One- and three-dimensional modelling of sub-surface solute transport processes in the region of Ranger uranium mine's tailings storage facility, Northern Territory, Australia

Alan Puhalovich[1], Keely Mundle[2], Russell Pol[2], Nathaniel Toll[3]

[1]*Golder Associates Pty Ltd, Level 1, 48-50 Smith St, Darwin, Northern Territory 0800*
[2] *Golder Associates Pty Ltd, Level 3, 1 Havelock St, West Perth, Western Australia 6005*
[3] *Energy Resources of Australia Ltd, Level 10, TIO Centre, 24 Mitchell St, Darwin, Northern Territory 0800*

Abstract

Solute transport modelling at Ranger Uranium Mine's tailings storage facility (TSF) has been undertaken to predict rates of tailings consolidation and pore pressure changes, vertical seepage flux rates and solute migration and to better understand the seepage mechanisms and implications.

The highest rates of vertical seepage are predicted to have occurred in the first two years of the TSF's operation with seepage fluxes estimated to vary between 90-100 m3/day (1982-2010). Contaminant plumes are predicted to occur within faulted/fractured pathways within the immediate vicinity of the TSF's walls, with seepage primarily to the north of the TSF along a major fault pathway.

Keywords: modelling, tailings, solute, predictions, seepage

Introduction

The Ranger Uranium Mine is located within the Ranger Project Area, about 250 km east of Darwin, Northern Territory and is owned by Energy Resources of Australia Ltd (ERA). It has been operating for over 30 years. The RPA is entirely surrounded by, but excluded from, the adjacent Kakadu National Park. Processing of ore has resulted in the production of processing wastes ("tailings"), which are deposited in a 1km^2 area tailings storage facility (TSF). Groundwater monitoring data indicate that seepage from the TSF has influenced local groundwater levels and groundwater quality.

One- and three-dimensional modelling of tailings consolidation and porewater solute transport has been undertaken to better understand the historic interactions between tailings porewaters and underlying groundwater systems, including the local and regional transport and fate of solutes.

Climate, Geology and Hydrogeology

The climate is characterised by a wet-dry season cycle, with rainfall mostly occurring through the wet season months of November to April. The average annual rainfall is 1,576 mm (Bureau of Meteorology, 2012). A significant rainfall-evaporation deficit exists in the months of April to November.

The site lies within the Alligator Rivers Uranium Field eastern part of the Pine Creek Geosyncline, which is a remnant of a deformed and metamorphosed Early Proterozoic sedimentary basin (Needham, 1982; Needham and Ross, 1990). The Early Proterozoic rocks are underlain by the Archaean granitoid basement of the

Nanambu Complex and unconformably overlain by flat lying Middle Proterozoic quartzites of the Kombolgie Formation and other unconsolidated sediments. The key units in the region of the TSF are easterly dipping schists, amphibolites and within the Upper, Middle and Lower Cahill Formation and Nanambu Complex granitic gneisses and schists.

Within the TSF area, mapped lineaments have been assessed by Coffey & Partners (1982), with a number inferred to be faults (Brown & Lowson, 1990). These include a major ENE thrust fault north of the north wall, dipping ~40^{o} south, a secondary series of NE trending normal faults under the north wall, a N trending normal fault, dipping ~40 ^{o} to the east, beneath Coonjimba Creek, and a similar fault east of the TSF and a NW trending normal fault.

Hydrogeological studies undertaken at Ranger have, over time, indicated that structural and weathering controls are more important factors in defining hydrogeological units at Ranger than geological controls. According to Brown & Lowson (1990), most faults appear to consist of a thin central zone of fractured pegmatite or sheared bedrock flanked by bedrock that is brecciated and sheared ('damaged'). When the damaged zone is absent, the fault usually has low permeability. On the other hand, faults with flanking zones of brecciation and shearing have higher permeability and act as conduits of groundwater flow. Key hydrogeological units defined by Puhalovich (2010), and relevant to groundwater conditions in the TSF region, include Primary Hydrogeological Units found within alluvial units and weathered and fractured rocks beneath creek lines and Secondary Hydrogeological Units which are found within weathered and fractured rocks away from creek lines and are less permeable and less extensive than the Primary units.

