Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)

Towards sustainable and safe tailings dams

Des barrages à stériles durables and sécuritaires

Luca Piciullo, Gabrielle Dublet-Adli, Yusuke Suzuki, Øyvind Torgersrud, Malte Vöge, Zhongqiang Liu, Santiago Quinteros, Vittoria Capobianco, Gudny Okkenhaug, Gijs Breedveld, Haoyuan Liu, Suzanne Lacasse

Norwegian Geotechnical Institute, Oslo, Norway

ABSTRACT: The paper describes the ongoing research at NGI on "sustainable mine tailings". The project aims to increase the safety of tailings dams, improve the geomechanical knowledge on tailings, implement InSAR data in early warning systems and develop a risk assessment and management approach for tailings dams. The research focuses on (1) the analysis of the chemical and geomechanical characteristics of tailings and the possibility of using waste materials as water-retention material for cover solutions with capillary barrier effect ; (2) the characterization of the chemical and geotechnical properties of bauxite residue, especially mineralogy, alkalinity, sodicity and leaching, and permeability and effect of sand amendment; (3) numerical modelling techniques for improving the prediction of static liquefaction; (4) the use of InSAR to monitor the displacement of tailings dams and for discerning failure; (5) a risk assessment approach for tailings dams and the use of statistics on tailings dam failures. Runout models to predict the propagation of failure masses and assess the potential consequences of a failure were also investigated,

RÉSUMÉ: L'article décrit les activités de recherche au NGI sur les résidus miniers. Le projet vise à accroître la sécurité des digues à stériles, améliorer les connaissances géomécaniques sur les stériles, mettre en œuvre les données InSAR dans les systèmes d'alerte précoce et à développer une approche d'évaluation et de gestion des risques. La recherche porte sur (1) l'analyse des caractéristiques chimiques et géomécaniques des résidus et la possibilité d'utiliser les stériles comme matériau de rétention d'eau pour les couvertures et barrière capillaire; (2) la caractérisation des propriétés chimiques et géotechniques des résidus de bauxite, en particulier la minéralogie, l'alcalinité, la sodicité et la lixiviation, ainsi que la perméabilité et l'effet de l'apport de sable; (3) les techniques de modélisation numérique pour améliorer la prédiction de liquéfaction; (4) l'utilisation d'InSAR pour surveiller le déplacement des digues et discerner une rupture imminente; (5) une approche d'évaluation des risques pour les digues à stériles et de la mobilité des glissements pour prédire la propagation des masses et évaluer les conséquences potentielles d'une rupture.

KEYWORDS: tailings, stability, geochemical characteristics, dam monitoring, risk assessment

1 INTRODUCTION

Tailings are a mixture of sand, silt and clay with high content of metals, chemical reagents and process water employed during raw material extraction. Tailings are usually stored in a Tailings Storage Facility (TSF) retained by dams or embankments. Tailings dams are built incrementally to increase the storage capacity of the TSF, usually without interruption of the mining activities. While advances in mining technology over the past 100 years have made it economically feasible to increase the excavated volumes, there has not been similar progress in the management and knowledge of tailings. The uncertainties on the physical and chemical characteristics of tailings together with varying dam management practices are of great concern. The lack of knowledge on tailings behaviour and the poor performance of the tailings dams have resulted in disastrous tailings dam failures. The challenge of safely storing mine waste is growing in scale and complexity (GRIDA, 2016) and exacerbated by extreme weather events due to climate change. There is an urgent need to improve safety and prevent failures from turning into catastrophes. NGI initiated in 2019 research on "Sustainable and safe tailings dams" (https://www.ngi.no/eng/Projects/Sustainable-mine-tailings), focusing on (1) sulphidic tailings and their potential valorisation; (2) geochemical and geomechanical tailings characterization; (3) numerical modelling of tailings behaviour; (4) use or remote sensing for early warning; and (5) risk assessment and management for tailings dams.

2 VALORISATION OF LOCAL WASTE MATERIALS FOR THE RECLAMATION OF ACID-LEACHING TAILINGS

Sulphidic mine tailings can generate acid mine drainage (AMD) characterized by high concentrations of metals and sulphates and low pHs. Regulations and practice significantly improved in the last decades and several approaches were developed to better control acid mine drainage. Typically, in humid climate, mine tailings are covered to reduce infiltration of precipitation and limit oxygen diffusion.

For the rehabilitation of older mine deposit, capping solutions with capillary barrier effect (CCBE) have been suggested as a preferred closure solution (Bussiere & Guittonny, 2020). However, older abandoned deposits are weathered and the sulphidic minerals oxidized, leading to highly acidic pore water and the precipitation of iron-rich (Fe(III)) secondary minerals. These minerals could easily be remobilized and Fe(III) could contribute to indirect sulphide oxidation under low pH conditions (Pabst et al., 2018). To date, it is not clear if a CCBE solution would decrease the generation of acid mine drainage sufficiently.

