# Tailings Water Hydraulics Analyses for Risk Based Design

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**Abstract** Commensurate objectives of optimal water use, as well as of risk based design criteria, require viable estimates of the hydraulic behaviour of impounded materials during deposition and post closure. The HYDRUS-2D soil-water physics model is used to illustrate ranges of hydraulic behaviour in cycloned and spigotting deposition in metal tailings impoundments for a range of deposition criteria. The results summarise criteria leading to optimal water use, impoundment instabilities and unacceptable leaching below the impoundment. These criteria can be applied to optimise water use during tailings deposition as well as satisfy predictions during risk based design.

**Key words** Tailings hydraulics, Risk based design.

## Introduction

Commensurate objectives of optimal water use in cost effective tailings impoundment development, as well as of risk based design criteria require viable estimates of the saturated and unsaturated hydraulic behaviour of impounded materials during deposition and post closure. Common methods of estimating drainage, seepage and phreatic surface development in tailings impoundments consider contributions from the pool and average atmospheric inputs at the tailings surface. However, detailed deposition sequences, rainfall and evaporation fluxes and the hydraulic behaviour of the material are often called for to satisfy risk based design criteria and to optimise water use. In particular, tailings deposition using centrifuge methods to separate coarse fractions (underflow) for deposition in the outer walls and fines (overflow) into the tailings beach, require consideration of water influxes into the outer edges, comprising high hydraulic conductivity underflow material, as well as variable influxes from the pool and tailings beach. While holistic risk based approaches are desired (Rademeyer et al. 2008; Yibas et al. 2012; Barrera et al. 2015), detailed technical analysis allows for optimising water use together with satisfying stability criteria and minimising environmental impacts through seepage. Excessive water deposition with underflow material may result in stability criteria being violated, whereas a reduction in water content deposited with the underflow may require adjustment of drain positioning to optimize water recovery and minimize head build-up on base liner systems. Accurate estimates of the development of positive hydraulic heads within the tailings are critical for stability estimates, drainage design, considerations of base lining methods and leachate predictions.

The HYDRUS-2D soil-water physics model is used to illustrate ranges of hydraulic behaviour in cycloned deposition as well as traditional spigotting in gold, copper and platinum tailings impoundments for a range of deposition criteria, daily atmospheric inputs, drain placement and base liner conditions. The examples are applied to a hillslope deposition, where a 2D analysis is warranted (Garrick et al. 2014).

## Methods

In order to simulate the hydraulic performance of a proposed platinum tailings dam, an existing dam was first characterised and the simulated phreatic surface position, fluxes to drains and hydraulic gradients were compared to those observed. Once satisfactory performance of the 2D model is obtained, the proposed design can be evaluated.

The hydraulic properties of the existing tailings dams were measured using in-situ double ring infiltrometer, tension infiltrometer and Guelph permeameter tests on site and supplemented with constant head laboratory tests on undisturbed samples. Gold, Copper and Platinum tailings materials were measured for comparative purposes. The depth of in-situ measurements was only possible to 2.5 m below surface and so the results of piezocone tests were analysed in an attempt to determine hydraulic conductivities in consolidated materials to a depth of 50 m below surface. However, the results were highly variable and were only used as a guide in the modelling.

In the Platinum tailings, in-situ observations of the phreatic surface levels were made through piezometers installed to below the saturated water level. Piezcone observations were interpreted together with the piezometer observations to determine effective vertical hydraulic gradients.

Observation of fluxes from the tailings dam drains were extracted from mine records, although some seepage was observed through the toe walls on occasions.

The simulation modelling included the rainfall and potential evaporation drivers as well as slurry water inputs. In the simulation of the cyclone deposition in the platinum tailings, the slurry inputs were divided between water deposited with the coarse underflow material on the edge and the overflow water deposited on the beach (fig. 1). Intermittent rain and slurry inputs to the surface of a 2D (Šimůnek et al. 2006) section of the tailings dam pose a difficulty in simulating the entire section (Rykaart et al. 2001; Rykaart and Wilson 2003) and so HYDRUS-1D (Šimůnek et al. 2009) simulations of rainfall, potential evaporation and intermittent slurry application were used to derive effective boundary fluxes on the surface. These were applied as variable flux or atmospheric boundary conditions (fig. 1). Drains were simulated by specifying seepage face boundary conditions and the pool was specified as a constant head boundary. Liner systems at the base of the tailings, comprising porous media materials were included by specifying the hydraulic characteristics of the liner materials. However, in order to simulate geomembrane liners, an iterative approach was used. Here, the fluxes through the liner cannot be derived through Darcy physics, so a relationship between the imposed head on the liner and the subsequent flux was derived for various liner qualities (Giroud and Bonaparte 1989; La Touche and Hollie 2012). The head-flux relationship was applied as a variable flux bottom boundary condition in an iterative simulation until the heads dictated by the saturated/unsaturated flow through the tailings and the flux through the liner were in equilibrium.

