Solving Tailings Impoundment Water Balance Problems with 3-D Seepage Software

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Abstract

Rehabilitation of tailings impoundments for final closure is one of the most challenging aspects facing engineers, as not only does the potential for producing leachate pose a challenge to the rehabilitation designer, but also other aspects such as stability and settlement must be considered. The water balance of a tailings impoundment is unique in the sense that it usually hosts a pond that in turn causes a phreatic surface in the impoundment. The position of the phreatic surface defines the saturated and unsaturated zones in the impoundment, which of course varies spatially and temporally. Predictive modeling for this hydrologic system becomes difficult, as numerical models capable of analyzing the combined saturated/unsaturated zones are not adequately refined to accurately solve the flux boundary problem for infiltration at the surface of the tailings.

This article describes the use of a net infiltration flux boundary function to bridge the gap between rigorous surface flux boundary calculations and multidimensional seepage analysis models. An evaluation of the flux boundary function was done with the aid of a full 3-D numerical model SVFlux™, developed by SoilVision Systems Ltd., and the article describes how the use of the flux boundary function allowed the 3-D model to be simplified, without sacrificing accuracy.

Introduction

The gold tailings impoundment described in this article is located in Queensland, Australia. The climate is semi-arid, with an annual rainfall of 702 mm, falling mostly as high intensity showers between November and March each year. The potential evaporation of 1650 mm per year results in the annual climatic water balance to be negative. The tailings impoundment was constructed in a stream valley by means of hydraulically placed tailings behind an engineered embankment. The embankment of 5.8 km long encircles 70% of the impoundment and the overall tailings area consist of 310 ha which includes a pool of approximately 100 ha. An additional 104 ha catchment impacts on the tailings impoundment due to the impoundment being constructed against a local hill. The embankment height and subsequent tailings depth varies between 32 m at its deepest to less than 1 m at its shallowest (Rykaart, 2001).

Distribution of Surface Flux Boundary Conditions on the Tailings Impoundment Surface

Both a saturated and an unsaturated zone exist in the tailings impoundment due to the presence of the pool. The established phreatic surface has a shape that is governed by the tailings properties, and the exit location is determined by the presence of drains in the embankment walls. If one thus considers a typical cross-section at any location through the tailings impoundment (Figure 1(a)) there would be an unsaturated zone of tailings which varies in thickness from the embankment end to the pool end.

The top tailings impoundment surface (beach profile) along this typical cross-section would be subject to all the usual water balance components of precipitation (P), evapotranspiration (ET), infiltration (I), runoff (R), recharge (R_e), and seepage (S). It would however be expected that there would be a spatial variation in the magnitude of these components as one move between the embankment and the pool. The reason for this is the availability of moisture in the profile, which is governed by the presence of the phreatic level (Staley, 1957). Therefore, at a point close to the embankment one would expect evaporation to be a minimum, and as one moves towards the pool the evaporation should increase until it reaches a maximum (potential evaporation) at the pool edge. Similarly one would expect infiltration to be a maximum close to the embankment, decreasing towards the pool. This

is simplistically illustrated by the graph in Figure 1(b).

Surface Flux Boundary Modeling

Estimating tailings impoundment water balances has always been an important issue, be it for operational- or closure water management. Most of the saturated zone water balance components are relatively well understood and can be estimated or measured with relative ease and with a high degree of confidence. However, the same cannot be said for the surface flux boundary components above the unsaturated zone. The measurement of these fluxes is difficult,

(Feddes *et al.*, 1984), HYDRUS (Simunek *et al.*, 1998), and SWIM (Ross, 1990), to name but the few most well known.

These models all attempt to calculate the surface flux boundary components using numerous methods and assumptions. The most important single component is calculation of evaporation, and one rigorous mechanistic method to calculate this is using the modified Penman formulation as proposed by Wilson *et al.* (1994). The only known model that currently uses the modified Penman formulation is SoilCover, and that makes it an appropriate tool to use.

Due to the detailed field data re-

tice to solve these water balance problems using multidimensional saturated/unsaturated flow seepage analysis models. However, these models do not allow for the calculation of the surface flux boundary conditions, but require some form of estimated recharge input. To obtain this recharge value the modeller will calibrate towards a known parameter, mostly being a phreatic level, and as such the most suitable recharge value might not represent the surface flux boundary situation correctly.