A challenge for a CCBE solution is the availability of cover material. The material used for building the CCBE is critical in terms of performance and can also have a significant impact on the surrounding environment and on the greenhouse gas production if the material has to be transported over long distances. Earlier studies show that mine tailings, with low hydraulic conductivity and high retention capacity, can have suitable hydrogeological properties for CCBE construction and be able to form strong capillary barriers for sand and gravel. For example, efficient moisture-retaining layers (MRLs) were constructed with non-reactive or desulphurized tailings (Bussiere & Aubertin, 1999; Bussiere et al., 2007; (Benzaazoua et al. 2000; 2008; Bussière et al. 2004). Environmental desulphurization is a promising avenue for active mines (Demers & Pabst, 2020).

On abandoned mine sites, the upper part of the tailings can have been extensively oxidized and their sulphides significantly depleted over several dozens of cm. This material could the hydrogeological and geochemical characteristics needed to build a MRL. However, the oxidation and contamination history and the presence of secondary precipitates and contaminated pore water could cause additional problems. The modification of exposition conditions (and especially the modification of the degree of saturation and redox conditions) may lead to the dissolution and mobilization of contaminants.

The valorisation of pre-oxidized tailings, as a MRL to build a CCBE was tested in the laboratory, as part of the reclamation of acid-leaching, high sulphide tailings (HS tailings) from the abandoned mine in Folldal, Norway. The HS tailings are generating AMD with high concentrations of Cu and contaminating the Folla River**Error! Reference source not found.**. Column tests were conducted over nearly two years, with HS tailings in the first meter (Fig. 1). The samples contained 8% pyrite and high concentrations of heavy metals (e.g. 3340 mg/kg Cu). The HS tailings were covered with 40 cm of pre-oxidized, low-sulphide tailings (LS tailings) (Column 1) or fine sand (Column 2) and placed between two 20 cm thick coarse-grained layers. For control, two 50-cm high and 15 cm internal diameter were tested with only HS tailings (Column 3) or only LS tailings (Column 4).

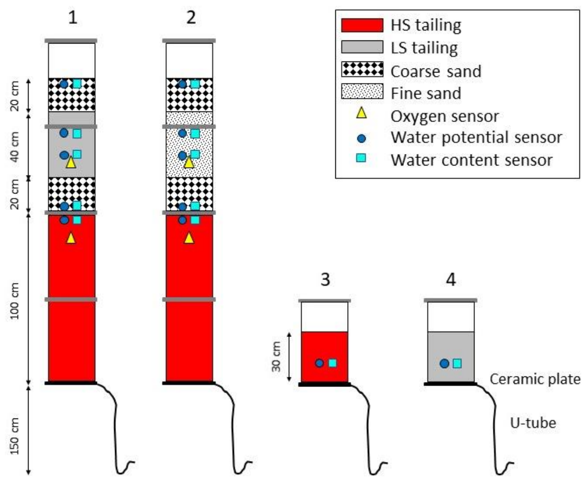

Figure 1. Instrumented columns design. Location of oxygen sensors (yellow triangles), water potential sensors (blue circles) and volumetric water content sensors (cyan squares) are shown.

The results of the study suggested that LS tailings were a suitable water-retention material for CCBEs for the HS tailings at the Folldal site. The degree of water saturation in the LS tailings remained above 85% during the entire test, which is a typical target for CCBEs (Aubertin et al. 1998; Dagenais et al. 2006). Using local waste as a raw material presents economic and practical advantages. Even if leading to low pH values and contaminating to a certain extent, the material did not seem to add significant contamination to the leachate from the HS tailings, compared to clean fine sand. A CCBE, even made with a somewhat reactive material, would in principle limit the volume of tailings reacting with oxygen.

The efficiency of a CCBE reclamation solution for the old and weathered tailings of the Folldal mine was, however, relative from a geochemical point of view. While Cu concentrations in the leachate were significantly decreased after seven months, sulphide oxidation continues and the pH values were only half a unit higher after two years. Possibly, a CCBE could become more efficient over longer periods of time. If a CCBE is used as reclamation solution, it would probably be good to complement the strategy with, e.g., leachate treatment, at least in the first months or years after setting up the CCBE.

3 TAILINGS MATERIAL BEHAVIOUR

A good understanding of the chemical and physical properties of tailings materials is essential, but their characteristics are complex due to varying mineral composition, chemical reactions, form and state of tailings materials at deposition and material behaviour. To better understand the geochemical and geomechanical aspects, critical parameters for tailings dams and landfill design and for closure were identified and method to characterize the parameters improved.

3.1 *Geochemical and geomechanical characterization of b auxite residue filter cake*

In cooperation with Hydro, the Federal University of Pará, University of Limerick, University of Oslo and the Norwegian University of Life Sciences, a "Bauxite residue network" was formed to exchange and discuss findings in the characterization of bauxite residue.

The production of aluminium has seen near exponential growth in the last 50 years and currently exceeds 60Mt/yr. Despite the increasing bauxite refinement, there is currently no reuse for bauxite residue, and large amounts must be stored in TSFs. One of the largest alumina refineries in the world, Hydro Alunorte, Brasil, is currently reviewing closure of a bauxite residue disposal area, targeting at nature-based solutions with vegetation and sustainable low costs. However, developing a basis for growth medium in bauxite residue is challenging, and requires a good understanding of the residue material.

