' = D'_L + D'_T \quad (4)$$

Mechanical dispersion relates to the seepage velocity, $u_d$:

$$D'_L = \alpha_L . \mid u_d \mid \quad (5)$$

$$D'_T = \alpha_T . \mid u_d \mid \quad (6)$$

Where $D'_L$ is the longitudinal dispersion coefficient, $D'_T$ is the transverse mechanical dispersion coefficient, $\alpha_L$ is the longitudinal dispersivity coefficient, and $\alpha_T$ is the transverse dispersivity coefficient.

Table 1. Input parameter to seep/w which have been iterated

| Material | Sample Material | Hydraulic Conductivity (m $s^{-1}$) | Saturated WC (%) |
|---|---|---|---|
| Bedrock | Gravel | $2\times10^{-7}$ | 30 |
| In-Situ Soil | Silty Clay | $5\times10^{-8}$ | 35 |
| Landslide / Colluvium | Silty Clay | $1\times10^{-6}$ | 35 |
| Tailing | Silt | $5\times10^{-6}$ | 35 |
| Zone 1 | Clay | $5\times10^{-9}$ | 40 |
| Zone 2 | Sand | $1\times10^{-5}$ | 40 |
| Zone 3 Fine | Silty Sand | $1\times10^{-8}$ | 30 |
| Zone 3 Rockfill | Gravel | $5\times10^{-4}$ | 30 |
| Zone 3 Rockfill & Fine | Gravel | $1\times10^{-6}$ | 30 |
| Zone 5 | Silty Sand | $5\times10^{-4}$ | 40 |

To align with the research objectives, this study employed a ”saturated/unsaturated” material model with a Ky/Kx ratio of 1 on SEEP/W. Key parameters used in this program are hydraulic conductivity and volumetric water content (VWC). Hydraulic conductivity is associated with changes in matric suction, calculated using SEEP/W software by inputting the saturated hydraulic conductivity value. The first step in the SEEP/W analysis involved determining the parameters to be used. The function of volumetric water content (VWC) with respect to matric suction was determined using the saturated water content obtained from laboratory testing. The hydraulic conductivity function was estimated using the Fredlund-Xing-Huang method based on the saturated hydraulic conductivity ($K_{sat}$) value. These parameters were further iterated through back analysis with field instrumentation data from vibrating wire piezometers (VWP). Boundary conditions are established in the analysis by assuming that the tailings area is saturated (constant water pressure head = 0), there is a sediment pond at the base of the dam, and a toe drain channel located at the base of the dam. This approach has been tailored to account for field conditions to ensure that the simulation reflects a representative scenario. Parameters that correspond to field conditions are identified by comparing data obtained from actual VWP readings with those generated by SEEP/W. In this analysis, piezometer readings recording pore water pressure at various depths are used as the primary reference. SEEP/W integrates this data with other parameters such as soil layer structure, aquifer configuration, and boundary conditions. SEEP/W then produces a simulation model that replicates the observed pore water pressure profile in the field according to the pore pressure readings. The input parameter can be shown on Table 1.

The analysis focuses on modeling the movement of dissolved chloride through porous media over time, considering the interaction between solutes and groundwater. The connection between transient pore water pressure analysis and solute transport analysis is crucial to understanding how long-term hydrological changes can affect contaminant transport. In this analysis, the input parameters for contaminant transport are adjusted based on previously cited references. These parameters are iteratively fine-tuned to match field conditions, validated by water quality sampling data from the TSF. The emphasis is on optimizing parameters to ensure that simulations and analyses closely reflect actual conditions, groundwater flow profiles are obtained from previous SEEP/W simulations. Water quality data is collected from four points as shown in Figure 3 with the results shown in Table 2.

