Mine Water and the Environment (2021) 40:1–5
https://doi.org/10.1007/s10230-021-00757-3

DEAR READERS

Introduction to this Special Issue on Tailings Storage: Challenges and Technologies

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Published online: 10 February 2021

Introduction

With this Special Issue, we are beginning the 40th year of publication of this journal. We are celebrating this achievement with more vibrant covers, which you probably already noticed, and a renewed intent to publish papers that will be interesting and relevant to mine water researchers and industry practitioners. This is the first of two special issues that will be produced this year, while the other two issues will include a few papers by authors who have been active in this field for several decades and who can provide some historical perspective.

This Special Issue is focused on the tailings produced by hydrometallurgical processing plants. Improvements in this processing technology continue to allow even lower grade ores to be economically processed, but this adds to the volume of tailings waste generated every day. Moreover, the rational management of these tailings is subject to many challenges, which must be dealt with using the best knowledge and experience available. This implies the need to follow this continuous and accelerated progress very closely to apply it in our daily work. It was our intent that this compendium of two dozen papers be an array of contributions provided by a global and multidisciplinary group of colleagues in the mining world who are sharing their knowledge and experience. We highlight with gratitude the contributions from authors from 13 different countries (Australia, Brazil, Canada, Chile, China, Colombia, Mexico, Peru, Portugal, South Africa, Spain, United Kingdom, and USA), who have contributed their experience. Gratitude also goes to the hundreds of reviewers who have done their silent and anonymous work, undoubtedly enhancing the quality of the final contributions submitted.

Although we recognize that the disastrous failures of tailings dams have caused tremendous losses of lives and property as well as serious environmental damage, we intentionally focused this issue on the paths forward. Recognizing that mining is and will always be a key component of progress, we focus on what is being done and what can be done to improve tailings facilities, prevent future catastrophes, and reduce the negative downstream effects of any tailings dam failures that do occur. It should be remembered that many mine employees and their family members lost lives and property in these failures as well. This publication is thus, in some small way, a tribute to the strong solidarity and brotherhood of the mining community, which helps forge our unity and comradeship (Fig. 1).

Papers Published in this Special Issue

It was not an easy task to place the papers of this Special Issue in a logical order because different topics are often addressed in the same paper, so we tried to organize

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Fig. 1 A photograph of the Aguablanca nickel and copper mine tailings storage facility in Spain

them with respect to their main subjects, while indicating other lateral topics to guide readers searching for specific information.

Safe Management of Mine Tailings Facilities

For safe management of mining tailings facilities, including governance structure and decision making, Gustavo Ramos Dantés dos Reis et al. (Brazil) propose the systematic and rigorous implementation of a management model integrating the principles developed by the Mining Association of Canada for sustainable mining with other guidelines proposed by the International Organization for Standardization (ISO-14001) and included in the Environmental Management Systems standard.

One of the most generally required conditions for any mining operation is the "social licence." In this context, Ivan Carrasco (Spain) provided a paper on the Las Cruces copper mine in Spain. This mine has faced important challenges during its 20-year history. Its design and planning were highly influenced by the earlier nearby Aznalcóllar tailings dam failure and a concern for environmental protection. The successful design, construction, and operation of a surface, dry stacking tailings facility, were key factors in regaining the confidence of local communities and in establishing social license. Currently, a new underground operation and renewed hydrometallurgical plant will extend the life of the project by more than 15 years, profiting from synergies between mine backfilling, dry in-pit tailings disposal, and environmental protection.

To reduce the surface storage area and the risk of tailings dam failures Carlos Villachica et al. (Perú and Spain) propose to classify the tailings size of the flotation units and to store the coarse tailings underground using backfilling. The authors propose dynamic neutralization and coagulation technologies for the fine tailings so that they become agents for acid effluent reduction.

The primary way to decrease the risk of a tailings facility failure is to reduce the amount of water in the stored tailings. Donald East and Rubén Fernández (Peru) present water reduction technology thickening of the slurry to varying degrees of solids content up to a highly thickened, paste consistency, using displacement pumps to transport the tailings or filters to mechanically decrease the water content and convey the tailings by truck or conveyor. The authors suggest a method to optimize water use and to evaluate and reduce project risks, at a conceptual development stage, for both thickened and filtered tailings.