A bauxite residue filter cake was sampled from the Alunorte plant and several geochemical and geotechnical tests were carried out. Emphasis was placed on mineralogy, alkalinity, sodicity (presence of high proportion of sodium ions), leaching, permeability and effect of sand amendment. Each is important for vegetation development. Investigations covered a broad spectrum of tests, including X-ray fluorescence analysis (XRF), X-ray diffraction (XRD), scanning electron microscopy (SEM), batch leaching tests, pH dependency tests, grain size distribution, oedometer and water holding capacity.

For sustainable land use, improvements of tailings properties are necessary, e.g., by making amendments for revegetation purposes. Revegetation of top of bauxite residue is under investigation: seeds are planted in the bauxite residue mixed with e.g., gypsum and organic matter in the laboratory. Evaluation of root growth can be quantified by X-ray analysis.

3.2 *Micromechanics evaluation of tailings shear behaviour*

The geomechanical behaviour of tailings us usually described in terms of state parameters and critical state soil mechanics. Series of laboratory triaxial tests need to be carried out to establish the critical state line (CSL). As undisturbed tailings samples are not easily accessible and seldom sampled in situ, it is necessary to reconstitute test specimens in the laboratory to initial void ratios derived from Cone Penetration Tests (CPT), if available. To reconstitute specimens in the laboratory, the moist tamping technique is widely used. A reliable measurement of void ratio can be challenging due to structure change and large deformation during flushing, saturation and consolidation, especially on loose tailings specimens. The slurry deposition technique is considered as a more representative alternative that mimic the depositional environment of tailings disposal. Yet it is difficult to target the initial void ratio, and there is significant segregation potential.

The micromechanics approach can tackle the initial fabric of the test specimen issue by using micro Computed Tomography (μCT) images and postprocessing techniques. The technique also provides an enhanced understanding of the true initial state of the soil (e.g., Andò, 2013; Viggiani & Tengattini, 2019).

Two triaxial systems were developed at NGI in cooperation with Imperial College London (ICL) to do so-called *in situ* triaxial testing, or a triaxial test inside the μCT-scanner in the laboratory with continuous scanning of the specimen (Quinteros, and Suzuki, 2021). Figure 3 shows a sketch of the two X-ray transparent triaxial cells and examples of μCT-images of tailings materials tested.

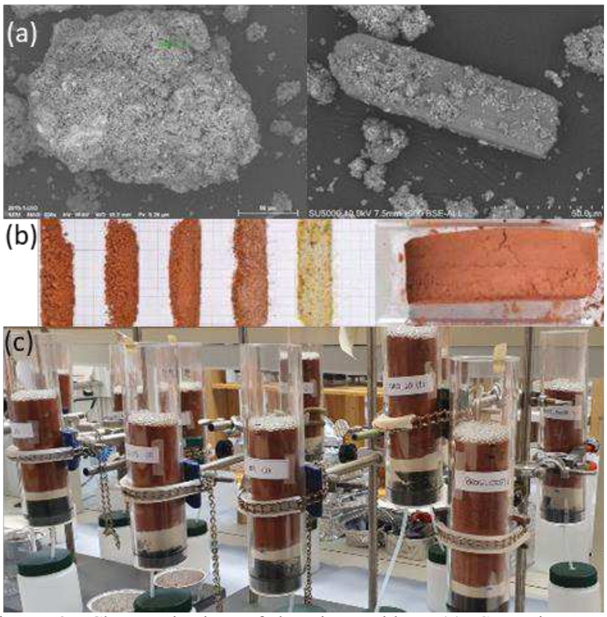

Figure 2. Characterization of bauxite residue: (a) SEM images; (b)oedometer specimens for hydraulic properties considering different sand concentration; (c) column tests for leaching and vegetation studies.

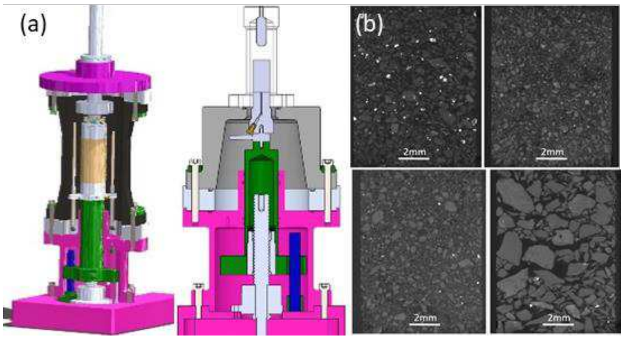

Figure 3. (a) X-ray transparent triaxial cells; (b) examples of μCT-images of tailings materials.

The μCT-images can be taken during all stages of triaxial testing (reconstitution, flushing, saturation, consolidation and shear), and provide quantitative information for understanding the specimen behaviour: the soil state in terms of not only measurements of void ratio but also initial fabric.

A comprehensive triaxial testing program on several tailings materials is presently underway, with a study of reconstitution method (moist tamping and slurry deposition), initial void ratio and initial water content, in a cooperation ICL, University of Western Australia, Golder Associates, Chile and NGI.