To overcome this problem, and thus bridge the gap between the two modelling systems, a system has been developed that allows for the calculation of flux boundary functions that best describe the surface flux boundary conditions for any tailings impoundment cross-section. These flux boundary functions can then be used as an actual boundary condition in regional 2-Dimensional (2-D) or 3-Dimensional (3-D) numerical modelling (Rykaart *et al.*, 2001).

Procedure for Calculating the Surface Flux Boundary Functions

The calculation of the surface flux boundary functions rests on a principle of selecting a generalized tailings impoundment cross-section and solving the actual surface flux boundary conditions along this cross section with the SoilCover model.

The generalized cross-section top physical boundary consists of the tailings impoundment beach profile. Due to the hydraulic deposition of tailings particle segregation takes place and an exponential expression can be developed to define the shape thereof. Accurate survey data and physical tailings property testing can be used to verify this function.

The phreatic surface, which location is determined by the tailings properties as well as the presence of any drains and the pond elevation, determines the base of the unsaturated zone that has to be modeled. Using observational techniques via piezometers it is possible to develop a mathematical function that will describe the shape of this boundary (Rykaart *et al.*, 2001).
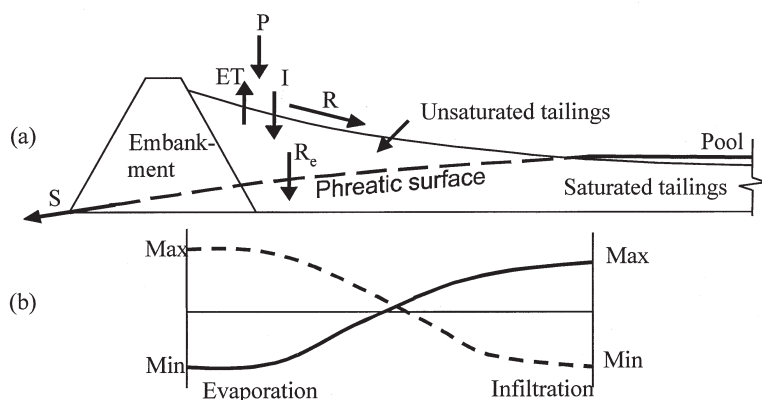
Figure 1. (a) Typical cross-section through a tailings impoundment, (b) Spatial distribution of surface fluxes of infiltration and evaporation.

expensive and time consuming, and as a result engineers look towards numerical modelling to provide the answers. Important advances have been made in this regard, with the development of codes such as SoilCover (SoilCover, 1997), HELP (Schroeder *et al.*, 1994), UNSAT-H (Fayer & Jones, 1990), SWACROP

quired for use of a model such as Soil-Cover, and the fact that it is only a 1-Dimensional (1-D) model, the surface flux boundary condition is often oversimplified using coarse recharge numbers when complex problems such as the tailings impoundment described here are modelled. It is common prac-

Table 1. Soil water characteristic curve properties for the three chosen tailings types used in the SoilCover modelling.

Tailings type	θ_s	AEV	Ψ_r
Coarse	38%	2.5 kPa	8.0 kPa
Intermediate	42%	3.2 kPa	10.0 kPa
Fine	44%	6.0 kPa	70.0 kPa

In order to conduct SoilCover modelling on the generalised tailings impoundment cross-section described above, the section is divided into a number of zones (the width of each zone is determined based on the section shape). For the study described here 13 zones, each 50 m wide was selected. An individual SoilCover model would then be run for each zone, and by integrating the computed surface flux boundary conditions over the entire tailings cross-section a good estimate of the cumulative result would be obtained. This approach thus allows for a 2-D solution using the 1-D SoilCover model (Rykaart *et al.*, 2001).