Hydrology and Hydrogeology

Hydrogeological and geotechnical controls in tailings dams facilities and their area of influence, and especially their interpretation are fundamental to management of a tailings facility. Kym Lesley Morton (South Africa) emphasizes the importance of installing multiple point piezometers. An accurate pattern allows the plotting of equipotentials and flow lines in three dimensions. Pore pressure monitoring in the tailings storage dam can guide and enable early intervention to prevent or delay dam failure. Remote monitoring linked to artificial intelligence and robotics can turn pumps on and open drains to remove water, the main cause of failure risk.

In the same regard, John Fortuna et al. (Australia) highlight the important role that the hydrogeological conditions plays in tailings storage facility design. The authors present hydrogeologic considerations associated with design and operations and some fundamentals for site characterization that can help reduce the severity of groundwater-tailings interactions. Examples of such interactions are provided to illustrate key points, including successful applications of hydrogeologic principles and unexpected interactions between tailings design elements and groundwater where hydrogeology was not properly considered.

Frequently, the capacity of a tailings storage facility must be increased. A specific example of this is presented by José Miguel Galera et al. (Spain), concerning the tailings facility of La Parrilla mine (tungsten and tin) located in western Spain. The main design and building constraint is that it has been constructed over an existing tailings facility from the 1980s. The construction activities involved removal and substitution of the old tailings (southern portion), emplacement of gravel columns over an area of about 10,000 m^2, and construction of the dyke's dam.

Different technologies used during tailings storage to isolate the reactive materials can actually cause acid drainage problems. Pedro Camero-Hermoza et al. (Perú and México) propose pyrite flotation separation and encapsulation as a way to chemically stabilize tailings in a process in which pyrite is separated by flotation from the coarse tailings and incorporated into the slime, thus avoiding acid water generation.

Based on research carried out at 67 tailings dams in Spain, Roberto Rodríguez et al. (Spain) conclude that: (1) tailings dams contain alternating layers with contractive and dilative geomechanical behaviors; (2) tailings saturate quickly but drain more than 10 times slower due to their high-suction capacity; and (3) over the long-term, a stationary flow regime is attained within a tailings basin. Four conditions must all be present for a tailing dams flow failure to occur: (1) tailings must experience contractive behavior; (2) tailings must be fully saturated; (3) effective stress load must approach zero; and (4) shear stress must exceed the tailings residual shear stress. The results indicate that the degree of saturation is the most influential factor controlling dam stability, while the pore-pressure coefficient controls geotechnical stability. They conclude that controlling the degree of tailings saturation is the key to preventing dam failures, and that this can be achieved using a double drainage system, one for the unconsolidated foundation materials and another for the overlying tailings.

Tailings Dam Failures, their Aftermath, and Mitigating Adverse Downstream Effects

After recent catastrophic tailings dam failures, monitoring systems have been improved and very good modelling tools have been developed to analyze tailings dam stability and forecast the downstream risk. A good example is the use of DAMSAT described by Darren Lumbroso et al. (United Kingdom) to investigate tailings dam structures and to assess the downstream risk, highlighting the increased amount and accuracy of remote sensing information, whilst its cost has decreased. The authors provide an overview of a web-based system that brings together earth observation and other data to help monitor tailing dams and estimate the downstream risk.

As described by Hossein Kheirkhah Gildeh (Canada and Chile), after recent catastrophic failures of tailings storage facilities, practitioners, owners, and operators are required to provide a unified understanding of a tailings dam breach analysis, to provide a high level of confidence within communities. His paper summarizes the currently available approaches and models for such breach analysis and when to use a particular method.

Gregor Petkovšek et al. (United Kingdom) explain that because the main causes of tailing dam breach are overtopping and the flow of liquefied tailings, the EMBREA-MUD model is suitable for use at tailings dams to simultaneously compute the outflow of water and tailings and the corresponding growth of the breach opening eroded by the shear forces exerted by either water or mud. Such a model was verified in laboratory cases as well as two field cases (the Mount Polley tailings dam in Canada in 2015 and the Merriespruit dam in South Africa in 1994).

The failures of the Mariana and Brumadinho tailings dams in Minas Gerais, Brazil, had severe environmental repercussions and caused many fatalities. Jair Carlos Koppe (Brazil) explains how intensive investigation of these accidents revealed some similarities (i.e. the failure mode for both tailings dams was liquefaction flow) and some discrepancies. The author discusses management practices, relevant legislation and supervision regarding the possible causes of these dam breaks, evaluating whether measures taken by the National Mining Agency (ANM) will prevent more such accidents.

