Numerical groundwater modelling of oil sands tailings facilities in support of seepage management design

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ABSTRACT
Oil sands tailings produced from the bitumen extraction process is contained in large ponds, primarily through dykes constructed of permeable tailings sand. Potential flowpaths for movement of process-affected water (PAW) into the environment are through the tailings dykes and the pond foundation. Regulatory requirements necessitate the need for seepage management systems (SMS) to contain and eventually reclaim tailings ponds. The SMS must also consider potential impacts to geotechnical stability of the dykes. This paper presents a methodology for developing numerical groundwater models to assess the quantity of PAW released from the tailings structure and to support the design of oil sands tailings facilities. The suggested approach couples several different software packages to develop a detailed geologic model, incorporation into a 3D finite-element model and calibration to steady-state pre-mine and transient mine conditions using an automated inverse algorithm. Typically, the components of a SMS consist of interception wells and/or cutoff walls directing PAW to closed surface water systems. Reference is made to several examples where the methodology has been successful in meeting regulatory commitments by oil sand operators.

RÉSUMÉ
Résidus de sables bitumineux produit par le processus d'extraction du bitume est contenue dans de grands étangs, principalement par des digues construites résidus de sable perméable. Flowpaths potentiels pour le mouvement de l'eau affectée (PAW) dans l'environnement sont à travers les digues de résidus et de la fondation de l'étang. Exigences réglementaires nécessitent la nécessité pour systèmes de gestion des infiltrations (SMS) pour contenir et éventuellement récupérer les étangs de résidus. Le service SMS doit également envisager des impacts potentiels sur la stabilité de la géotechnique des digues. Ce livre présente une méthodologie pour le développement de modèles numériques des eaux souterraines pour évaluer la quantité de PAW libéré de la structure de résidus et prise en charge de la conception des installations de résidus de sables bitumineux. L'approche proposée couples plusieurs logiciels différents pour développer un modèle géologique détaillé, incorporation dans un modèle 3D de fini-élément et l'étalonnage à pre-mine en régime permanent et transitoire mine les conditions à l'aide d'un algorithme inverse automatisé. En général, les composants d'un SMS consistent en des puits d'interception ou coupure murs diriger PAW à fermé des systèmes de l'eau de surface. Il est fait référence à plusieurs exemples où la méthodologie a réussi en réunion réglementaire engagements par les opérateurs de sable d'huile.

1 INTRODUCTION

Bitumen extraction technology used in the surface mining of oil sands results in a tailings stream that must be contained in large tailings ponds or depleted open pits. Typically, these tailings ponds are sited in areas of lean oil sands or buried channel aquifers to limit sterilization of the oil sands resource.

Seepage management systems (SMS) are integral to the design and reclamation of tailings ponds. The SMS must also consider potential impacts to geotechnical stability of the dykes. Numerical model development of the tailings facility and surrounding groundwater regime is undertaken in support of the SMS design.

2 CONCEPTUAL MODEL DEVELOPMENT

Prior to development of the numerical model, a conceptual model to describe the groundwater flow system is required. Assumptions made during development of the conceptual model will propagate throughout the modelling process so acquiring all available hydrogeologic background data is an important step in the conceptual modelling process. The conceptual model represents a schematic of the flow system that attempts to capture the fundamental aspects of groundwater behaviour but also represents a simplification, since a complete representation of the real system is not feasible due to data and numerical model size limitations.

Conceptual model development draws upon a diverse set of information:

- Geologic maps and cross-sections;
- Topographic maps showing surface water bodies;
- Assigning model boundaries (no flow, constant head, constant flux);
- Contour maps of aquifer and aquitard surfaces;
- Piezometric maps of the aquifers;
- Hydrographs of surface water;
- Range of hydraulic parameters for the aquifers and aquitards;

- Variation in recharge, evapotranspiration, and surface/groundwater interaction across the model domain; and
- Water budget based on field observations.

Each tailings site has a unique set of hydrogeologic conditions and, therefore, requires a conceptual model that captures this behaviour.

Within the oilsands, the primary aquifers of interest are the surficial Quaternary sands and the deeper basal watersands overlying Devonian limestone. Since external tailings facilities (ETF) are normally sited at original ground surface, the surficial aquifers are the primary flowpaths for potential movement of PAW. If the tailings facility is located above a buried Pleistocene channel aquifer then this aquifer is the primary flowpath. If the buried channel aquifer is contributing baseflow to nearby surface water then the potential exists for PAW to reach these receptors.

3 GEOLOGIC MODEL DEVELOPMENT

Extensive site characterization is necessary to define geologic and hydrogeologic conditions that affect the design of the SMS. As a framework for compilation and interpretation of this data use is made of the software package Mincom Minescape® Stratmodel. This is a client-server application driven by the Oracle® database. This product allows development of a 3D geologic model based on a user-defined schema. The schema defines important lithologic units that will be incorporated into the 3D groundwater model.

3.1 Oilsands Geologic Schema

A typical schema developed for the oilsands is shown in Table 1.

Slice No.	Lithologic Unit	Geologic Description	Hydrogeological Description
1	H	Holocene muskeg and sand	Surficial aquifer
2	PI	Pleistocene lacustrine clay	Surficial aquitard
3	PF1	Pleistocene fluvial sand	Surficial aquifer
4	PG1	Pleistocene glacial till	Surficial aquitard
5	PF2	Pleistocene fluvial sand	Surficial aquifer
6	PG2	Pleistocene glacial till	Surficial aquitard
7	PF3	Pleistocene fluvial sand	Surficial aquifer
8	PG3	Pleistocene glacial till	Surficial aquitard
9	Kc	Clearwater Formation	Aquitard
10	Km	McMurray Formation	Aquitard

For the site in question, the conceptual model and field investigation did not identify a need to include the basal watersand so the base of the geologic model is the top of the McMurray Formation. The first column in this table refers to the numerical model slice number.

