Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.

Progressing beam centrifuge physical modelling techniques of tailings storage and disposal

Gonzalo Zambrano Narvaez, Yazhao Wang, Dmytro Pantov & Rick Chalaturnyk
University of Alberta, Canada, gonzalo@ualberta.ca

ABSTRACT: Engineering solutions for tailings storage and disposal hinge on addressing the influence of gravity. Centrifuge physical modelling provides an accurate and rapid method for calibrating and verifying large-scale gravity-driven problems. A centrifuge model under hypergravity shares the same stress-strain distributions as an in-situ structure. Consequently, centrifuge modelling enables cost-effective field-scale data collection with well-defined tailings parameters and boundary conditions. The Geotechnical Centrifuge Experimental Research Facility at the University of Alberta has advanced physical modelling techniques for tailings storage and disposal over the past decade. Initially focusing on single-column self-weight settlement simulations, the facility expanded to include multi-lift pond construction, tailings co-depositions, and capping. Complex models have been developed for scenarios such as tailings consolidation in 3D-printed end pit lakes, slope stability of multi-stacked dried tailings, and runout simulations of collapsed tailings embankments. This paper reviews these research techniques, emphasizing the advantages of using the geotechnical beam centrifuge for tailings storage and disposal solutions, including the use of miniaturized tools, monitoring methods and data collection efficiency.

KEYWORDS: beam centrifuge, physical modelling, mine tailings

1 INTRODUCTION

1.1 Physical modelling of tailings storage and disposal

Tailings management is a fundamental component in the design and operation of mining projects. The objective of tailings management is to confine the mine tailings and provide for their safe, long-term disposal. The characteristics of tailings material and site-specific conditions are the crucial design parameters. A wide variety of management strategies are adopted based on the combination of the parameters, such as tailings ponds, backfilling, dry stacking, etc. The geotechnical design of tailings storage and disposal focuses on the foundation bearing capacity, embankment stability, and long-term deformation prediction. Physical modelling serves as a crucial tool, and it resolve the influence of gravity from the settlement rate to the stability of the embankment.

1.2 Beam centrifuge physical modelling

A geotechnical beam centrifuge can be used to physical model tailings structures and serves as a quick and accurate alternative to pilot scale trials or scaled-down laboratory replicas. Centrifuge modelling relies on the concept of geometric similitude, that a centrifuge model under hyper gravity shares the same stress-strain distributions of an in-situ structure (i.e. protype). The centrifuge scaling laws is well established and covered by several publications (Croce et al. 1984, Taylor 1995, Garnier et al. 2007). Equations 1 illustrate the scaling laws in terms of stress and strain between a model and a prototype where, h_p is the height of the prototype being simulated, h_m is the height of the centrifuge model and N is the multiple of earth gravity that the model is subject to in the forms of centrifugal force.

$$h_p = N * h_m \quad [1]$$

Another advantage of centrifuge modeling is that it exponentially speeds up the time required to modelling darcy's flow mechanics, notably the consolidation of tailings. Equations 2 illustrate the scaling laws in terms of time, where t_p is the duration of the prototype being simulated and t_m is the duration of the centrifuge experiment.

$$t_p = N^2 * t_m \quad [2]$$

With accurately scaled centrifuge models and reduced modelling time frame, the beam centrifuge is capable of "calibrating" and verifying the diverse tailings storage and disposal designs.

Additionally, the platform of the beam centrifuge allows for detailed instrumentation for in-flight mechanisms and data collection, provided that they were miniaturized and designed for the hype-gravity environment.

1.3 GeoCERF

The Geotechnical Centrifuge Experimental Research Facility (GeoCERF) at the University of Alberta, operates a 2-m radius geotechnical beam centrifuge – the first of its kind in Western Canada (Zambrano-Narvaez&Chalaturnyk 2014). The facility can model high-gravity environment up to 150 time of earth gravity (Zambrano-Narvaez and Chalaturnyk, 2014). Since the establishment 11 years ago, GeoCERF has been expanding on its the physical modelling capabilities of mine tailings with a diverse portfolio of research projects. Providing safe, time- and cost-effective solutions to tailings research has been a primary directive for the research team. In this paper, a range of tailings modelling scenarios will be presented along with the solutions that GeoCERF has implemented. The progression of tailings physical modelling abilities demonstrated demonstrate the feasibility and advantage of using the geotechnical beam centrifuge to deliver tailings storage and disposal solutions.