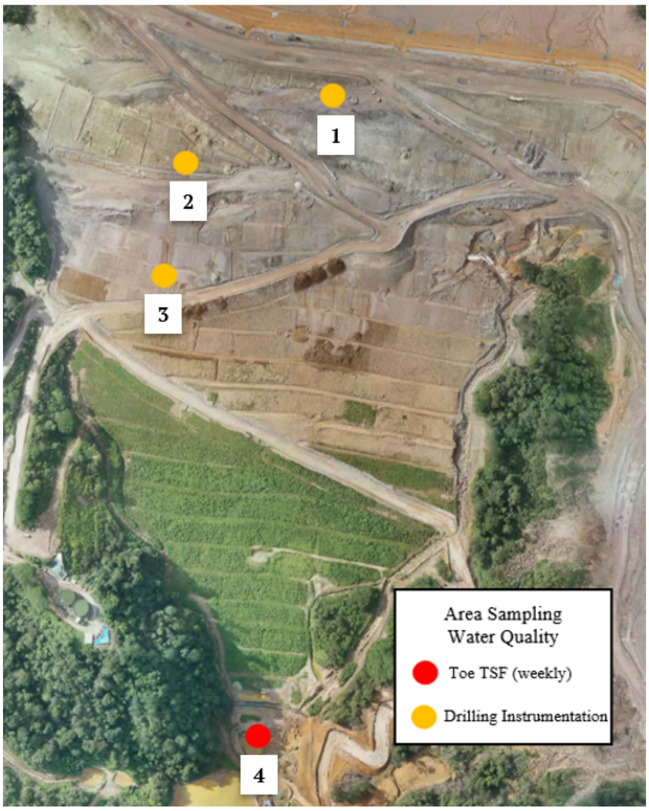


Figure 3 Water quality sampling area

The initial concentration of contaminants in the tailing materials is modeled as a non-reactive solute, specifically chloride ($Cl^{-1}$), with a concentration value of 10 g $m^{-3}$. This value represents the rounded average of the data from feed discharge processing to the TSF between May and July 2023. In the modeling, it is assumed that there is no initial concentration of contaminants in the dam material in Zone 1, Zone 2, Zone 3, and Zone 5 as shown on Figure 4. Adsorption factors are not considered, and the diffusion of contaminants is based on previous research on the diffusion coefficient values of chloride in various tailing dam experiments. The diffusion coefficient for chloride can vary between 1.5 to $4.25 \times 10^{-9}$ $m^2$ $s^{-1}$ (Song et al., 2017). The determination of the chloride diffusion coefficient is based on the uniformity level of the material, where the lowest diffusion

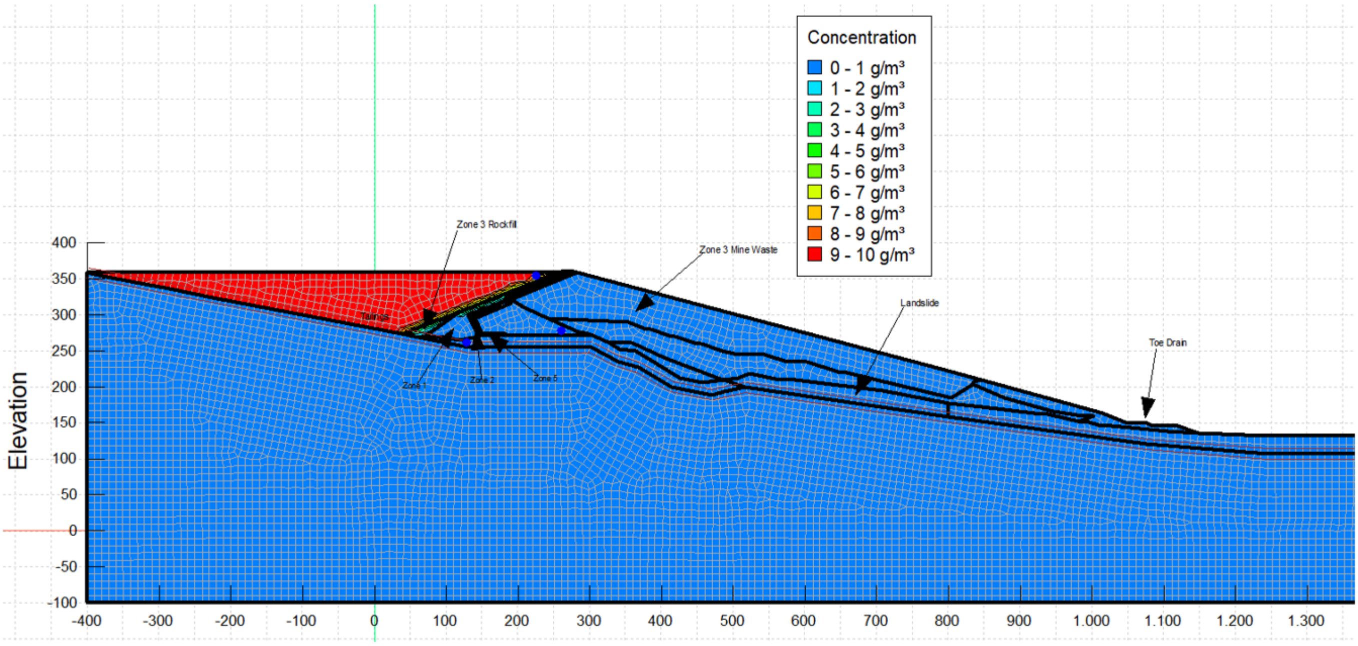


Figure 4 Initial concentration at CTRAN/W

Table 2. Water quality sampling result as shown on figure 3

| ID | Project | Location | Depth (m.b.g.l) | Sampling Date | pH S.U. | Chloride ($Cl^{-1}$) mg $L^{-1}$ |
|---|---|---|---|---|---|---|
| 1 | ICN-24 | Embankment | 57 | 10-Mar-23 | 2.55 | 0.449 |
| 2 | ICN-22 | Embankment | 69 | 30-Mei-23 | 3.03 | 0.186 |
| 3 | PZ-18 | Embankment | 34 | 06-Jun-23 | 6.02 | <0.002 |
| 4 | Weekly Water Quality Testing | Toe | 0 | 23-Mei-23 | 5.99 | <0.002 |
| 4 | | Toe | 0 | 30-Mei-23 | 6.11 | <0.002 |
| 4 | | Toe | 0 | 06-Jun-23 | 6.47 | <0.002 |
| 4 | | Toe | 0 | 13-Jun-23 | 6.11 | <0.002 |
| 4 | | Toe | 0 | 20-Jun-23 | 6.06 | <0.002 |
| 4 | | Toe | 0 | 27-Jun-23 | 5.46 | <0.002 |
| 4 | | Toe | 0 | 11-Jul-23 | 6.2 | <0.002 |