The material properties required for the SoilCover modelling was determined from an extensive field and laboratory testing program, consisting of 66 grain size distribution- and 25 soil water characteristic curve tests. The tailings varies from well graded sands (SW) (Unified Soil Classification System, Holtz & Kovacs (1981)), with an average D_{50} of 0.26 mm, to fine sands (ML), and an average D_{50} of 0.03 mm (Rykaart, 2001). The soil water characteristic curves indicated a saturated volumetric water content (θ_s) ranging between 34 and 56%, an Air-Entry Value (AEV) ranging between 1.5 and 12 kPa and a residual suction (ψ_r) ranging between 3.5 and 700 kPa (Rykaart, 2001). The data base of tested tailings properties was used to define three main tailings types for modelling purposes; coarse, intermediate and fine. Using a single averaged material type for the entire tailings impoundment cross-section would not be appropriate as measured data had shown that the tailings becomes progressively finer as one moves away from the embankment towards the beach (due to natural particle segregation). The choice of three material types was also based on work done by Kealy & Busch (1971), where they modelled seepage from mill-tailings, and found that three tailings types best describe the model.

The three soil water characteristic curves for these tailings types were respectively selected based on the 75, 50 and 25%-tile values of the θ_s, AEV and ψ_r measured values (Table 1). The
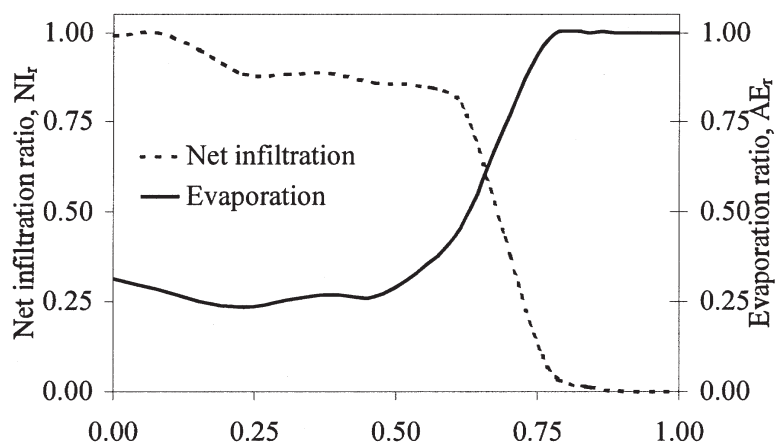

Figure 2. Combined spatial evapotranspiration and net infiltration distribution along the generalised tailings impoundment cross-section.
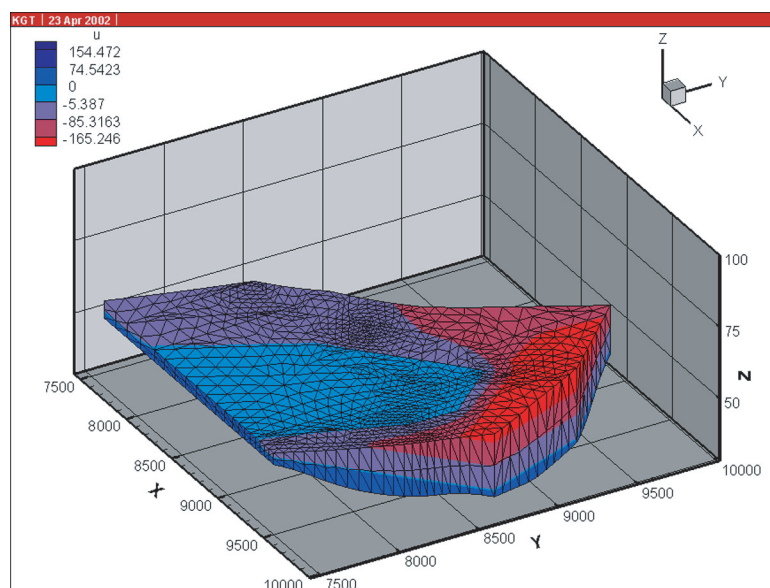

Figure 3. Representation of SVFluxTM finite element results of pressure head at steady state (pressure, u (kPa); dimensions (m)).

steepness of the curves caused modelling instability and these curves had to be flattened in the high matric suction range.