Tailings Storage Facility Design

Prior to construction, the TSF floor was cleared of vegetation leaving clay and weathered rock as the foundation. A compacted clay core was, however, constructed on the face of the TSF's walls and is keyed into weathered gneiss and schist bedrock by an excavated cutoff. The TSF's foundations were not grouted around the entire length of the Dam's walls, although some grouting was undertaken along the northern wall in zones identified from air photos as lineaments, inferred to be related to faulting within bedrock materials (Coffey Mining, 2010).

Conceptual Model of Solute Transport

The migration of solutes from the TSF is primarily a function of (1) process water levels, tailings materials properties and geotechnical/hydraulic processes within the TSF (2) the vertical hydraulic gradient that exists between the lower-most tailings deposits and the underlying highly weathered schistose rocks beneath the TSF and (3) hydrogeological properties and groundwater flow / solute transport processes beneath and beyond the TSF's footprint. Figure 1 illustrates the key processes. Process water levels in the TSF are a function of tailings slurry discharge, Rainfall (R) and Evaporation (E) and provide a "driving force" for seepage. As tailings pore pressures increase with the thickness of tailings, the tailings hydraulic conductivity (K) and storage coefficients (S) all decline with time as the consolidation process progresses and the dry density of the tailings deposits increases. Fluids migrate vertically downward to the underlying extremely weathered rock layer depending on the vertical hydraulic gradient and hydraulic conductivities in the two materials. Solute migration beneath and away from the TSF is primarily controlled by K, S and boundary conditions**.**

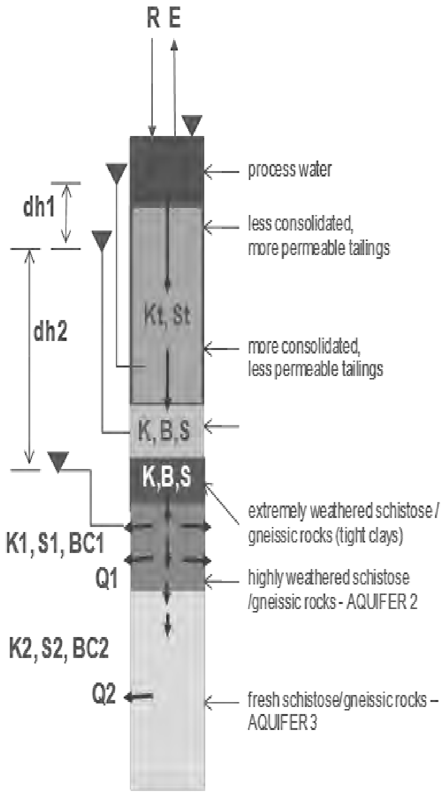
Modelling Approach – One Dimensional Modelling

One-dimensional consolidation modelling of tailings was undertaken using the *PLAXIS 2D* software package (version 2010.1.0.6019) (Brinkgreve *et al.*, 2011). The non-linear, time dependent and anisotropic behaviour of soils or tailings is simulated, using measured process water levels and production rates as key inputs. The model assumes 'no flow' boundaries on the sides with a head equal to the elevation of the upper surface of the tailings. Assumed tailings material properties are based on in-situ and laboratory testing data. The tailings were modelled using the 'Hardening Soil Model' which allows the model to account for the increase in stiffness of the tailings as it is compressed and using relationships available of tailings porosity versus effective stress. In developing the model, the seepage flux and the effective stress within the tailings due to consolidation were calculated using a range of appropriate hydraulic conductivities, with the seepage flux calculated with a changing hydraulic conductivity, related to the effective stress induced during consolidation. Potential maximum vertical seepage flux rates were predicted assuming a 'free draining' layer at the base of the TSF and assuming various tailings hydraulic conductivity values. The modelling results indicate that the highest rates of vertical seepage occurred in the first two years of the TSF's operation, with rates stabilising thereafter (Figure 2). The rate of seepage, over the 30 years of its operation, is predicted to have fluctuated only slightly depending on whether it operated primarily for storage of process water or tailings.