Table 3. Parameter input in CTRAN/W

| Material | Diffusion, D* ($m^2$ $s^{-1}$) | Longitudinal Dispersivity (m) | Transversal Dispersivity (m) |
|---|---|---|---|
| Bedrock | - | - | - |
| In-Situ Soil | 3.00E-12 | 18 | 3,6 |
| Landslide / Colluvium | 3.00E-12 | 18 | 3,6 |
| Tailing | 4.00E-12 | 10 | 2 |
| Zone 1 | 3.00E-12 | 18 | 3,6 |
| Zone 2 | 3.00E-12 | 24 | 4,8 |
| Zone 3 Fine | 3.00E-12 | 30 | 6 |
| Zone 3 Rockfill | 2.50E-12 | 30 | 6 |
| Zone 3 Rockfill & fine | 2.50E-12 | 30 | 6 |
| Zone 5 | 2.50E-12 | 24 | 4,8 |

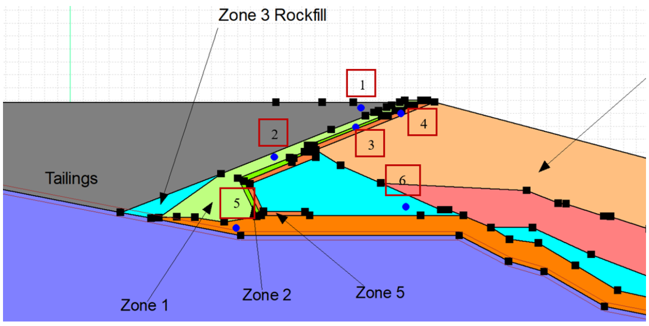


Figure 5 Particle tracking analysis point of observation as detailed on table 4

value is in bedrock and the highest in tailing material (slurry). As for the longitudinal contaminant dispersivity values, they vary within the range of 0.001 to 5 meters, as indicated by laboratory tests. Empirical observations suggest that in actual field conditions, dispersivity can exceed laboratory-tested values by a factor of 100 to 1000. According to theoretical guidelines, the transversal dispersivity coefficient ($\alpha t$) is set at 10 30% of the longitudinal dispersivity value (Wang, 2008).

After successfully adjusting the parameters through

Table 4. Particle tracking analysis location

| Particle | Location | Condition | Coordinate (m) | |
|---|---|---|---|---|
| | | | Horizontal | Vertical |
| 1 | Tailing | Saturated | 226 | 354 |
| 2 | Zone 1 | Saturated | 159 | 317 |
| 3 | Zone 2 | Unsaturated | 223 | 341 |
| 4 | Zone 5 | Unsaturated | 258 | 350 |
| 5 | In-situ Soil | Saturated | 128 | 261 |
| 6 | Zone 3 Rockfill | Saturated | 262 | 278 |

back analysis in CTRAN/W, the subsequent step involves conducting simulations for the coming 100 years. These simulations aim to examine the evolution of contaminant transport behavior over time, emphasizing the roles played by advection and dispersion mechanisms. It is important to note that this analysis does not take into account adsorption processes. The parameter input for CTRAN/W can be shown on Table 3.

Furthermore, to enhance our understanding of contaminant transport further, a particle tracking analysis is carried out on six specifically chosen particles at predetermined locations. These particles are strategically positioned along horizontal or vertical axes at different points to explore the variances in particle migration behavior across various depths, elevations, and materials. This methodology facilitates a nuanced examination of the movement of contaminant particles in a three-dimensional space, taking into account the differences in depth, elevation, and material composition. The initial coordinates for the placement of each particle are detailed in Table 4 and illustrated in Figure 5.

## 3 RESULTS

### 3.1 Groundwater Flow Modeling with SEEP/W

The back analysis results have effectively demonstrated a pore water pressure profile that aligns with the data gathered from Vibrating Wire Piezometer (VWP) readings. Across seven VWP location points along the cross-section, the pore water pressure profile produced through this back analysis process is represented, where a blue dashed line signifies zero pore water pressure. Figure 6 presents the groundwater findings alongside readings from the VWPs, based on the collected data. Additionally, Figure 7 highlights the variation in pore water pressure outcomes from the modeling, identifying specific regions that exhibit suction (negative water pressure).

A transient analysis is performed spanning 100 years into the future, with the main goal of examining the evolution of pore water pressure conditions over the long term. This extended timeframe allows for the observation of substantial variations in conditions, offering a more detailed perspective on potential changes. Moreover, the outcomes of this analysis will lay an essential groundwork for further studies on contaminant transport. Figure 8 displays the results of the transient groundwater flow over this century-long period.

Table 5. Comparison between the analysis results and field water quality sampling results

| ID | Chloride $Cl^{-1}$ (mg $L^{-1}$) | |
|---|---|---|
| | Analysis Result | Water Quality Sampling Result |
| 1 | 0.4 | 0.449 |
| 2 | 0.2 | 0.186 |
| 3 | 0 | <0.002 |
| 4 | 0 | <0.002 |

### 3.2 Contaminant Transport Modeling with CTRAN/W

Figure 9 illustrates the state of contaminant transport in the 10th year since the dam's inception and the completion of tailings deposition. The objective of the back analysis is to investigate the dynamics of contaminant transport within the first decade following the construction of the dam and the filling of tailings. The analysis reveals no detectable contaminant transport at monitoring points 3 and 4, contrasting with conditions at points 1 and 2 where contaminants are present. The validity of these findings is supported by water quality testing, which corresponds closely with the results of the analysis. This agreement between the analysis findings and water quality test data indicates a concordance that affirms the model's accuracy in reflecting real field conditions. A detailed comparison of the analysis results with water quality testing data for the 10th year post-dam construction is provided in Table 5. Figure 9 presents the profile of contaminant transport across this 10-year span.