2 CENTRIFUGE PHYSICAL MODELLING

2.1 Self-weight consolidation modelling

The mining industries are actively developing new extraction techniques that have resulted in a variety of tailing types. Consolidation tests on tailings provide critical data for operators to design the appropriate storage and disposal facilities. Through

1D consolidation of a tailings' slurry, the consolidation curve can be obtained and be used to derive consolidation characteristics, including compressibility and permeability parameters. These parameters help tailings engineers to predict the long-term settlement behavior of a tailings discharge area and optimize the designs for the containment structure.

Traditionally consolidation tests are performed with odometers, where artificial load in steps to simulate the evolvement of stress conditions. Compared with the odometer tests, centrifuge physical modelling preserves the field stress-strain conditions where the settlement of tailings was achieved through self-weight (Toh, 1992. Sorta et al., 2016). The self-weight consolidation tests are made possible with the beam centrifuge with elevated gravity through proven scaling laws. In addition to accurate representation of field stress-strain conditions, centrifuge physical modelling can provide decades the settlement response in a matter of days, revealing the anticipated life cycle of a tailing's storage and disposal project.

GeoCERF has iterated the self-weight consolidation tests in multiple projects and with more than 50 types of tailings materials, with the majority from oil sands tailings in Northern Alberta. The core testing equipment is cylindrical consolidations cells. Multiple sizes have been developed to meet unique testing requirements (Figure 1).

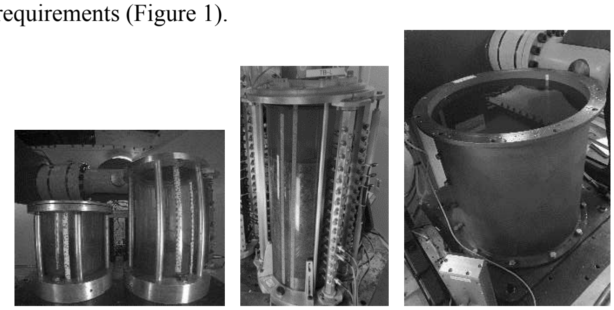

Figure 1 Consolidation cells developed for modelling the self-weight consolidation of tailings

These consolidation cells house pressure transducer ports that provide real-time monitoring of the dissipation of pore pressures. Laser sensors and LVDTs can be attached to detect the settlement, in addition to the high-frequency photos from high-resolution cameras. Miniaturized T-bars and CPT probes can be mounted on the consolidation cell to provide in-flight estimation of the strength profiles. The cell has multiple drainage points that can be configured to represent single or double drainage conditions.

GeoCERF has conducted extensive research on the self-weight consolidation of tailings. Combining the centrifuge scaling effect with comprehensive instrumentation package, the platform offers an accurate and efficient modelling approach. Figure 2 shows a typical tailings self-weight consolidation test while it was conducted under 80G in the centrifuge. The settlement profile, pore pressure dissipation curves and undrained shear strength profile can be obtained in real time while using the onboard instrumentation.

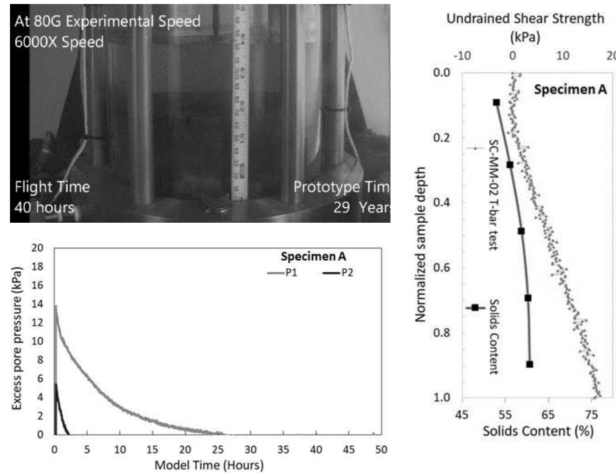

Figure 2. Tailings consolidation test on the beam centrifuge

Comparative analysis is a major strength of centrifuge physical modelling as it offers a highly fixable testing environment while greatly speeding up the evaluation time. This is especially useful for industries actively developing new tailings treatment techniques such as the oil sands operators in Canada (Ansah-Sam et al. 2019, Dunmola et al. 2019, Zambrano-Narvaez et al. 2018a, Zambrano-Narvaez et al. 2018b). Research conducted in GeoCERF compared decades of settlement behaviors from 8 types of different treated oil sands tailings (Figure 3). The effectiveness of each new type of tailing was experimentally assessed in a matter of days compared to years of field study. Centrifuge modelling offers cost-effective verification tools compared to convention field test when conducting comparative analysis of new tailing types.