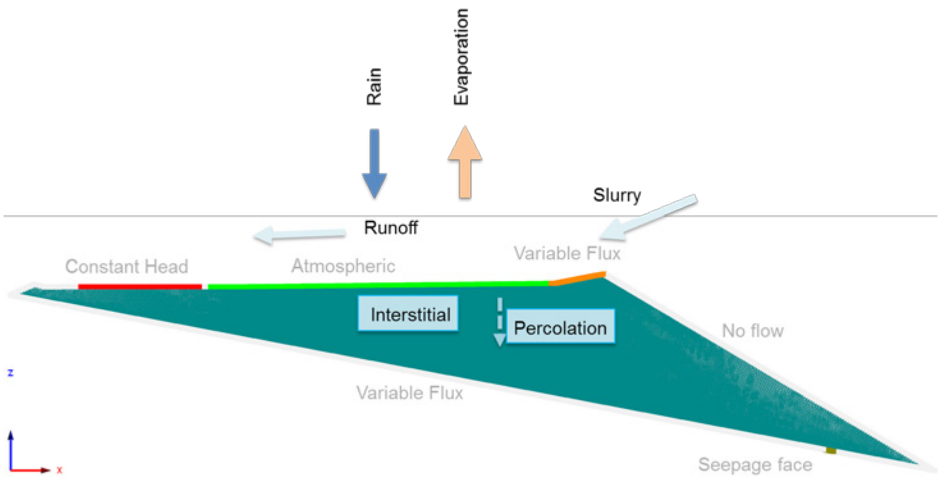


***Figure 1*** *Illustrated processes and boundary conditions of the 2D simulated tailings dam*

## Results

The results of typical hydraulics conductivity measurements on the tailings surface are presented in tab. 1. No significant differences between the saturated hydraulic conductivities on the surface were found between the edge and pool of the tailings as listed for the gold tailings. However, significant differences of the hydraulic conductivities at small tensions (200 mm) were measured. These decreased from the edge of the tailings to the pool location,

***Table 1*** *Surface Hydraulic Conductivities of Gold, Copper and Platinum Tailings.*

| Material | Position | Ksat (m/s) | K(200) (m/s) |
|---|---|---|---|
| Gold | Edge | $2.6 \times 10^{-6}$ | $6.1 \times 10^{-7}$ |
| Gold | Middle | $1.9 \times 10^{-6}$ | $1.0 \times 10^{-7}$ |
| Gold | Pool | $2.8 \times 10^{-6}$ | $6.3 \times 10^{-8}$ |
| Copper | Edge | $3.9 \times 10^{-6}$ | $3.7 \times 10^{-7}$ |
| Platinum | Underflow | $7.9 \times 10^{-6}$ | |
| Platinum | Overflow Edge | $5.6 \times 10^{-6}$ | |
| Platinum | Overflow Middle | $5.4 \times 10^{-6}$ | |
| Platinum | Overflow Pool | $5.9 \times 10^{-7}$ | |

Ksat = Saturated hydraulic conductivity
K(200) = Hydraulic conductivity at tension 200 mm

Differences between the platinum underflow material and the overflow material were evident with depth below the surface (fig. 2). Here, the coarse underflow material is an order of magnitude higher than the overflow material at depth below 1 m.

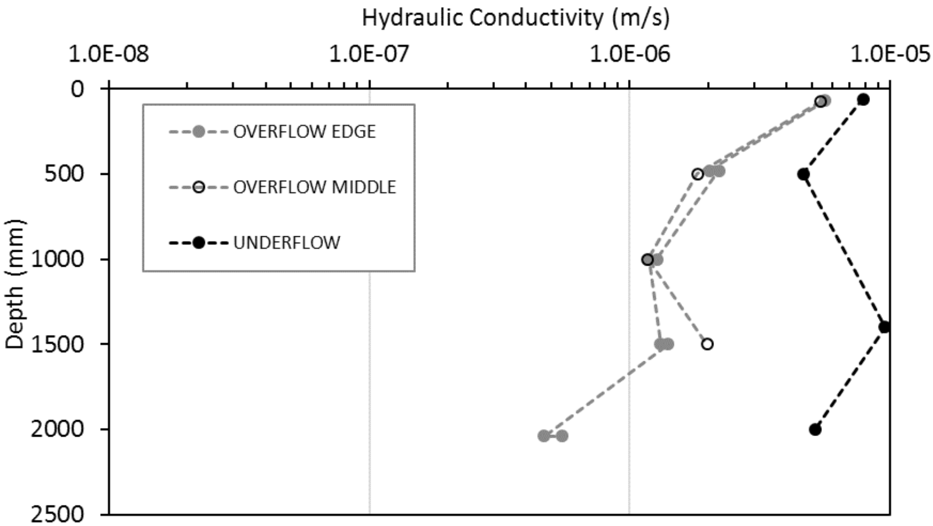


***Figure 2*** *Saturated hydraulic conductivities in the Platinum tailings.*

The HYDRUS-2D simulations of the phreatic surface of the existing platinum dam compared favourably to the observed levels. The simulated fluxes from the drains ranged from 120 $m^3$/day to 425 $m^3$/day, whereas observed values ranged between 184 $m^3$/day and 272 $m^3$/day. The higher simulated peak values were considered feasible due to the observed seepage from ungauged sources.