In this same field of tailings dam failures, Chi Yao et al. (China) describe a series of physical tests carried out using different particle sizes to investigate the influence of tailings size on the failure process for a dam subjected to overtopping. The failure processes were also simulated using a computational fluid mechanics model.

The mechanisms and causes of the sudden failure of the Aznalcóllar tailings pond is presented by Joaquín Martí et al. (Spain). The dam underwent displacements of up to 55 m along a 700 m length, releasing large quantities of acidic waters and 5.5 million m^3 of pyrite and pyroclastic tailings. It was a progressive type of failure, caused by the brittle response of the pre-consolidated and cemented clays substrate and the high pore pressures left from the incomplete consolidation of the dam's foundation. Special modelling difficulties were posed by the need to incorporate the strain softening behavior of the clays. The results show that although the timing of the failure could have been approximated using equivalent ductile properties, predicting the shallow, planar geometry of the failure surface observed would have required a precise representation of the brittle response. The failure triggered liquefaction of the tailings, which accelerated at more than 0.1 g. This transition was modelled by migrating from a coupled effective stress approach employing implicit integration to a total stress formulation using an explicit solver.

Modeling a tailings dam failure, considering all geotechnical and hydrogeological parameters, is a basic tool. Eduardo E. Alonso (Spain) reviews the Aznalcóllar dyke failure that released much of its stored, saturated pyritic tailings after a process of progressive failures in the foundation clay. The main geotechnical aspects that contributed to the development of a sliding surface under the dyke were: its downward construction procedure, the brittle nature of the over-consolidated high plasticity foundation clay, and the high pore pressures in the clay. The downward construction method created a “wave” of high stress ratios under the advancing toe of the dyke capable of taking the strength from peak to residual values. The brittleness of the foundation clay was considerable because of its high plasticity and the presence of montmorillonite among its constituents. The high pore pressures are a consequence of the high tailing density, the low permeability of the clay, and the consolidation process in a dominant upward direction. Also, the author discusses the dynamics of the dam failure, the geometry of the dyke, and its relationship to the direction and dip of the clay layer.

One aspect that could not be missed in this special issue is the extent of contamination produced by the flow of sludge after breakage of a storage structure. This topic is dealt with in two papers. In the first, Miguel Ángel Díaz-Puga et al. (Spain) describe how, after an intense precipitation event in October 1966, an old tailings structure in the southeast of Spain failed. The Pb-F rich sludge flowed for more than 12 km through dry riverbeds, damaging infrastructures and crops. Over 40 years later, the groundwater fluoride levels in the area are close to 1 mg/L, surpassing the normal geogenic concentration (and in some cases, exceeding the WHO maximum recommended value for drinking water). Less mobile elements, such as Pb and Zn, were also found at elevated concentrations in the area affected by the sludge flow.

Similarly, Manuel Olías et al. (Spain) address the environmental consequences of the Aznalcóllar tailing dam failure (SW Spain), in two rivers and in its small alluvial aquifer. The mine closed because of the spill but a new project to reopen it is currently being developed. The area covered by the spill ($\approx$ 60 km long) was later transformed into a protected green corridor, connecting two important natural reserves. The authors describes the effectiveness of the remediation measures taken and analyzes water quality evolution in the area since 1980 (almost 20 years before the accident occurred). The contaminant levels in surface and groundwater showed a sharp decrease during the first years, followed by a stabilization of pollution levels. Nowadays, pollutant concentrations in surface waters are even less than those recorded before the spill. The alluvial aquifer close to the mining zone is still polluted, with acidic pH values in some areas, probably due to the slow movement of groundwater together with the existence of some areas with polluted soils. Some groundwater pollutants (e.g. Al, Cd, and Zn) reach the surface waters. Final remediation of polluted soils and alluvial aquifer is recommended to achieve complete rehabilitation.

Reevaluation of Old Tailings

Three papers, in one way or another, are related to the reclaiming of residual minerals still present in tailings storage structures. The first, written by Oscar Jaime Retrepo et al. (Colombia–USA) discuss several artisanal and small-scale gold mining sites in Colombia. After establishing contact with the stakeholders, the team conducted a tailings sampling and analysis campaign. The authors demonstrate the inefficiency of mercury-use in gold extraction and the superior efficiency of centrifugation and gravimetric methods for reprocessing mining residues produced by such artisanal gold miners.