4 NUMERICAL MODELLING

Having reliable models for predicting the behaviour of tailings under loading is as important as an essential step for the evaluation of sustainable and safe mine tailings (Schnaid 2020). Tailings are usually deposited in a loose state: under undrained (quick) loading, the material may contract and lose strength. If the tailings are subjected to a shear stress higher than the undrained shear strength, the material becomes unstable state and a very small trigger (or change) can cause a progressive failure due to strain-weakening, often referred to as static liquefaction. This type of failure has been the cause of several recent breaches (e.g., Fundão and Feijao). This failure mode can easily be overlooked if stability is assessed by traditional limit equilibrium analyses.

The research focuses on: (1) the use of numerical modelling with the finite element method (FEM) for simulating the initiation of strain softening; and (2) the use of the discrete element method (DEM) as an alternative to laboratory testing for the characterization of constitutive model parameters.

4.1 *Numerical modelling of static liquefaction*

The work aimed at demonstrating that the initiation of static liquefaction can be simulated by FEM together with a suitable constitutive model. Back-analyses of an actual dam breach, Fundão Dam, Mariana, Brazil, were carried out using Plaxis with the SANISAND material model proposed by Dafalias & Manzari (2004).

In the back-analysis in Figure 4, the dam failure was triggered by increasing the dam gravity with a small portion (less than 5%) under undrained conditions. The model was capable of modelling the strain-weakening behaviour (i.e., the shear strain keeps evolving with decreasing shear stress due to the shear-induced pore water pressure). The input data for the back-analyses were based on information from the Fundão failure review panel (Morgenstern et al., 2016) and piezocone interpretation by Reid (2019). The latter indicated a zone of looser material within the sand tailings. The FEM back-analysis showed the following:

- The field of shear strain increments under the peak load is illustrated in **Error! Reference source not found.** (top). Point A, with the maximum shear strain increment, is within the possible loose zone indicated by Reid (2019). In the analysis, failure started within this weaker zone.
- Figure 4 (middle) shows the effective stress path for Point A, during the undrained phase. The figure shows the reduction in the mean effective stress p' due to shear-induced pore water pressure.
- The stress strain behaviour of point *A* is given in **Error! Reference source not found.**4 (bottom). Strain-weakening is observed immediately after the material state is switched from the drained to undrained phase, at a deviatoric stress (shear stress) of about 420 kPa.

In this back-analysis, the initiation of the failure only, including the progressive development of a shear band, was modelled. The initial strain-weakening prediction relies heavily on the estimation of the material state parameter.

The next step for the numerical simulation is developing a probabilistic approach, using FEM and a response surface combined with the First Order Reliability Method to estimate the failure probability and the relative importance significance of the uncertainties in the analyses.

4.2 *Material characterization by DEM*

The characterization of the mechanical behaviour of tailings, especially the determination of the critical state line in the laboratory, is challenging, due to (1) strain localization (Salvatore et al., 2017); (2) uncertainty in the critical void ratio, and (3) limitations in the achievable strain levels (typically less than 30% in a triaxial test).

To circumvent these limitations, a numerical approach using the recently developed Level Set Discrete Element Method (LS-DEM) by Kawamoto et al. (2016) was tested. The method can model the shape of individual grains with level set functions, where the grain shape is obtained from μCT images. Recent studies have shown that DEM is well suited to simulate the behaviour of granular assemblies to large strains (e.g., Wang et al., 2017). However, most studies to date are done with circular or elliptical particles and do not account for the effect of the irregular particle shapes.

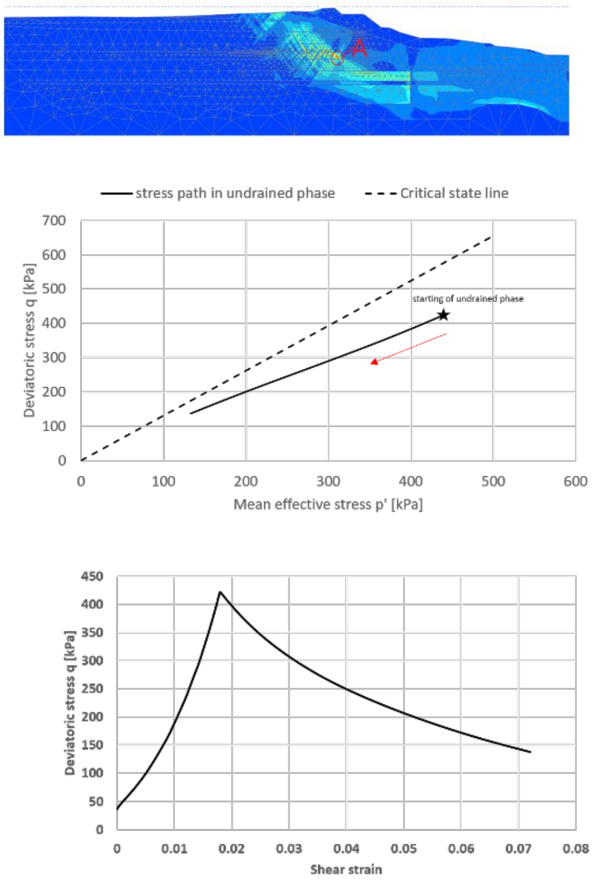

Figure 4. FEM back-analysis with Plaxis and SANISAND model: Top: Shear strain field at peak load; Middle: Effective stress path, Point A, undrained phase; Bottom: Stress-strain response of Point A