The analysis results regarding contaminant transport are depicted in Figure 10, which shows the contaminant transport profile over a 100-year period. Meanwhile, Figure 11 displays the solute mass flux during the same timeframe, using black arrows to denote the direction of contaminant movement. This analysis sheds light on the manner in which contaminants navigate and disperse within the TSF dam over this extended period, offering insights into the interactions between water and materials in facilitating this movement. Notably, by the conclusion of the 100th year, there is only a minimal presence of chloride contaminants in the toe area of the TSF.

The simulation outcomes for particle displacement over a 100-year period are illustrated in Figure 12, where particle number 5 is shown to travel the greatest distance at the highest velocity compared to other particles. Conversely, particles number 2, 3, and 4 exhibit negligible movement, a result that can be attributed to

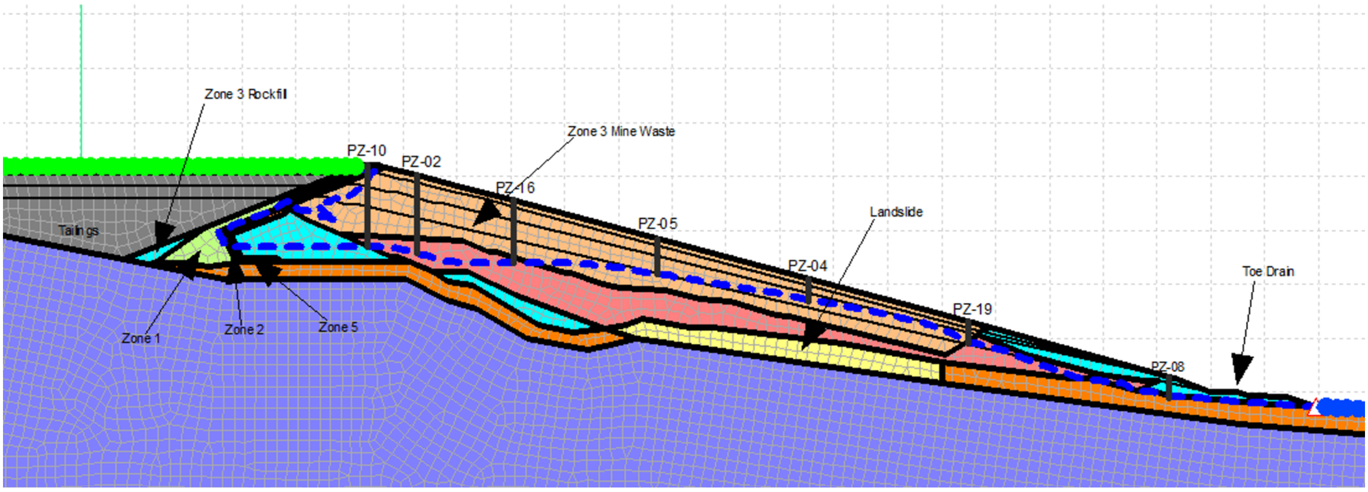


Figure 6 Groundwater flow result and VWP reading comparison

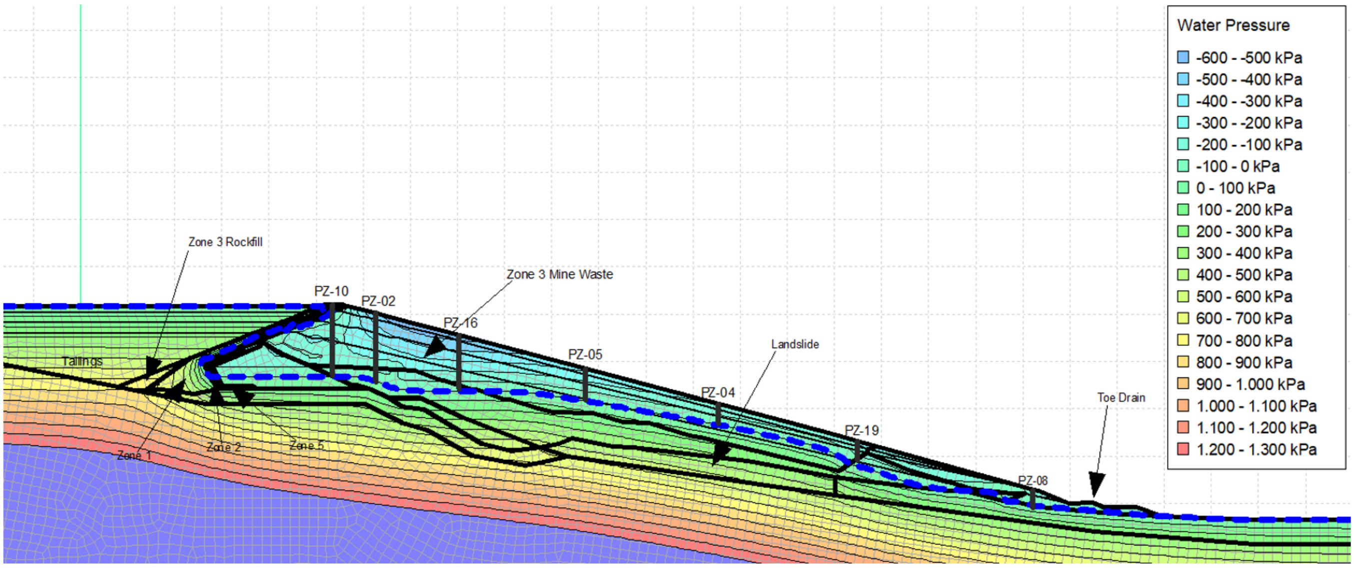


Figure 7 Pore water pressure result value

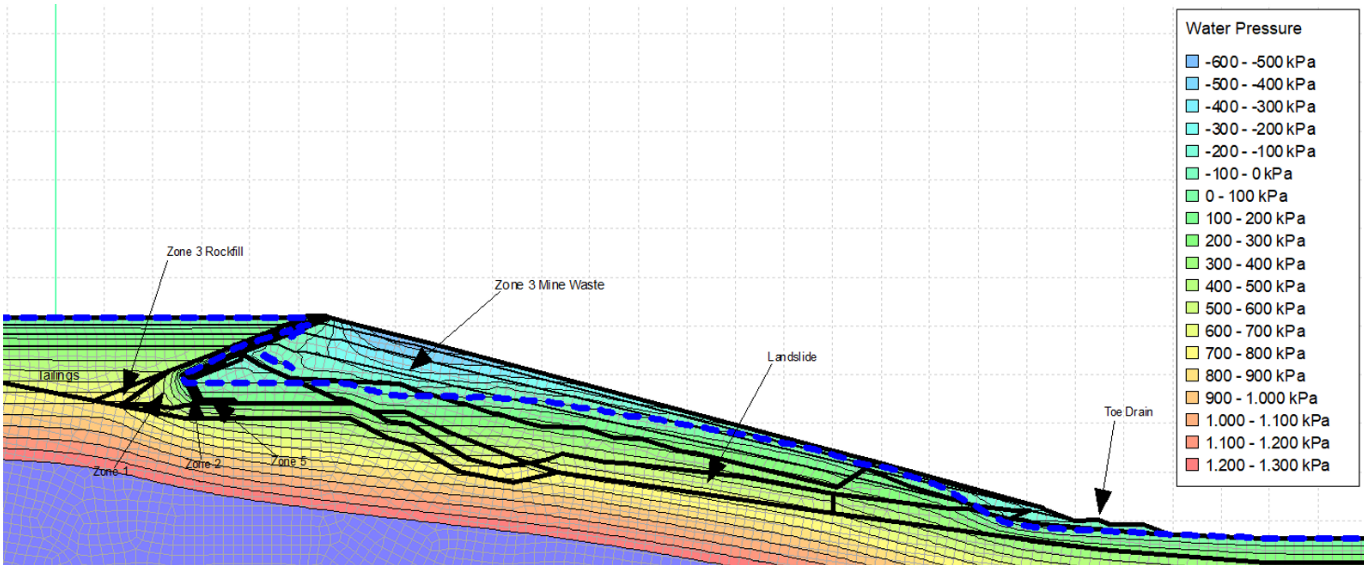