Modelling Approach – Three Dimensional Modelling

A numerical flow and solute transport model was developed using the computer program, *Feflow* (version 6.0), developed by Wasy Institute (DHI-WASY, 2010). Feflow is a finite element modelling code able to simulate three-dimensional groundwater flow and solute movement. The model covers an area of about 10 km^2 with local creeks mostly assumed to represent constant head or head dependent boundary conditions. A total of seven layers were assumed in the model, reflecting residual soils, laterisitic soils and clays, moderately to highly weathered gnerissic/schistose rocks, slightly-moderately granitic gneisses/schistose rocks and fresh rocks. The modelling approach is an 'Equivalent Porous Media' (EPM) approach, with elevated hydraulic conductivities assumed in regions where faults are thought present. The calibration process of steady and transient state and solute transport was an iterative approach. The parameters calibrated during the transient flow simulation were TSF seepage rate, specific yield and specific storage, with results from the 1D seepage model used during calibration. The seepage curves developed through the 1D modelling were used as a transient flux in the model. The resulting groundwater levels from the applied seepage rate were compared to measured data, in order to identify the most likely seepage scenario.

The results of model sensitivity testing indicate that assumptions relating to vertical fluxes from the tailings mass and geochemical conditions within the lower-most layers of the tailings mass significantly influence predictions to downstream groundwater quality. Groundwater quality changes are most significant to the north of the TSF along a major fault pathway, with a magnesium-sulphate plume extending approximately 800m to the north of the TSF (Figure 3). Preferential pathways were required in the model mesh to simulate the observed distribution of solutes and observed solute velocities along this fault. The modelling results indicate that the plume lies within the immediate vicinity of the dam walls in other areas.



KEY

R=rainfall
E=evaporation
dh1=vertical hydraulic gradient between tailings & underlying soils
dh2=vertical hydraulic gradient between soils & underlying highly weathered schistose/gneissic rocks
Kt=hydraulic conductivity of tailings (time-dependent)
Ks=storage coefficient of tailings (time-dependent)
K=hydraulic conductivity of soils/extremely weathered rocks
B=thickness of soils/extremely weathered rocks
S=storage coefficient of soils/extremely weathered rocks
Q1=horizontal flow within highly weathered rocks
K1= hydraulic conductivity flow within highly weathered rocks
S1= storage coefficient within highly weathered rocks
BC1= flow boundary conditions to highly weathered rocks
Q2=horizontal flow within fresh schistose/gneissic rocks
K2= hydraulic conductivity within fresh schistose/gneissic rocks
S2= storage coefficient within fresh schistose/gneissic rocks
BC2=flow boundary conditions to fresh schistose/gneissic rocks

Figure 1 *Conceptual model of solute transport processes (images courtesy of NT Geological Survey and ERA)*