Analyses with an accurate description of the particles shapes of an angular sand were done with LS-DEM to determine the critical state line and calibrate the input parameters to a constitutive model. A series of simulations of a volume element (Fig. 5a) under triaxial stress conditions were run to investigate the macro- and micro-responses towards critical state. The analyses showed a clear trend towards a critical void ratio independent of the initial void ratio (Fig. 5b) and a well-defined CSL (Fig. 5c). This approach could well supplement physical laboratory testing for characterization of the mechanical behaviour of tailings and other granular materials.

5 REMOTE SENSING TECHNIQUES

Failure of TSFs can have catastrophic consequences. Monitoring is critical to sustainable mining practice. To assess the feasibility of satellite-based radar interferometry (InSAR) for monitoring tailings dams, two case studies, where ground displacements were mapped by InSAR, were analysed: the Zelazny Most tailings dam in Poland and the Feijão Mine tailings dam in Brazil. For both, data from the Sentinel-1 radar satellite constellation were obtained from the EU Copernicus Programme.

Two different processing methods, Persistent Scatterers (PS, Ferretti et al., 2000) and Small Baseline Subset Algorithm (SBAS, Berardino et al., 2002), were applied and compared. For both dams, the SBAS method provided better coverage, but the measurements close to the crest of the dam seemed affected by the spatial filtering, which "smeared" the high displacement velocities of the beach tailings onto the dam. The PS method provided more accurate measurements, but coverage with measurements on the dam slopes was sparse (Fig. 6).

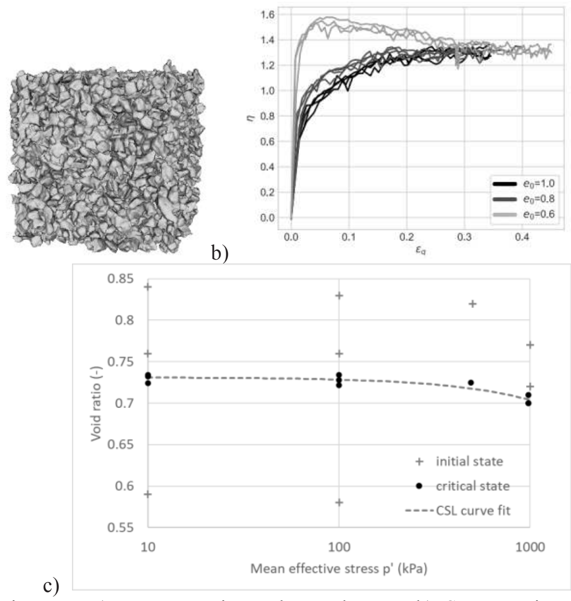

Figure 5. a) Representative volume element; b) Stress-strain curves from the simulations; c) Well-defined CSL.

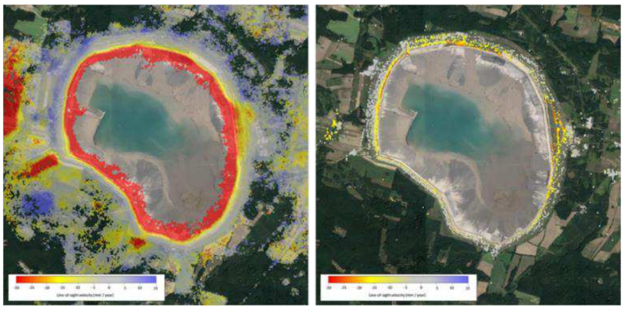

Figure 6. Displacements measured by InSAR at Zelazny Most. Left: SBAS results in line-of-sight; Right: PS results in line-of-sight.

For the Zelazny Most dam, data from two different acquisition geometries were analysed, which allows to decompose horizontal and vertical displacements from the line-of-sight displacements. This was done for the data processed with the SBAS method. The vertical displacements (Fig. 7, left) showed a pattern that was very similar to the corresponding line-of-sight displacement (Fig. 6, left). Along the eastern flank of the dam, at the lower part of the dam face, the vertical displacement values are smaller compared to the line-of-sight displacement. Therefore, a horizontal displacement component, directed outward, is observed (Fig. 7b). The same can be observed on the western side of the dam.

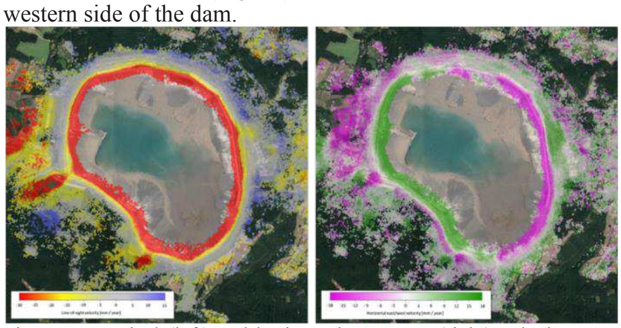

Figure 7. Vertical (left) and horizontal east-west (right) velocity maps (Zalasny Most): Negative values (red) represent settlements, positive values (blue) represent heave; Negative values (pink) represent westward movement, positive values (green) represent eastward movement.