Figure 8 Transient groundwater flow result over 100 years period

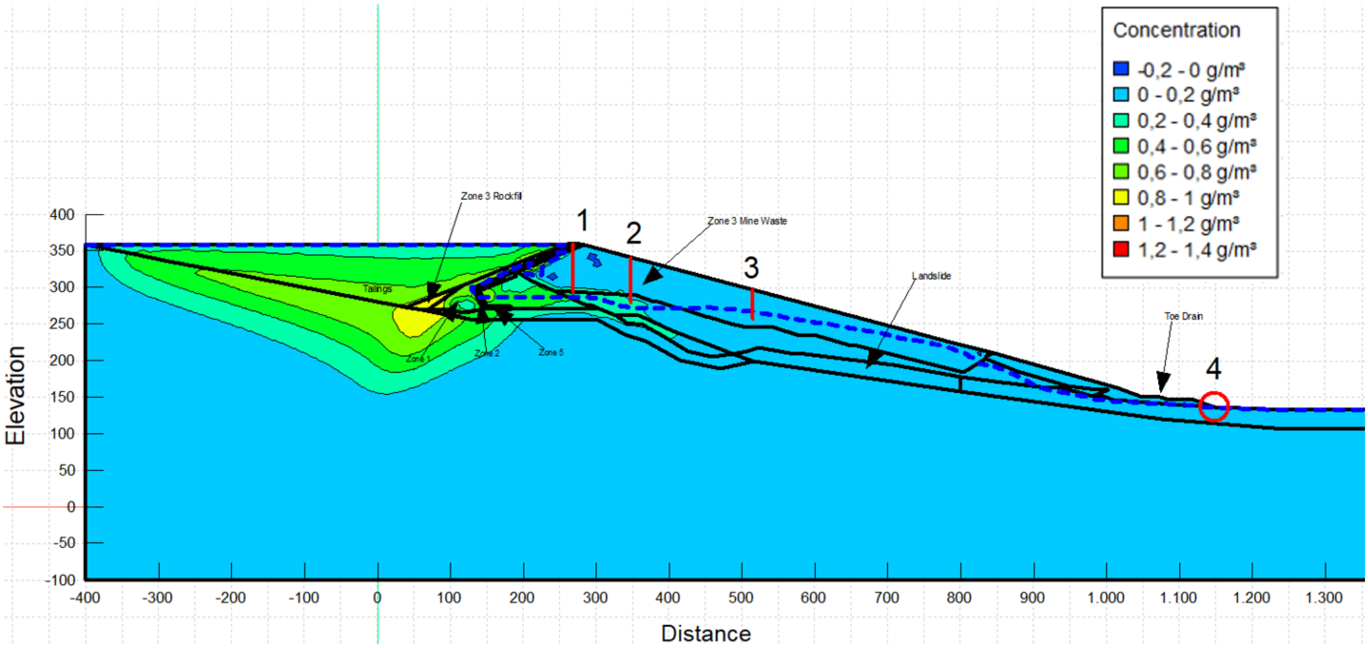


Figure 9 Contaminant transport profile over 10 years period

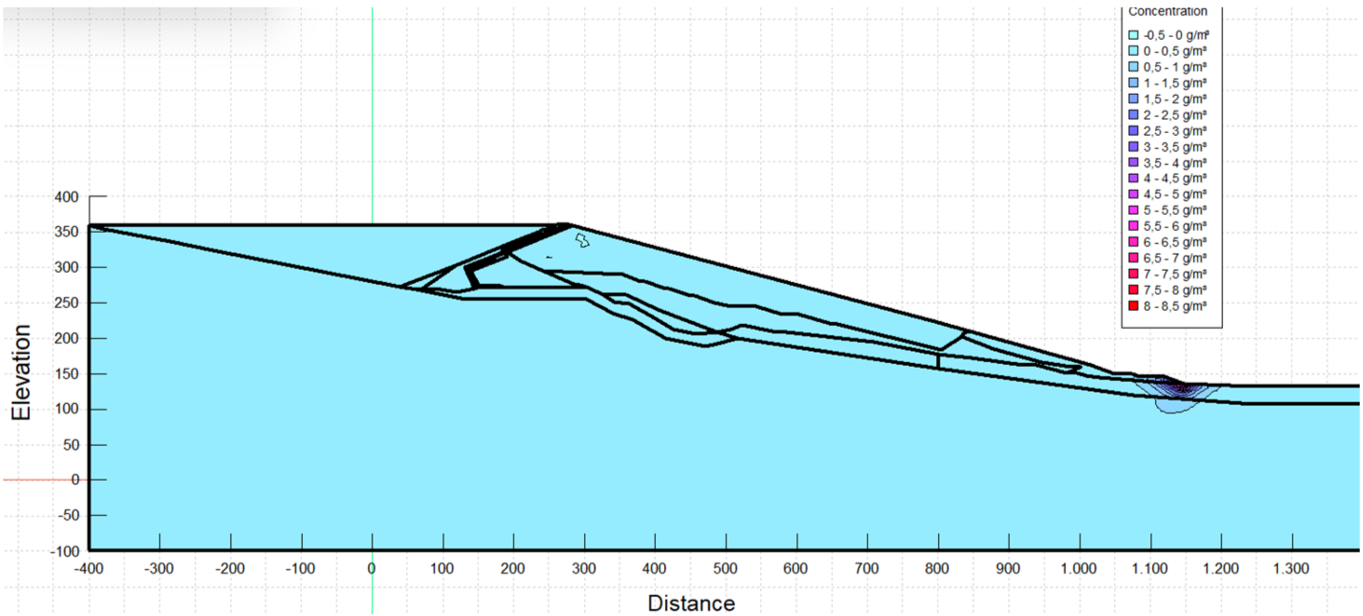


Figure 10 Contaminant transport profile over 100 years period

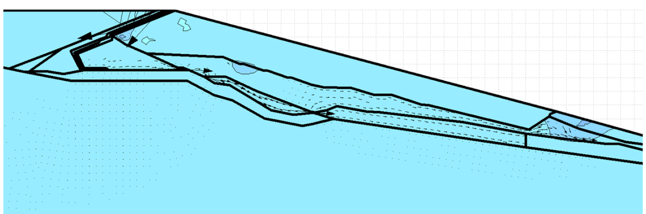

Figure 11 Solute mass flux over 100 years

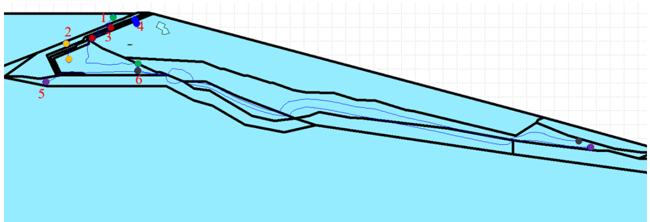

Figure 12 Particle tracking analysis over 100 years

the positioning of particles 3 and 4 above the groundwater level. Figure 12 provides the findings from the particle tracking analysis for the 100-year scenario.