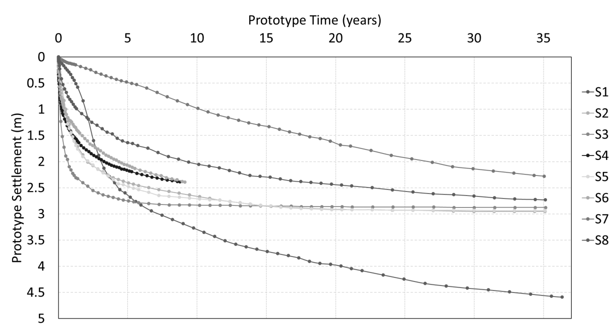

Figure 3. Research conducted at GeoCERF shows consolidation behavior of 8 different types of oil sands tailings.

2.2 Multi-stage consolidation modelling

Building upon the one-dimensional self-weight consolidation models, multi-stage and multi-layer consolidation models are developed to reflect on the unique deposition and consolidation plan of tailings facility in operation.

GeoCERF conducted a multi-stage physical modelling project aimed to replicate the multi-stage filling process of the oil sands tailings and the long-term self-weight consolidation behavior of the pond in the centrifuge lab environment (Zambrano-Narvaez et al. 2021, Zambrano-Narvaez et al. 2022). Each centrifuge lift was created with regards to the centrifuge dimensional scaling law and represented a full deposition stage in the field. With the temporal upscaling effect of the centrifugal law, the sequence and duration of lifts matched the field staging schedule provided by an oil sands operator. A consolidation cell with extended height was manufactured to accommodate 15 stages of tailings deposition. Each fill of tailings was achieved through a customized tailings dispenser that recreated the single discharge action of tailings in quick succession for the centrifuge environment. With spacing markers in between, the evolution of individual lift was modelled simultaneously. Long-term consolidation characteristics of each layer as well as the entire tailings pond were successfully obtained and interpreted to provide valuable data for the tailings pond operator. Figure 4 shows the tailings dispensers used and the 45-year consolidation curve.

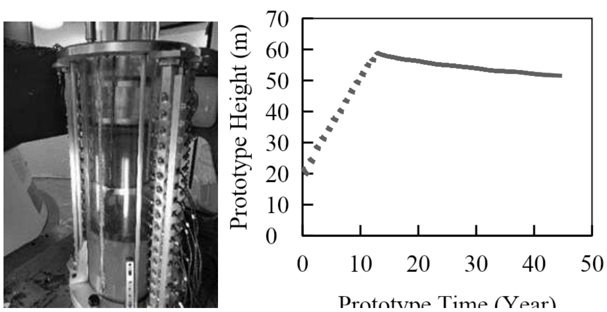

Figure 4. Multi-stage tailings dispenser and muti-stage consolidation curve

Co-deposition of tailings is a management strategy for mine operators. It involves a two separate tailings treatment plan and deposition of two types of tailings in a single storage facility to save space. Due to the difference in nature of the two types of tailings streams, the co-deposition could affect the displacement and run-off conditions. Centrifuge physical modelling proves to be a reliable approach. A project in GeoCERF successfully demonstrated to be capable of simulating large-scale field co-deposition problems. The effectiveness of tailings co-deposition technique was experimentally verified in a matter of days instead of years of field study. Critical process such as segregation are evaluated as the centrifuge model truthfully recreated the field stress and strain conditions.

2.3 Stacked tailings and slope stability modelling

Stacked tailings is a deposition and storage option for mine operators to manage tailings with low moisture content by stacking tailing, often in layers, to form engineering structures that vary in shape and size depending on the specific site and requirements. Stacked tailings require less space and have reduced environmental footprint, however management of stacked tailings requires careful planning, especially in maintaining the slope stability. Beam centrifuge can be used to simulate tailings stacking and analyze the slope stability with significantly downsized model while maintaining the stress-strain field of insitu conditions. The construction of stacked tailings models allows for single or multi-material setup. The model can be well-instrumented with pore-pressure sensors and LVDTs to monitor the progress of slope failures. High speed camera with up to 100Hz refresh rate can be used to capture the failure mechanism in great clarity and smoothness. Figure 5 shows a centrifuge test program conducted by GeoCERF that simulate the long-term self-weight consolidation and slope stability of graphite mine tailings under 100G. In this test, the slope remained intact while significant vertical deformation was observed.

