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Application of a one-dimensional large-strain consolidation model to a full-scale tailings storage facility

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ABSTRACT

The objective of this study was to evaluate applicability of a commercially-available, one-dimensional (1-D) large-strain consolidation model to predict mine tailings consolidation in a full-scale tailings storage facility (TSF). Data pertaining to tailings production, cyclone operation time, impoundment height, and impoundment volume were made available for a full-scale copper mine TSF. A numerical model was applied to predict tailings consolidation for two considerations: Design Assessment – based on design estimates, and Operation Assessment – based on actual operational data. Comparison between actual average tailings dry density (ρ_d) during the first 4 yr of operation and predicted ρ_d yielded coefficients of determination (R^2) as high as 0.81 for the Operation Assessment and 0.93 for the Design Assessment. Predictions of tailings height for both assessments also agreed well with actual impoundment heights for the first 6 yr of operation. A procedure was developed to predict average ρ_d of a full-scale TSF that includes (i) estimating TSF volume based on predicted impoundment height and (ii) using TSF volume with dry tailings mass to compute ρ_d. The main finding was that the modeling of gradual tailings deposition via a 1-D large-strain consolidation model can provide a reliable prediction of tailings height and capacity during TSF operation.

1. Introduction

Mine tailings are a by-product of ore processing that predominantly consist of fine-grained particles with high water content and residual chemicals from ore extraction (e.g., Bussière 2007; Blight 2010). Tailings generally are transported and disposed as slurry into large impoundments called tailings storage facilities (TSFs). The mass and corresponding volume of tailings generated at a given mine currently is increasing due to the increasing prevalence of mining low-grade ores (West 2011). Processing low-grade ores increases the volume of tailings that require management in TSFs. For example, Chuquicamata Mine located in Atacama, Chile produced approximately 161,000 metric tons per day (1 mtpd = 1 Mg/d) of ore production, which generated a comparable mass of tailings following ore extraction (Wels and Robertson 2003).

Understanding and predicting physical and chemical processes of tailings following deposition in TSFs present challenges to the mining community. In particular, consolidation of tailings presents a challenge at nearly all mines due to increasing tailings generation and disposal of tailings as slurry. Consolidation relates to the decrease in volume of tailings that is attributed to the dissipation of excess pore water pressure, discharge of pore water, and increase in effective stress. Thus, high water content, low hydraulic conductivity fine-grained mine tailings can yield large volume reductions and long elapsed times for completion of consolidation (e.g., Carrier et al. 1983; Znidarčić et al. 1984; Abu-Hejleh et al. 1996; Consoli and Sills 2000). Thickening of mine tailings via water extraction is an alternative tailings management option that can reduce consolidation settlement and increase water reclamation for reuse in mining operations (Bussière 2007; Blight 2010). However, consolidation of tailings remains a relevant challenge for mine planners and owners as consolidation affects stability, storage capacity, and final closure of TSFs.

Gibson et al. (1967) presented a governing equation for one-dimensional (1-D) large-strain consolidation of saturated clays and other fine-grained soils that undergo considerable volumetric deformation. The model developed by Gibson et al. (1967) accounts for changes in soil compressibility and hydraulic conductivity during deformation, which addresses the constraint of small-strain deformation (i.e., constant material properties) assumed in Terzaghi's consolidation theory (Terzaghi, 1996). Considerable research has been conducted on large-

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strain consolidation model formulation (e.g., Koppula 1970; Somogyi 1980; Pane and Schiffman 1981; Znidarčić et al. 1984; McVay et al. (1986); Abu-Hejleh et al. 1996; Fox and Berles 1997; Fox and Pu 2012; Ito and Azam 2013) and laboratory evaluation of compressibility and hydraulic conductivity constitutive relationships (e.g., Znidarčić et al. 1992; Aubertin et al. 1996; Suthaker and Scott 1996; Priestley 2011; Znidarčić et al. 2011; Estepho 2014). Additionally, large-strain consolidation computer programs have been developed and adopted in mining practice for one-, two-, and three-dimensional (1-D, 2-D, and 3-D) consolidation that can aid TSF design (e.g., Gjerapic et al. 2008; Fredlund and Gitirana 2009; Coffin 2010). Although large-strain consolidation has been studied extensively since the late 1960s, there are few full-scale TSF case studies that have been evaluated to document performance of large-strain consolidation models (e.g., Geier et al. 2011; Bhuiyan et al. 2015). Furthermore, there has been limited application of 1-D consolidation models in the early stages of tailings deposition to estimate volumetric storage capacity in full-scale TSFs.

The objective of this study was to evaluate the applicability of a commercially-available 1-D large-strain consolidation program in predicting tailings consolidation to estimate tailings dry density and storage capacity of a full-scale TSF. Four years of data pertaining to the following operations were made available to the authors for a full-scale copper TSF: monthly average whole tailings production rates, cyclone operation time, tailings underflow production, impoundment height, and impoundment volume. An additional two years of data were provided for impoundment height and impoundment volume. Consolidation models were conducted to predict tailings dry density considering an as-designed scenario (Design Assessment) as well as actual tailings production and discharge operations (Operation Assessment).