## 4 DISCUSSION

The findings demonstrate that over a century, excluding the impact of rainfall infiltration, contaminants are transported throughout the dam's structure, with concentrations progressively reaching the toe of the Tail-

Table 6. Comparison between the analysis results and field water quality sampling results

| Particle No. | Location | Transportation Distance (m) | Transportation Time (year) | Average speed (m day$^{-1}$) |
|---|---|---|---|---|
| 1 | Tailing (Upper) | 164.08 | 100 | 0.0045 |
| 2 | Zone 1 | 24.89 | 49 | 0.000792 |
| 3 | Zone 2 | 32.08 | 88 | 0.00099 |
| 4 | Zone 5 | 5.12 | 75 | 0.000146 |
| 5 | In-situ Soil | 818.9 | 100 | 0.0224 |
| 6 | Zone 3 Rockfill | 672.36 | 80 | 0.01844 |

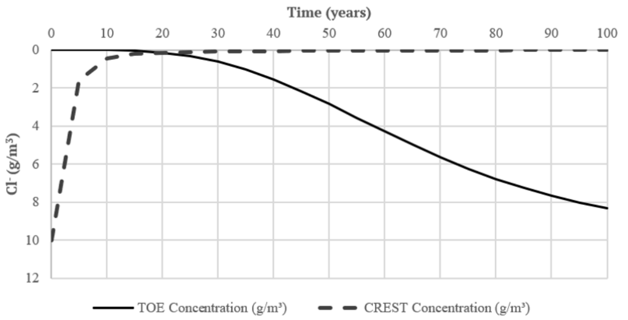


Figure 13 Graph of chloride concentration over time at the crest and toe areas

ings Storage Facility (TSF) dam. Importantly, there is no evidence of contaminant migration beyond the TSF dam's boundaries, indicating that contaminant distribution remains localized and confined within the dam's designated perimeter. This pattern of contaminant transport aligns with groundwater flow within the TSF dam, as depicted in Figures 11 and 12, showcasing the role of advection in the transport process. Advection refers to the movement of contaminants via flowing fluid, driven by a hydraulic gradient. Additionally, the dispersion process, which involves the spread of contaminants from higher to lower concentration areas, is observed in the movement of contaminants from the dam's crest to its toe. This dispersion further supports the observed distribution patterns within the TSF dam, corroborating the theoretical understanding of how contaminants disseminate and settle within the structure.

Figure 13 presents the chloride concentration trends over time at both the crest and toe areas of the dam. Initially, the contaminant concentration at the dam's toe is 0 g m$^3$, while at the crest, it starts at 10 g$^3$. Over time, from year 20 to year 100, the concentration at the crest decreases towards 0 g$^3$. Simultaneously, the concentration at the toe area exhibits a steady increase until year 100. Despite this, both the toe and crest areas witness a reduction in contaminant concentration by the end of the period. Specifically, by year 100, the concentration at the toe reaches 8.3039 g$^3$, and at the crest, it is significantly lower at 0.0092 g$^3$. This reflects the substantial relocation of contaminants from the crest towards the toe area, a movement facilitated by groundwater flow through the advection process. The analysis reveals a 17% variation between the initial and final chloride concentrations, attributing this change to the decay life of the contaminants. Decay life is a critical factor that indicates the duration needed for contaminants to diminish from their original concentration. It plays an essential role in assessing the pace at which contaminant or chemical levels reduce in the environment. The faster the decay life, the quicker the concentration decreases. This study does not specify the decay life's exact value, highlighting the need for further investigation to accurately determine this parameter. The particle displacement simulations over a 100-year period indicate that these particles are minimally influenced by groundwater movement, tending to stay near their original locations. This suggests that a particle's position relative to the groundwater level significantly affects its mobility over a given time frame. Notably, Particle 1 exhibits a larger displacement than Particles 2, 3, and 4. This disparity is attributed to Particle 1 being located in the slurry-consistency layer within the tailings pond area. Furthermore, Particles 5 and 6 are observed to undergo the most significant displacement among the particles studied. Their substantial movement, apart from occurring in the groundwater area, is due to their positions outside the designated zonation layers (Zones 1, 2, and 5), responding to hydraulic condition changes in their vicinity. These findings underscore that implementing zonation layers effectively mitigates contaminant transport. Thus, the simulation results offer valuable insights into particle interactions with soil layers and surrounding water, demonstrating how variations in hydraulic conditions influence particle displacement patterns within the TSF dam studied.

In evaluating the contaminant transport analysis over a 100-year period, focusing on concentration distribution and particle tracking, it is beneficial to compare this study's findings with those from a previous investigation into contaminant transport at Zhaoli Ditch Dam (Wang, 2021). Both studies initiated with a similar contaminant concentration of 10 mg L$^{-1}$. The key difference between the current study and Wang (2021) work is the geometry of the TSF dam. Wang's study featured tailings encased by impermeable cover layers, contrasting with the design considered in this analysis. Nonetheless, outcomes from both studies consistently indicate that the concentrations remain confined within the tailings dam boundaries. Regarding particle tracking analysis, the previous study reported a maximum travel distance of 189.2 meters for tailing particles, with a transport velocity of $7 \times 10^{-8}$ m $s^{-1}$. Table 6 in this study offers a detailed comparison of particle transportation characteristics, noting significant findings. For instance, Particle 1, originating from the upper tailings, travels 164.08 meters over 100 years, achieving an average velocity of 0.0045 m $day^{-1}$ (approximately $5.2 \times 10^{-8}$ m $s^{-1}$). This comparison indicates the representativeness of the tailing's parameters employed in our study. Moreover, particles from various zones, such as Zone 1, Zone 2, Zone 5, In-situ Soil, and Zone 3 Rockfill, display distinct transportation paths, durations, and velocities. Notably, Particle 5, associated with In-situ Soil, traverses the longest distance of 818.9 meters within the study period. This highlights the complex dynamics governing particle movement within the system, further enriching our understanding of contaminant transport mechanisms within Tailings Storage Facilities.