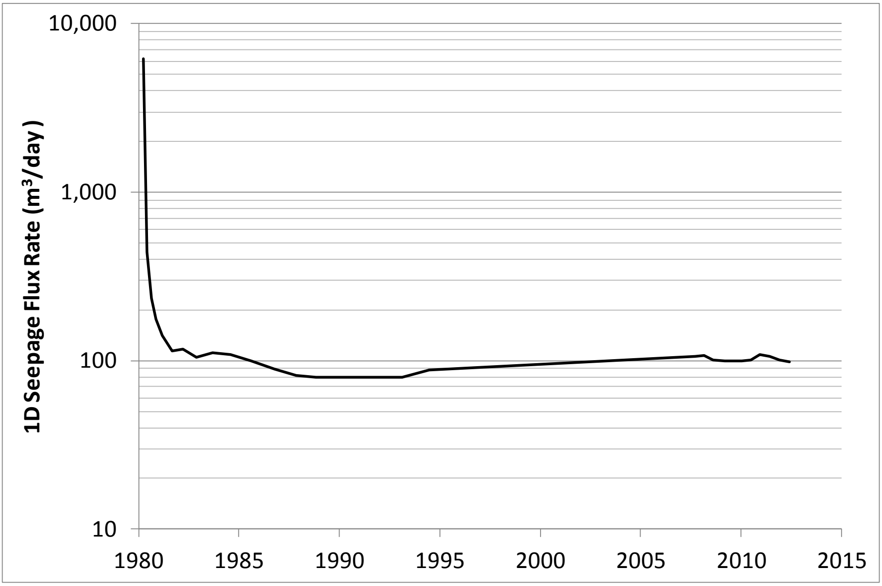


***Figure 2** Estimated total seepage flux from the base of the TSF ("central estimate")*

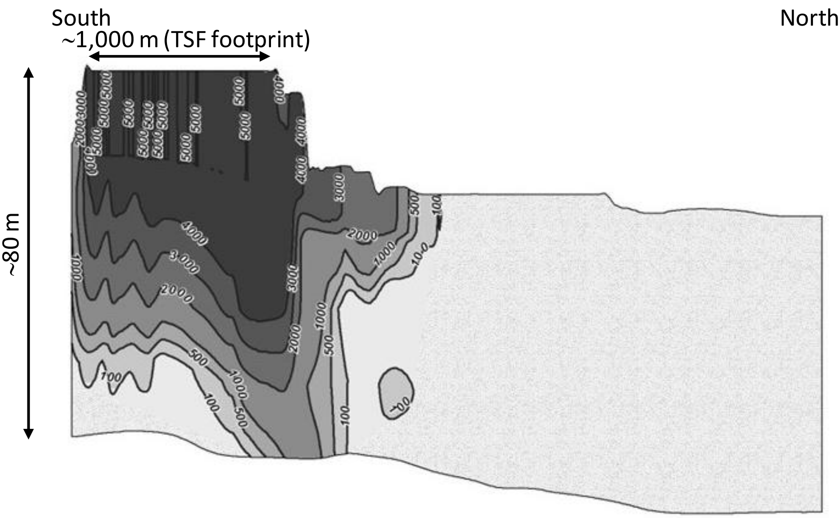


***Figure 3** Predicted sulfate concentrations (mg/L) (cross-section view through centre of TSF)*

Conclusions

It is concluded from the study that the highest rates of vertical seepage occurred in the first two years of the TSF's operation, with rates stabilising at around 90-100 m^3/day thereafter. The rate of seepage, over the 30 years of its operation, is predicted to have fluctuated slightly depending on whether it operated primarily to store process water or tailings. A two stage modelling approach has been successfully employed to assess and better understand solute transport within and beyond the limits of the TSF. The models indicate the importance of understanding transient conditions within the tailings mass and the role that preferential flow paths have on long-term solute transport processes.

Acknowledgements

The authors thank ERA for supporting this study and permitting publication of its outcomes.

References

Brown, PL and Lowson, RT (1990). An Interim Report to Ranger Uranium Mines on Tailings Dam Seepage. Australian Nuclear Science and Technology Organisation (ANSTO) Lucas Heights Research Laboratories. March 1990 - Commercial-in-Confidence.

Brinkgreve, RBJ, Swolfs, WM and Engin, E (2012) PLAXIS 2D 2011. Manual. Plaxis BV, Netherlands.

Bureau of Meteorology (2012) Average Annual Rainfall (1984-2012), Jabiru Airport Station No. 14198 (www.bom.gov.au)

Coffey & Partners (1982) Groundwater Investigation and Monitoring System. Report to Ranger Uranium Mine - Commercial-in-Confidence. Report No. HB57/1-A.

Coffey Mining Pty Ltd (2010) Ranger Tailings Dam – Annual Dam Inspection, 2010, Report for ERA Ltd – Commercial-in-Confidence. 21 September 2010.

DHI-WASY (2010) DHI-WASY Software, FEFLOW 6, User Manual.

Needham, RS (1982) Cahill 1:100 000 Geological Map Commentary Bureau of Mineral Resources, Geology and Geophysics. Canberra.

Needham, RS and De Ross, GJ (1990) Pine Creek Inlier - Regional Geology and Mineralisation. Geology of Mineral Deposits of Australia and Papua New Guinea (Editor: FE Hughes). The Australasian Institute of Mining and Metallurgy: Melbourne. pp 727-737.

Puhalovich, AA (2010) Evolution of Conceptual Hydrogeological Models, Ranger Uranium Mine, Northern Territory. Proceedings "Groundwater 2010", National Groundwater Conference, International Association of Hydrogeologists. November 2010.