Figure 8 shows the velocity map for the SBAS processing method for the Feijão Mine tailings dam. As for Zelazny Most, the largest displacement rates were observed along the beach, close to the crest of the dam, which is likely related to the tailings settlements. Along the crest and the upper part of the dam, the measurements indicated an average displacement rate of about -15 mm/year in line-of-sight, corresponding to a downslope movement. With -10 mm/year, the lower part of the dam showed less movement. This is expected for a dam constructed with the upstream construction method, as the upper part of the dam will be supported by thicker layers of soft tailings.

Figure 8 presents results from time-series analyses on three areas. A smaller part in the centre of the dam face appeared to show an increased downward movement following December 17, 2018. This could indicate a precursor of the upcoming failure. However, as this increase in velocity is only covered by three acquisitions, the signal should be interpreted with great care and comparisons with ground-based measurements would be necessary to conclude whether the InSAR method was able to capture an increase in the velocity just before failure.

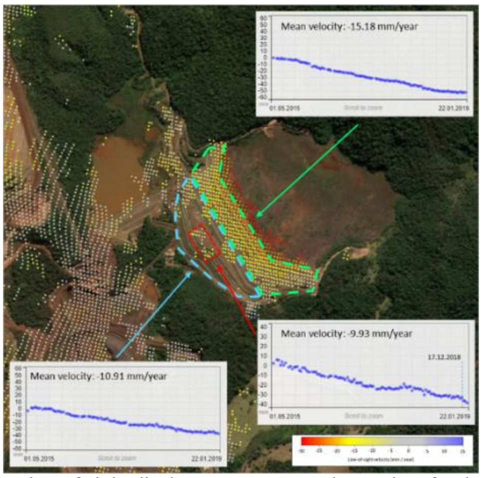

Figure 8. Line-of-sight displacements averaged over time for three areas on the Feijão Mine tailings dam B-I, from May 2015 until just before failure on January 25, 2019.

6 RISK MANAGEMENT FOR TAILINGS DAMS

Appropriate actions are needed as the number of tailings dam failures may increase in the future. In addition to critical evaluation of the analysis of tailings dam safety, implementing risk assessment and management is essential for tailings dams.

To date, 256 cases of tailings dam wall failures and 95 accidents among components and other elements have been compiled by CSP² worldwide (http://www.csp2.org/tsf-failures-from-1915). Figure 9 illustrates that the number of tailings dam failures has remained high the last 60 years. Since 1960, 256 dam wall failures have been registered (or 3–4,5 failures/yr). Given the current number of tailings impoundments of 3500, the rate of failure is ca. one in 800 dams. This is a much higher rate than for water-retaining dams, which is, in any given year, roughly 1 in 10,000 (Davies, 2000, Davies et al., 2000).

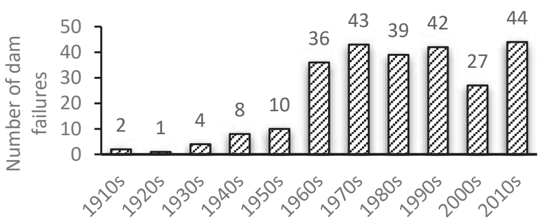

Figure 9. Number of tailings dam failures vs time (from CSP² database).

6.1 *Existing risk management frameworks for tailings dams*

There is a wide range of guidelines, standards and regulatory documents available to assist a mineral operator in establishing a tailings management system for an individual operation, such as MCMPR and MCA (2003), DITR (2007) and FERC (2016). Mining companies have also become more vigilant by implementing environmental policies and management systems to take more control over their tailings storage practices.

Morgenstern (2018) outlined a tailings dam management system for Performance-Based, Risk-Informed Safe Design, Construction, Operation and Closure of tailings facilities (PBRISD). He also recommended that "International Council on Mining & Metals (ICMM) supports the tailings management system based on PBRISD and funds the development and publication of a guidance document that would facilitate its adoption in mining practice."

Cruz & Rodovalho (2019) presented the implementation of ISO 31000: Risk Management to the safety management of tailings dams. The expected result is a systematic structure with the involvement of all levels of the mining company, assigning clear responsibility for the safety management of the dam. Identifying and analysing a broad range of issues and providing a systematic way to make informed decisions are prioritized, with focus on communication within the company and with the external community. The approach stimulates the identification of opportunities for continuous improvement.

6.2 *Tailings mobility and quantitative risk assessment*

While predicting the initiation of failure is important, the mobility (runout distance, velocity and debris thickness) needs to be predicted to help reduce the consequences of a failure. Liquefied tailings can travel many km, disrupt infrastructure and environment over large areas and cause loss of life.

A tailings flow slide following a liquefaction event can be approached by non-Newtonian fluid mechanic models, in particular the Herschel-Bulkley or Bingham model (Oboni & Oboni, 2020). The flow of liquefied tailings has also been shown to depend on the downstream slope and flow velocity, being mainly laminar on flatter slopes and turbulent on steeper slopes with higher velocity (Pirulli et al., 2017). New computational tools have recently become available.