2. Methods and materials

A cross-sectional schematic of the TSF at the full-scale copper mine evaluated in this study is shown in Fig. 1a. The TSF had been operational for approximately 8 yr at the time of this study and is designed to have a maximum embankment height of 260 m (at centerline) at completion of construction. A rock-fill starter dam was constructed to retain tailings within the TSF and subsequent embankment dam raises were constructed from coarser tailings (i.e., underflow tailings) extracted from whole tailings via a cyclone. A schematic of the tailings generation and management operations at the full-scale copper mine is shown in Fig. 1b. Whole tailings (WT) refer to the bulk tailings generated at the concentration plant that were subsequently passed through a thickener and onto the cyclone. Whole tailings analyzed in this study were those tailings received at the cyclone or deposited directly into the impoundment when the cyclone was not operational. Overflow tailings (OT) refer to the finer tailings fraction that was discharged to the TSF when the cyclone was operational. The underflow material predominantly was free-draining coarse sand, and the OT or WT were discharged to the TSF for disposal and management. Limited information about the mine has been provided herein due to proprietary requirements stipulated by the mine owner.

2.1. Mine tailings

A summary of select geotechnical characteristics for WT and OT from the copper mine are summarized in Table 1. Two samples of whole tailings (WT-1 and WT-2) were used in this study, whereby WT-1 represents whole tailings characterized during pilot-scale planning for the mine site and WT-2 represents whole tailings characterized during full-scale operation of the copper mine. Overflow tailings (OT) refer to the finer-grained, overflow material produced during cycloning, which was the primary material discharged into the TSF when the cyclone was operational. These three copper tailings were used in consolidation modeling for the case study.

The WT-2 classified as low plasticity clay/silt (CL-ML) with approximately 60% fine-grained material (i.e., passing the No. 200

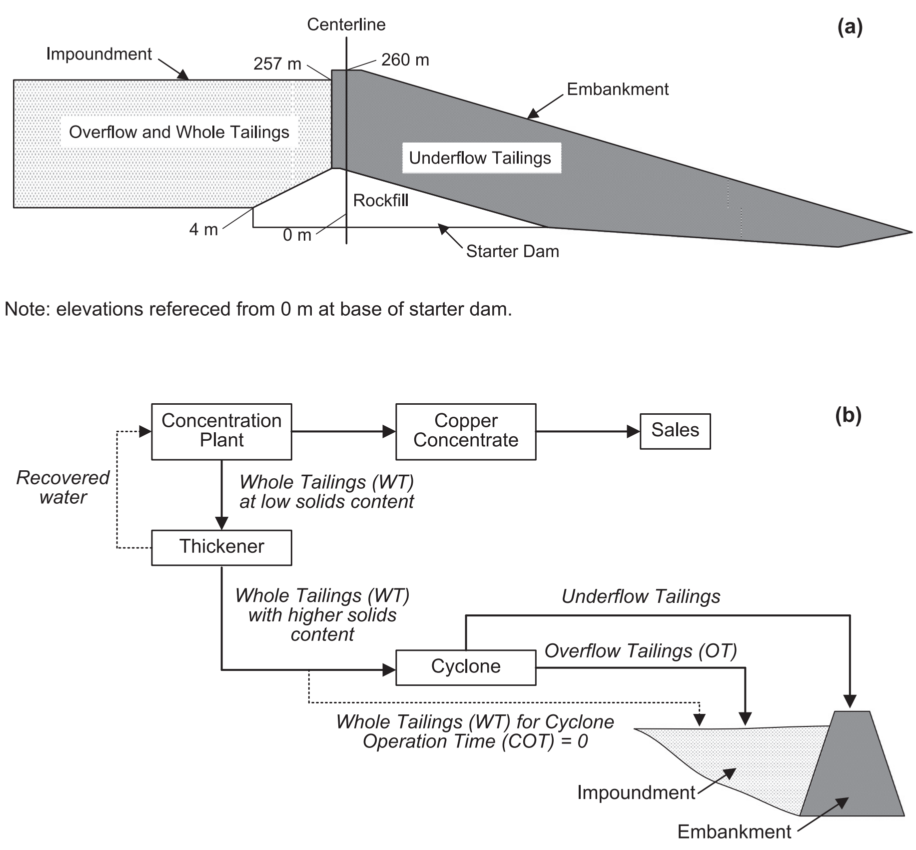

Fig. 1. Schematics of (a) a typical cross-section of the centerline embankment dam and (b) an operational diagram for tailings generation and management at the full-scale tailings storage facility case study. The maximum embankment height = 260 m (at centerline) and maximum tailings impoundment height = 253 m. The impoundment contains overflow tailings (OT), which are the finer fraction after cycloning, and whole tailings (WT), which are bulk tailings discharged directly from the concentrator plant without cycloning (i.e., cyclone operation time, COT, = 0). The embankment is built from underflow tailings (UT) that are the coarse fraction after cycloning. Note: elevations referenced from 0 m at base of starter dam.