Where the transitions between these tailings types down the beach profile would be was determined by solving of the quasi-2-D SoilCover model. For the

generalised tailings impoundment cross-section in this study a final tailings zone ratio of 5:5:3 was adopted as a good transition for the tailings types. This means that for the first five of the 13, 50 m wide modelled zones, coarse tailings was used, the next five intermediate tailings, and the final three zones
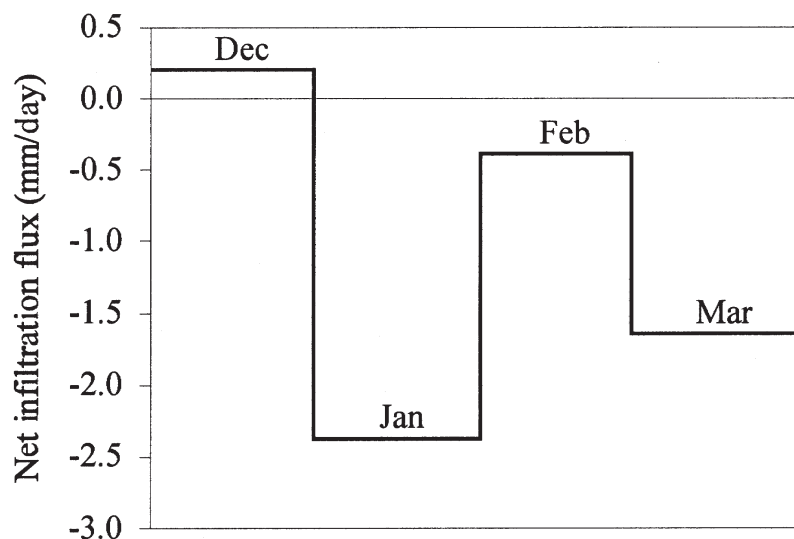
Figure 4. Typical flux boundary function for one of the zones, presenting monthly distribution of net infiltration.

were modelled with fine tailings (250 m: 250 m: 150 m for this 650 m section).

To define the vertical saturated hydraulic conductivity, k_s (m/s), on the tailings beach profile for each of the zones, a theoretical function for saturated hydraulic conductivity was developed. This function was verified using measured field data consisting of 29 laboratory saturated permeability tests, 62 Guelph permeameter tests, 8 doubleing infiltrometer tests and 14 rainfall simulator tests (Rykaart, 2001).

The function is described by the following expression:

[Eq.1]
$$k_s = 1.94 \times 10^{-5} \cdot e^{(-0.00977.H)}$$

Where H (m) is the distance along the beach profile as measured from the embankment, and e is the base of the natural log. Any vertical tailings profile is not homogeneous, and the physical and hydraulic properties of each of the horizontal tailings layers can vary significantly. However, physical tailings characterisation and model calibration supported the assumption that for the purpose of the modelling described here homogeneous vertical profiles would suffice.

The Flux Boundary Functions

Solving of the individual SoilCover simulations, using each of the chosen tailing types, as well as the final optimal combined solution, each presents different spatial flux boundary functions for the surface flux boundary components. Figure 2 presents the evapotranspiration ratio, AE_r combined with the net infiltration ratio, NI_r. The evapotranspiration ratio essentially presents the relationship between actual- and potential evaporation, and the net infiltration ratio (NIR) is used to present the net infiltration (NI) data on the same basis as the evapotranspiration ratio (Rykaart *et al.*, 2001). These ratios are defined as:

[Eq. 2]
$$AE_r = \frac{AE_z}{AE_{max}}$$

Where AE_z = the individual zonal evaporation, and AE_{max} = maximum individual zonal evaporation.

[Eq. 3]
$$NI_r = \frac{1 - (NI_z - NI_{max})}{-([NI_{max}] + [NI_{min}])}$$

In equation 3, NI_z = the zonal net infiltration for each of the 13 modelled zones, NI_{max} = maximum individual zonal net infiltration, and NI_{min} = minimum individual zonal net infiltration. The NI is defined as:

[Eq. 4]
$$NI = P - R - ET$$

It is evident that the evapotranspiration ratio is the least close to the embankment and gradually increases to a value of 1, near the edge of the pool. This is consistent with the proposed hypothesis in Figure 1(b). Similarly the net infiltration ratio trends in Figure 2 follow the spatial infiltration hypothesis, with the maximum net infiltration occurring at the embankment end, and the least happening at the pool end of the tailings impoundment.

The application of the above flux boundary functions allows for the calculation of a water balance for the generalised tailings impoundment cross-section. Expressing all data in terms of annual precipitation, suggests that 40% runoff occurs, 114% evapotranspiration, and 55% net infiltration. The negative net infiltration indicates a net negative water balance from the system, which in this case would imply the lowering of the phreatic level in the long-term.