Figure 10 presents the simulation of the runout distance with debris thickness in m, as modelled with the BingClaw software (Kim et al., 2019). The input source volume was estimated from the topography before and post-failure. Figure 10 also superposes, in a red contour, the extent of the tailings deposits at the end of the sliding, based on the interpretation of satellite images. There is a good agreement between the predicted and observed runout distance and shape of the tailings distribution.

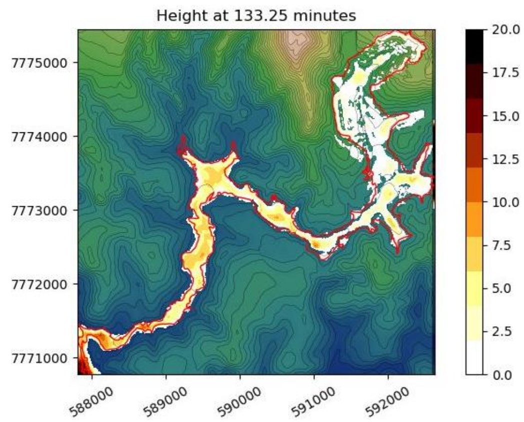

Figure 10. Plan view of predicted runout of tailings at time 133 min: red curve is the mapped runout extent. scale on right is debris thickness in m.

7 SUMMARY AND CONCLUSIONS

The paper describes the main research axes of a 3-year research on Sustainable Mine Tailings at NGI. The objective of the project is to reduce the risk associated with failure of TSFs. This will be achieved by (1) improving the characterization of the properties of tailings materials, (2) developing an improved understanding of their behaviour, (3) improving the predictive capabilities related to static liquefaction, (4) using remote sensing and InSAR data into an early warning system for tailings dams and (5) developing a risk assessment and management framework, using available statistical data, observations and conclusions from earlier tailings dam failures.

Given the record of earlier failures and their catastrophic consequences, there is an urgent need to understand and model the behaviour and mobility after failure of tailings materials. This understanding is required to establish potential precursors of failure, develop suitable material models for tailings materials and enable a reliable prediction of potential failure modes and runout of tailings materials, as well as evaluating the consequences of failure. Such efforts are important to prevent future failures and reduce the risk of human and animal losses, irreparable damage to the environment and huge property destruction. The project "Sustainable Mine Tailings, will hopefully contribute to reduced number of failures, improved safety and sustainable mine tailings.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Norwegian Geotechnical Institute (NGI) and The Research Council of Norway for their support. The authors would like also to thank MSc students Gard Hofshagen, Oda Mohus and Anna Eikebrokk at the Norwegian University of Science and Technology, Jan Schneider and Sebastian Aas Wik at the University of Oslo and PhD student Yuuki Silveira Miura at the Norwegian University of Life Sciences for performing simulations and helping out with the activities presented in this paper. The research activities presented in this paper have been funded by internal funds at NGI on the project SP12: "Towards sustainable mine tailings" (https://www.ngi.no/eng/Projects/-Sustainable-mine-tailings/About-the-project).

REFERENCES

Ando, E. (2013). Experimental investigation of microstructural changes in deforming granular media using-ray tomography. Université de Grenoble, 2013. Thesis.

Aubertin, M., Bussière, B. & Chapuis, R.P. (1998). Field investigation of covers with capillary effect to control acid mine drainage. Paper at the CIM/CMMI/MIGA98, Montréal, Québec (pp. Au1–Au9).

Benzaazoua, M., Bussière, B., Kongolo, M., McLaughlin, J. & Marion, P. (2000). Environmental desulphurization of 4 Canadian mine tailings using froth flotation. International Journal of Mineral Processing, **60**(1):57–74. https://doi.org/10.1016/S0301-7516(00)00006-5.

Berardino, P., Fornaro, G., Lanari, R., Sansosti, E. 2002. A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. IEEE Trans. Geoscience and Remote Sensing, 40(11), 2375–2383. doi:10.1109/TGRS.2002.803792

Bowker, L.N. & Chambers, D.M. (2015). The Risk, Public Liability, & Economics of Tailings Storage Facility Failures. Earthwork Act.

Bowker, L.N. & Chambers, D.M. (2016). Root Causes of Tailings Dam Overtopping: The Economics of Risk & Consequence. 2nd International Seminar on Dam Protection Against Overtopping. Ft. Collins, Colorado, USA, 7-9 September 2016.

Bussière B. & Aubertin M. (1999) Clean tailings as cover material for preventing acid mine drainage: an in situ experiment. *In Proceedings of Sudbury*, **99**:19 –28

Bussière, B. & Guittonny, M. (Eds.). (2020). Hard Rock Mine Reclamation: From Prediction to Management of Acid Mine Drainage. CRC Press.

Bussière, B., Aubertin, M., Mbonimpa, M., Molson, J. W., & Chapuis, R. P. (2007). Field experimental cells to evaluate the hydrogeological behaviour of oxygen barriers made of silty materials. *Canadian Geotechnical J.* **44**(3):245–265. https://doi.org/10.1139/t06–120.