The second corresponds to a revaluation of tailings on a larger scale. Mariana Gazire Lemos et al. (Brazil and Portugal) characterized the chemical, mineralogical, and metallurgical aspects of the Santa Barbara dam (Minas Gerais, Brazil), and performed an environmental evaluation of the alkaline water (maximum pH values of $\approx$ 10), at the surface of this facility, containing Sb (up to 0.500 mg/L), As (up to 0.080 mg/L), and Cu (up to 20 mg/L). The potential recovery of elements such as Sb, As, and Au was considered for potential tailings reprocessing. Gold enrichment areas were found in the tailings dam, with concentrations up to 0.5 g/t. Alignment exists among tailings management and increased interest in the reprocessing of low-grade ores, which is important in the context of the circular economy. The authors suggest that valorization of tailings, although challenging, can be achieved by economic recovery of the more valuable metals.

In the third paper, Eduardo Ruiz et al. (Spain and Perú) discuss the reprocessing of the some of the oldest tailings of the San Rafael mine (southern Peru), as they comprise a large volume and high tin concentrations. This tailing storage facility was partially saturated and required a dewatering process to allow remining. The authors describe the conducted activities for this dewatering, including basic engineering studies focused on hydrogeological characterization of the tailings, recommended tests and modelling to define a detailed engineering design, and developing an appropriate construction strategy. In addition, there were tasks associated with operating the dewatering system, infrastructure maintenance, and a real-time follow-up implementation program to monitor the desaturation. The system’s historical evolution, a year of dewatering, and the beginning of remining activities are reviewed.

Geophysical Aspects of Tailings Dams

Finally, three papers present geophysical contributions relative to the study of tailings dams. In the first, Pedro Martínez-Pagán et al. (Spain) shows how geophysical methods based on electrical properties can be used to study tailings ponds, taking advantage of the fact that spatial and temporal subsurface electrical resistivity values vary depending on the physical and chemical properties of the water (e.g. contaminant content, temperature, pH, salinity, texture, metals content). This paper reviews published case studies in which electrical resistivity tomography was successfully used to characterize and monitor tailings ponds.

In the second paper, Javier Rey et al. (Spain) explain how the combined use of two geophysical techniques (electrical resistivity tomography and induced polarization), together with hydrochemical studies, were used to verify and assess the effectiveness of encapsulating and sealing abandoned tailings ponds facilities.

In the third paper, Erika Juliana Aldana Arcila et al. (Brazil) discuss the use of geophysical methods to study the potential risk of a tailings dam failure, based on an investigation carried out on the Osamu Utsumi uranium mine in Minas Gerais, Brazil. The site has a deactivated rock-soil tailings dam with a fractured rock substrate and a confined water flux upwelling downstream. Electrical geophysical research identified a structurally continuous low resistivity zone, which indicates water infiltration in the bedrock under the dam, reducing the risk of geotechnical instability and failure.

Concluding Remarks

However, many challenges remain, including:

- the essential need not to increase the number of tailings storage facilities that use upstream dam construction (which is already a legal requirement in many countries) and the need to carefully investigate old storage facilities that have been built using this technology;
- reducing the pore pressure in stored tailings through adequate drainage to prevent liquefaction processes;
- the priority of storage with minimal water in the tailings, either by thickening or by filtration;
- the convenience of storing tailings properly in mining voids; and
- the need to continue to improve monitoring and warning systems for tailings dams and their surroundings. This applies to the varied geotechnical aspects, but especially the hydrological ones that are often neglected because they are approached by technicians from other disciplines without the knowledge of the complexities that water brings to these installations.

We plan to publish more papers on this important topic, including a synthesis by the senior author, based on his many years of experience in the hydrological and hydrogeological management of these tailings' facilities. The work involved in preparing this Special Issue impeded this, but you can expect such a paper to be published in this journal later this year.

The International Mine Water Association (IMWA) was born in Granada (Spain) more than forty years ago (1979), and this journal was first published there three years later (1982). We hope that the scientific community, as well as consultants and those who are responsible for mining operations, will find in this Special Issue much useful explanation and suggestions for future research and applications that in the end will effectively aid the sustainable mining that society demands of us. Friends forever!