3-D Seepage Modeling

In order to prove that the spatial flux boundary functions presented in Figure 2 are in fact a reasonable approximation of the actual surface flux boundary conditions, it had to be used as an input in multidimensional seepage analysis models, and the seepage rates from the drains of the tailings impoundment had to be predicted. If the seepage rates were in fact a good match the flux boundary functions could be considered to have fulfilled their function. Modeling of seepage in the tailings impoundment presented a unique challenge. Firstly, the complexity of the model dictated that a 3-D seepage model be used. A 2-D cross-section of the tailings impoundment would not capture the essence of the problem nor would it yield representative flow rates. The actual 3-D modeling of the flow regime through the tailings impoundment presented a significant challenge in itself. The model requirements included complex, irregular geometry, unsaturated flow, irregular flux sections, and highly complex boundary conditions. For practical purposes the development of the 3-D model was also required to be able to be done within a reasonable time period. The SVFlux™ (SoilVision Systems, 2001) model developed by SoilVision Systems Ltd. was selected based on its ability to model complex, highly irregular

3-D problems with a relatively short learning curve.

3-D Model Soil Properties and Boundary Conditions

The selected material properties were identical to those used in developing the surface flux boundary functions described in earlier sections of this article, resulting in the use of three soil-water characteristic curves and a saturated surface hydraulic conductivity function.

Detailed survey data was present for the base and surface topography of the problem and would have to be used to describe the model. The survey data resulted in a grid of 2000 points. Furthermore, 13 zones had been isolated containing flux boundary conditions. However, the detailed data was simplified to a geometry grid of 120 points and four flux zones to allow solution of the model within a reasonable time frame. The simplification of the geometry grid allowed reasonable representation of the model topology. The flux zones were averaged in a way as to allow the total volume of flux to remain the same. SVFlux™ allowed the flux boundary conditions to be entered as free-form equations for each soil region. A water table formed the bottom boundary condition and was entered according to actual piezometer data.

3-D Model Solution

A steady state model was first run to provide initial conditions for the transient state model. The automatic mesh generation and refinement of SVFlux™ allowed a steady state solution in 19 seconds on a PIII 866 with 2946 nodes, 1417 cells, a single element error of 9.35e-5m and a maximum problem error of 0.001 m. The steady-state model solution may be seen in Figure 3.

The transient state model was run for a period of 121 days (the same period as for developing the flux boundary functions). The flux boundary functions were added on the top boundary to simulate the combined effects of precipitation and evaporation, i.e. net infiltration. The transient model solved in a period of 13 minutes on a PIII 866. An example of the flux boundary function for one of the zones is presented in Figure 4.

The combined flux boundary functions caused a net loss of water from the system over the four-month period. Flow upward through the unsaturated zone is significant, as the net flow is negative. The negative flux boundary was countered by the water source of the pond at the center of the tailings (the level of which was varied according to a function describing actual measured pond levels). Seven seepage flux surfaces were placed in the 3-D model to monitor seepage outflow from the tailings impoundment. A total volume of water exited the problem over a period of four months with an average flow rate of 7.6 L/s. Actual seepage flow rates from the tailings impoundment measured over the 4 months suggests an average seepage rate of 10.8 L/s (Rykaart, 2001). Considering the inaccuracies involved in the actual seepage measurements, which includes an estimated 15% overestimation due to surface run-off intercepted in the seepage drains, combined with the complexity of the problem as a whole, the flux boundary function seems to provide an excellent solution for the problem.

Summary

The use of a flux boundary function to describe and predict the surface flux boundary conditions through the top unsaturated tailings cross-section in itself is a great benefit for the tailings engineer. The combined advantage of using this function as a direct input, into 3-D seepage modeling software to assist in long-term water balance calculations makes it a worthwhile effort altogether. Another great benefit of this study is the way the 3-D model could be simplified using the same boundary conditions and material properties used in developing the flux boundary function, effectively eliminating the guesswork normally associated with setting up complex 3-D problems. This could all be done without sacrificing accuracy. Finally, no 3-D modeling is ever easy, and the tool used invariably affects the reliability of the results. The authors used SVFlux™ due to its relatively short learning curve, and found it to be highly effective, as an engineering tool.

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