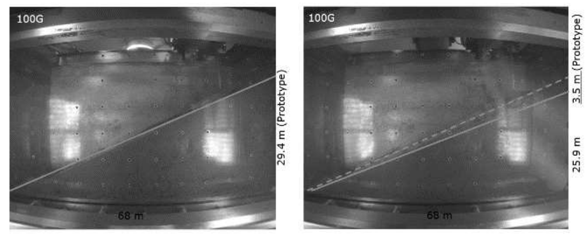

Figure 5. Deformation captured from a stacked graphite tailings slope in a centrifuge test

Plain load can be applied to the crest of the stacked tailings or a slope embankment to simulate the artificial loading due to human activity or environmental impact. This is achieved with the actuator from the beam centrifuge. The actuator can be programed to be constant speed or constant load. Figure 6 shows a centrifuge test conducted at GeoCERF that simulate the stability a clay embankment under a vertical plain load (Simms et al. 2023). The constant speed loading was maintained with a vertical actuator and the actual load was measured with a load cell. The failure process lasted only 2 seconds but was captured with the on-board camera.

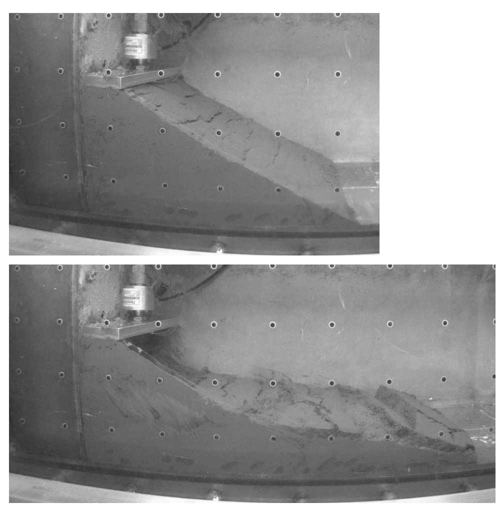

Figure 6. Slope failure after applying plain load in a centrifuge test

The in-situ tailings strength data can be collected in a variety of methods, and some can be miniaturized to work in the centrifuge environment. Figure 7 shows the fall cone tests conducted in 1G environment and mini-CPT penetration tests conducted in-flight. Both equipment can be positioned precisely with the dual-axis actuator and can be conducted at multiple locations throughout the test.

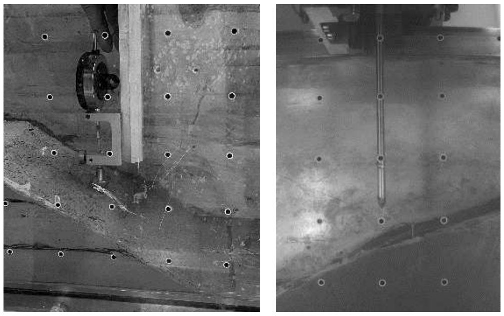

Figure 7. Fall cones and mini-CPT (in-flight)

2.4 End-pit consolidation modelling

End pit lakes (EPL) are used at many mine sites and are a preferable solution for reclamation and closure. Developing a successful pit lake requires advanced planning and iteration of research results. The self-weight consolidation behavior of tailings is crucial to the design of EPL and an accurate and timely prediction will greatly facilitate its planning and management. There has been limited experience with 3D modelling of the EPL consolidation of tailings, which are subject to substantial post-placement settlement and associated water release. Physical modelling in the geotechnical centrifuge is well suited to explore a variety of EPL geometries and deposition processes. Integrating 3D printing rocks advance laboratory facility (GeoPrint) and physical modelling of self-weight consolidation of soft tailings in hyper gravity environment (GeoCERF) allow to 3D printing of a mine pit geometry and centrifuge tests to assess tailings deposition and characterize lateral infiltration inflow or outflow conditions.

GeoPrint utilizes ExOne M-Flex 3D printer, using sand to create physical test models for model verification is an unprecedented achievement that integrates geoscience and engineering to model (Osinga et al., 2015, Primkulov et al, 2017, Gomez et al, 2019, Ardila et al., 2019, Song et al., 2020). For this application the 3D printer modeled the downscaled pit base (Figure 8). The pit base is printed in several pieces and fitted together with binder. The pit base is impermeable.