Bussière, B., Benzaazoua, M., Aubertin, M., & Mbonimpa, M. (2004). A laboratory study of covers made of low-sulphide tailings to prevent acid mine drainage. Environmental Geology, 45(5), 609–622. https://doi.org/10.1007/s00254-003-0919-6.

Cruz, C.O. & Rdovalho E. C. (2019). Application of ISO 31000 standard on tailings dam safety. REM, Int. Eng. J., Ouro Preto, 72(1), 47–54.

Dafalias, Y.F. & Manzari, M.T. (2004). Simple plasticity sand model accounting for fabric change effects. Journal of Engineering mechanics, **130**(6):622–34.

Dagenais, A.M., Aubertin, M. & Bussière. (2006). Parametric study on the water content profiles and oxidation rates in nearly saturated taillings above the water table. Paper at 7th International Conference on Acid Rock Drainage, St-Louis, MO (pp. 405–420).

Davies, M.P. & Martin, T.E. (2000). Upstream Constructed Tailings Dams - A Review of the Basics. Proc. Tailings and Mine Waste '00, Fort Collins, January, Balkema Publishers, pp. 3–15.

Davies, M.P., Martin, T.E., Lighthall, P. (2002). Mine tailings dams: when things go wrong. Tailings Dams, pp. 261–273, 2000. Demers I. & Pabst T. (2020). Waste, Integrated Mine. 13 Alternative and Innovative. Hard Rock Mine Reclamation: From Prediction to *Management of Acid Mine Drainage*: 321.

DITR (2007). Lpsd: Tailings Management. Department of Industry, Tourism, and Resources, Canberra Australia.

FERC (2016). Risk-Informed Decision Making (RIDM) Risk Guidelines for dam safety. US Federal Energy Regulatory Commission.- Interim Guidance. Version 4.1

Ferretti, A., Prati, C & Rocca, F. (2000). Nonlinear Subsidence Rate Estimation Using Permanent Scatters in Differential SAR Interferometry IEEE Transactions on Geoscience and Remote Sensing, **38**(5).

Kawamoto, R., Andò, E., Viggiani, G. & Andrade, J.E. (2016). Level Set Discrete Element Method for 3-D Computations with Triaxial Case Study. J. of the Mechanics and Physics of Solids **91**:1–13.

Kim, J., Løvholt, F., Issler, D. & Forsberg, C.F. (2019). Landslide material control on tsunami-genesis - the Storegga Slide and tsunami (8100 y BP). Journal of Geophysical Research: Oceans. **124**(6): 3607–3627. doi:10.1029/2018jc014893.

MCMPR & MCA (2003). Strategic Framework for Tailings Management. The Ministerial Council on Mineral and Petroleum Resources, and Minerals Council of Australia, Canberra.

Morgenstern, N.R., Vick, S.G., Viotti, C.B. & Watts, B.D. (2016). Fundão tailings dam review panel: Report in the immediate causes of the failure of the Fundão Dam. New York: Cleary Gottlieb Steen & Hamilton LLP.

Mudd, G.M. (2007). Global trends in gold mining: Towards quantifying environmental and resource sustainability. Resources Policy, **32**(1): 42–56.

Oboni, F. & Oboni, C. 2020. Tailings Dam Management for the 21st Century: What Mining Companies Need to Know and Do to Thrive in Our Complex World.

Pabst, T., Bussière, B., Aubertin, M. & Molson, J. (2018). Comparative performance of cover systems to prevent acid mine drainage from pre-oxidized tailings: A numerical hydro-geochemical assessment. Journal of contaminant hydrology- **214:** 39–53.

Pirulli, M., Barbero, M., Marchelli, M. & Scavia, C. (2017). The failure of the Stava Valley tailings dams (Northern Italy): numerical analysis of the flow dynamics and rheological properties. Geoenvironmental Disasters. 4(3).

Quinteros, S., and Suzuki, Y. (2021), Development of in situ triaxial testing devices for use in CT scanner." in preparation

Reid, D. (2019). Additional analyses of the Fundao tailings storage facility: in situ state and triggering conditions. J. Geotechnical and Geoenvironmental Engineering, **145**(11). 04019088.

Salvatore, E., Modoni, G., Andò, E., et al. (2017). Determination of the critical state of granular materials with triaxial tests. Soils and Foundations, 57(5): 733–744. https://doi.org/10.1016/j.sandf.2017.08.005.

Schnaid (2020). Geomechanics and Geocharacterization of Tailings. 9th Mitchell lecture

Viggiani, G. & Tengattini, A. (2019). Recent developments in laboratory testing of geomaterials with emphasis on imaging. Proc. 17th ECSMGE Reykjavik IS. doi: 10.32075/17ECSMGE-2019-1112

Wang, R., Fu P., Zhang, J-M. & Dafalias, Y.F. (2017). Evolution of Various Fabric Tensors for Granular Media toward the Critical State. J. of Eng. Mechanics **143**(10): 04017117. http://ascelibrary.org/doi-/10.1061/%28ASCE%29EM.1943-7889.0001342