Comparing the simulated vertical gradients with those inferred from piezocone/piezometer observations revealed an under simulation of the vertical gradient. However, with a seepage loss from the base of the dam specified at 3.5 mm/day, the gradient matched. Nevertheless, the interpretive work between piezocone and piezometer observation is continuing in order to improve these comparisons.

With the model performing suitably, illustrative scenarios of the proposed design were performed at a development stage of 100 m. The phreatic surfaces resulting from conventional tailings deposition are illustrated for gold, copper and platinum tailings in fig. 3a. These indicate the drawdown to a blanket drain which results in stable tailings slopes.

However, deposition of large quantities of water with coarse underflow material in cyclone deposition could impose a stability risk (fig. 3b). Slurry water from the underflow moves rapidly through the material until it reached the underflow/overflow interface. Here, the water does not preferentially discharge down the high conductivity underflow material, but is drawn into the overflow tailings along a length of the interface. This results in a raised phreatic surface unless the water deposited with the underflow is reduced from 25% to 8% of the total slurry water (fig. 3b). The phreatic surface position is worsened if intermediate drains, placed between the toe drain and the blanket drain fail.

The addition of a further drain, 150 m upslope of the blanket drain, alleviates the phreatic surface further (fig. 3c). Seepage losses through a geomembrane liner also lowers the phreatic surface. Here, environmental impacts need to be evaluated and improved liner conditions specified, if required.

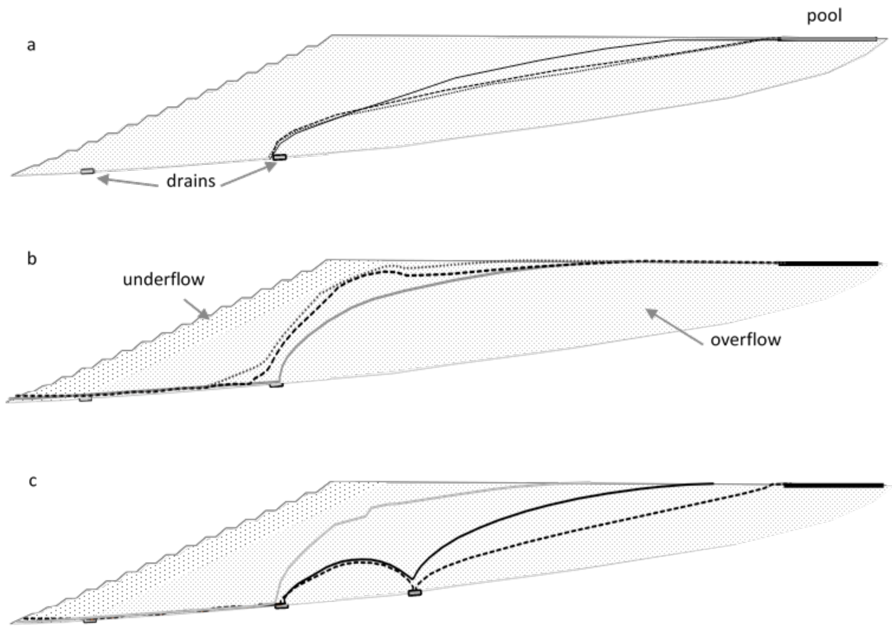


***Figure 3*** *Simulated phreatic surfaces of a) conventional deposition of platinum (solid grey line), gold (dashed line) and gold (dotted line) tailings; b) cyclone deposition of platinum tailings with 8% of the slurry water deposited with the underflow (solid grey line), 25% of the slurry water deposited with the underfow (dashed line) and 25% of the slurry water depoisted with the underflow without intermediate drains between the toe drain and the blanket drain and c) cyclone deposition with 15% of the slurry water deposited with the underflow (solid grey line), with a second drain 150mm upslope of the blanket drain (solid black line) and with a second drain with seepage from the base (dashed black line).*

## Conclusions

The results summarise criteria leading to optimal water use, impoundment instabilities and unacceptable leaching below the impoundment. In particular, results of cyclone deposition indicate that reducing the water:solids ratio of underflow deposition on a 100 m high tailings impoundment from 25% to 8% of the total slurry water, improves the stability criteria with drains positioned between 200 m and 350 m from the toe, while effectively capturing percolating water for recirculation and minimizing the pressure head on the base.

These criteria can be applied to optimise water use during tailings deposition as well as satisfy predictions of tailings hydraulic fluxes and pressure distribution during risk based design.

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