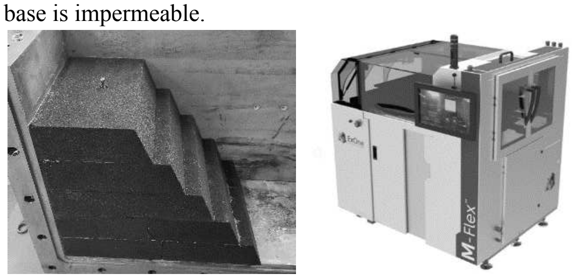

Figure 8. A pit base model printed by ExOne M-Flex 3D printer (GeoPRINT)

Placed within a strongbox, a pit consolidation commissioning test was conducted with multiple deposition of clays materials. Each layer was marked with linings of petroleum coke powder and spun for one prototype year before the subsequent layer was deposited. A fully filled in-pit deposit was spun for an additional 50 prototype years. Results showed that the self-weight consolidation behavior of each layer as well as the entire deposit can be obtained and analyzed using the photographic method as well as interpreting pore pressure data (Figure 9).

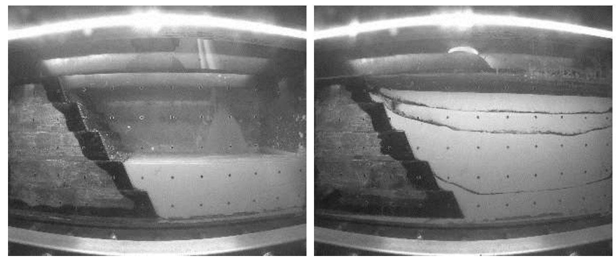

Figure 9. 50 years of self-weight consolidation of in-pit clay deposits

3 CONCLUSION

The geotechnical beam centrifuge is a powerful tool offering both accuracy and efficiency in modelling tailings storage and disposal problems. The fundamental principles of physical modellings are the scaling laws, with which the centrifuge model can be designed and tested that resembles the stress-strain conditions of the prototype while greatly reduces the space and time required for full simulation. GeoCERF has successfully completed a range of tailings physical modelling. Starting with the fundamental one-dimensional self-weight consolidation tests, a wide range of consolidation cells are manufactured to accommodate the large range of tailings deposition depth and drainage conditions. Instrumentation such as pore pressure transducers, LVDTs, high speed cameras, penetrometers can be fitted to the consolidation cell to obtain additional in-flight measurement. Multi-stage consolidation can be simulated by expanding upon the single stage scenario by introducing customized tailings dispensers to simulate multi-lift construction or creating co-deposition models of tailings. In addition to one dimensional modelling consolidation, the beam centrifuge can also be used to evaluate the deformation and stability of stacked tailings. The stacked models follow the centrifuge scaling laws and can be constructed with one or multiple types of materials in multiple stages. The strongbox can provide more space with this type of simulation and a dual axis actuator be installed to conduct in-flight penetration tests and apply plain loading to an embankment. Combining with 3D printed rock formations, a custom-designed pit base model can be fitted inside the strongbox to allow for in-pit consolidation simulation of tailings, another common option for tailings storage and disposal.

Centrifuge physical modelling proves to be an accurate and quick approach of "calibrating" and verifying the tailings storage and disposal problems driven by gravity. As centrifuge modelling is built upon geometric similitude, the in-situ tailings structure can be replicated in the same stress-strain conditions. Combined with the use of onboard instrumentation centrifuge modelling facilitates the collection of field-scale data in a cost-effective manner while maintaining the well-defined tailings parameters and boundary conditions. This paper introduces the well-instrumented centrifuge modelling package and reviews simulation projects covering a range of tailing types and storage options. It has demonstrated centrifuge physical modelling as a highly valuable toolset in the design and management of tailings storage and disposal facilities.

4 Acknowledgements

We gratefully acknowledge the support of the Natural Science and Engineering Research Council of Canada (NSERC) Discovery Grant (RGPIN-2023-04981).

5 References

Ansah-Sam, M., Stianson, J., Rudolf, K., & Zambrano Narvaez, G. (2019). Comparison of oil sand tailings consolidation properties derived from beam centrifuge and large-strain consolidometer testing. Proceedings of Tailings and Mine Waste 2019, Vancouver, Canada, November 17–20, pp. 865-878.