## 5 CONCLUSION

Based on the analysis results, several conclusions can be drawn from this study. This analysis encompasses various material zones, including impermeable clay soil, filter sand, transitional gravel, mining waste zones (comprising fine sub-zones, rock fill, and rock fill with fines), bedrock, in-situ soil, colluvium soil, and tailings. The contaminant transport analysis was conducted with an initial chloride concentration of 10 g $m^{-3}$ and chloride diffusion coefficients ranging from 1.5 to 4.25 × 10-9 $m^2$ $s^{-1}$. Through iterative adjustments of longitudinal and transverse dispersivity parameters via back analysis to align with water quality testing data at various points at the toe of the TSF dam and drilling locations, the study validates the model's accuracy in representing contaminant movement under field conditions. The analysis over 100-year period shows a gradual distribution of contaminants toward the toe of the TSF dam, with no indication of contaminants spreading outside the TSF dam boundary. Contaminants tend to concentrate within the dam boundaries, following the groundwater flow within the TSF dam. This indicates the influence of advection in the transport process, while dispersion demonstrates the movement of contaminants from areas of high concentration to low within the dam. The reduction in contaminant concentration from the initial 10 g $m^{-3}$ to 8.5 g $m^{-3}$ over 100 years underscore the significance of decay life in assessing the rate of contaminant decrease in the environment, though further research is required for a more comprehensive understanding.

Particle Tracking analysis reveals that particles within the groundwater flow area undergo the longest displacement and highest velocity compared to particles at other areas. In contrast, particles outside the groundwater flow area exhibit negligible movement, underscoring the critical role of particle position relative to the groundwater level in determining particle movement over time.

This research advances the understanding contaminant transport within Tailings Storage Facilities (TSFs) by analyzing various material zones and validating the model against water quality testing data. The findings highlight the TSF design's effectiveness in containing contaminants within dam boundaries, with contaminant distribution following groundwater flow. Additionally, the study points out the significance of Particle Tracking analysis in revealing the vital influence of particle position on movement, offering insights for future research and potential impacts on TSF design and management.

## DISCLAIMER

The authors declare no conflict of interest.

## REFERENCES

Bear, J. (1972), *Dynamics of Fluid in Porous Media*, American Elsevier Press.
**URL:** *https://doi.org/10.1016/B978-0-08-095703-9.00012-X*

Cao, G. et al. (2019), 'Experimental study of shear wave velocity in unsaturated tailings soil with variant grain size distribution', *Construction and Building Materials* .
**URL:** *https://doi.org/10.1016/j.conbuildmat.2019.06.169*

Domenico, P. A. and Schwartz, W. (1998), *Physical and Chemical Hydrogeology*, 2 edn, John Wiley & Sons Inc.
**URL:** *https://doi.org/10.1002/9780470172766*

GEOSLOPE International Ltd. (2018), *Heat and Mass Transfer Modeling with GeoStudio*. [Brochure]. Calgary, Alberta, Canada.

Glotov, V. E. et al. (2018), 'Causes and environmental impact of the gold-tailings dam failure at karamken, the russian far east', *Engineering Geology* .
**URL:** *https://doi.org/10.1016/j.enggeo.2018.08.012*

Jewell, R. (1998), 'An introduction to tailings', *Case Studies on Tailings Management* **1**, 7–8.

Kim, S. Y. et al. (2023), 'Estimation of soil porosity in mine tailing using parameters from instrumented oedometer test', *Engineering Geology* .
**URL:** *https://doi.org/10.1016/j.enggeo.2023.107065*

Owen, J. K., Kemp, D., Lèbre, A. et al. (2020), 'Catastrophic tailings dam failures and disaster risk disclosure', *International Journal of Disaster Risk Reduction* **42**.
**URL:** *https://doi.org/10.1016/j.ijdrr.2019.101361*

Piciullo, L. et al. (2022), 'A new look at the statistics of tailings dam failures', *Engineering Geology* .
**URL:** *https://doi.org/10.1016/j.enggeo.2022.106657*

Rana, N. M. et al. (2021), 'Catastrophic mass flows resulting from tailings impoundment failures', *Engineering Geology* .
**URL:** *https://doi.org/10.1016/j.enggeo.2020.105978*

Reichl, C. and Schatz, M. (2023), *World Mining Data 2023*, Federal Ministry of Agriculture, Regions and Tourism, Vienna.

Rico, M. et al. (2008), 'Reported tailings dam failures: a review of the european incidents in the worldwide context', *Journal of Hazardous Materials* .
**URL:** *https://doi.org/10.1016/j.jhazmat.2007.05.057*

Song, S., Yan, S. and Liu, X. (2017), 'Influence of iron ore tailings powder on the performance of high fluidity concrete', *Concrete* **11**, 77–80.

Villavicencio, G., Espinace, R., Palma, J., Fourie, A. and Valenzuela, P. (2014), 'Failures of sand tailings dams in a highly seismic country', *Canadian Geotechnical Journal* **51**, 449–464.
**URL:** *https://doi.org/10.1139/cgj-2013-0142*

Wang, H. (2008), *Dynamics of Fluid flow and contaminant transport in porous media*, Higher Education Press.

Wang, V. (2021), 'Analysis of seepage, contaminant transport, compaction and safety of the zhaoli ditch dam, a tailing reservoir'. Dissertation.

[This page is intentionally left blank]