Ardila, N., Zambrano-Narvaez, G., & Chalaturnyk, R. J. (2019). Wettability measurements on 3D printed Sandstone Analogues and its implications for fluid transport phenomena. Transport in Porous Media, 129, pp. 521–539.

Croce, P. (1984). Evaluation of consolidation theories by centrifuge modeling. In Proceedings of the Symposium on Application of Centrifuge Modeling to Geotechnical Design (pp. 381-402).

Dunmola, A., Mikula, R., Ali, M., Siman, R., Lorentz, J., Zambrano Narvaez, G., & Chalaturnyk, R. J. (2019). Impact of residual bitumen on the long-term consolidation of FFT. Calgary, Canada, June 3-4.

Garnier, J., Gaudin, C., Springman, S. M., Culligan, P. J., Goddings, D., König, D., ... Thorel, L. (2007). Catalogue of scaling laws and similitude questions in geotechnical centrifuge modeling. International Journal of Physical Modelling in Geotechnics, 7(3), pp. 1-23.

Gomez, J. S., Chalaturnyk, R. J., & Zambrano-Narváez, G. (2019). Experimental investigation of the mechanical behavior and permeability of 3D printed sandstone analogues under triaxial conditions. Transport in Porous Media, 129, pp. 541–557.

Osinga, S., Zambrano-Narvaez, G., & Chalaturnyk, R. J. (2015). Study of geomechanical properties of 3D printed sandstone analogues. In 49th U.S. Rock Mechanics/Geomechanics Symposium, San Francisco, California, June 28-31.

Primkulov, B., Chalaturnyk, R. J., & Zambrano-Narváez, G. (2017). 3D printed sandstone strength: curing of furfuryl alcohol resin-based sandstones. 3D Printing and Additive Manufacturing, 4(3), pp.149-156.

Simms, P., Xia, X., Patel, A., Parent, E., Beier, N., & Zambrano-Narvaez, G. (2023). Rheology for deposition control and deposit failure risk analysis. Proceedings of the 25th International Conference on Paste, Thickened and Filtered Tailings, April 29 – May 3, 2023.

Song, R., Wang, Y., Ishutov, S., Zambrano-Narvaez, G., Hodder, K. J., Chalaturnyk, R. J., ... Gamage, R. P. (2020). A comprehensive experimental study on mechanical behavior, microstructure, and transport properties of 3D-printed rock analogs. Rock Mechanics and Rock Engineering.

Sorta, A. R., Sego, D. C., & Wilson, W. (2016). Physical modeling of oil sands tailings consolidation. International Journal of Physical Modelling in Geotechnics, 16(2), pp. 47-64.

Taylor, R. E. (Ed.). (2018). Geotechnical centrifuge technology. CRC Press.

Toh, S. H. (1992). Numerical and centrifuge modeling of mine tailings consolidation (PhD diss., University of Western Australia).

Zambrano-Narvaez, G., & Chalaturnyk, R. (2014). The new GeoREF geotechnical beam centrifuge at the University of Alberta, Canada. 8th ICPMG, Perth, Australia, January 14-17, (1), p. 163.

Zambrano-Narvaez, G., Wang, Y., Chalaturnyk, R. J., Zahabi, A., & Rennard, D. (2018a). Assessment of self-weight consolidation of co-deposition deposits in the geotechnical beam centrifuge. Sixth International Oil Sands Tailings Conference, Edmonton, Alberta, December 9-12.

Zambrano-Narvaez, G., Wang, Y., & Chalaturnyk, R. J. (2018b). Comparative study of consolidation behavior of differently-treated mature fine tailings specimens through centrifuge modeling. Proceedings of 9th International Conference Physical Modelling Geotechnics, City, University of London, July 17-22, pp. 1271-1276.

Zambrano-Narvaez, G., Wang, Y., & Chalaturnyk, R. (2021). Assessing consolidation performance for multi-lift in-pit oil sands tailings with a geotechnical beam centrifuge. Proceedings of Tailings and Mine Waste 2021, November 6–10, 2021, Banff, Canada.

Zambrano-Narvaez, G., Wang, Y., & Chalaturnyk, R. (2022). Predicting multi-lift mine tailings consolidation with centrifuge physical modeling and numerical simulation. 10th International Conference on Physical Modelling in Geotechnics (ICPMG 2022).