During development of the geologic model numerous cross-sections are reviewed and correlated to the drillhole and seismic survey data to ensure a consistent 3D stratigraphic model is defined.

3.2 Stratigraphic Surfaces

Once the geology data is correlated to 2D cross-sections of the posted drillhole and seismic survey data the Stratmodel is run to generate 3D surfaces of the schema intervals. These surfaces form the basis for development of the 3D groundwater model. The surfaces can be queried within Mincom using the MPL scripting language to generate a series of xyz data points. The xy locations correspond to the finite-element mesh defined for the groundwater model. These data points are directly imported into the groundwater model without smoothing or interpolation. The end result is the groundwater model geology is a close match to the geologic model. This approach also has the advantage that the geologic model can be quickly updated through the addition of new drillhole information. Once the Stratmodel is regenerated using the updated drillhole information the groundwater model layers can also be easily revised to assess any changes in groundwater flows due to the new geology information.

This process is particularly advantageous when the groundwater model is used as an operational tool to assess performance of the SMS relative to model predicted scenarios.

4 GROUNDWATER MODEL DEVELOPMENT

Information from the conceptual and geologic models is used to define the requirements of the groundwater model. The steps involved in development of the model are discussed in the following sections.

4.1 Mesh Development

In a numerical model, the continuous problem domain is replaced by a discretized domain consisting of an array of nodes and finite elements. The software adopted for this process is Feflow®, a 3D finite-element model capable of modelling both saturated and unsaturated groundwater flow. Finite elements allow more flexibility compared to finite difference cells in designing a grid and are more appropriate to represent irregular shapes (i.e., rivers, lakes, open pits, tailings ponds, buried channel aquifers, cutoff walls etc.). Finite elements are also more accurate in representing point sources such as dewatering and interception wells.

Feflow uses the concept of super elements when developing the finite element mesh. Super elements form the basis of the supermesh and incorporate significant features in the model mesh including the mine plans, surface waters, proposed dewatering wells, cutoff walls, etc. Consideration must be given to the SMS design at this stage of model construction since the SMS elements have to be represented within the mesh. Once the supermesh is complete a triangulation algorithm is used to produce the finite element mesh that automatically honours the super elements in the process.

A typical finite element mesh is illustrated in Figure 1. Mesh sizes vary depending on the level of detail required but are typically in the order of 50,000 element nodes per model layer with a total model size of approximately 2 million finite elements.

Feflow is not a true 3D model in the sense that the 3rd dimension is generated by vertically extrapolating the planar 2D finite element mesh to layers. This results in triangular prism elements where the top and bottom of an element correspond to the top and bottom model slice.

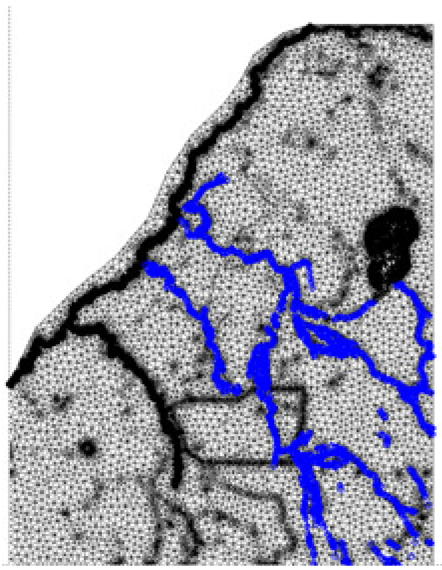

Figure 1. Example of a Feflow Mesh

4.2 Incorporation of the Geologic Model

As discussed in Section 3.2, the xy locations of the finite element nodes are queried against the structural surfaces defined in the Statmodel. The resulting xyz files are then imported into Feflow to build the 3rd dimension to the groundwater model.

Pinching out of aquifers or aquitards need special consideration. Due to issues with matrix solvers all model layers must be continuous across the model domain. Where model layers are discontinuous based on the geologic model interpretation, the layers are assigned the hydraulic properties of the overlying model layer to simulate the discontinuity in the groundwater model representation.

A level of vertical discretization is achieved in the model to allow a single hydrostratigraphic layer per model layer, as indicated in Table 1. This has advantages when calibrating the model using the inverse algorithm PEST®, as described in a later section.

4.3 Numerical Representation of the SMS Components

Seepage management systems for the large tailings facilities typically consist of a combination of cutoff walls and interception wells to control movement of PAW from the facility directing PAW to closed surface water systems. In the case of interception wells this is straightforward through the use of well boundary conditions applied to finite element nodes in the model. The Feflow mulit-layer well function allows a single well to extract from multiple aquifers in the model and automatically prorates flows from each aquifer as a function of the hydraulic conductivity assigned to the aquifer. This has advantages when simulating wells that penetrate the interbedded Quaternary sands common to many of the oil sand leases.

Cutoff walls consisting of a bentonite slurry mix are numerically represented by a row of finite elements assigned a hydraulic conductivity representative of the cutoff wall materials (typically k values of 10^{-8} to 10^{-9} m/s). A minimum of two rows of elements are used to minimize averaging of hydraulic conductivity between the wall elements and the surrounding aquifer/aquitard elements. To maintain a reasonable model size a minimum element thickness of 5 m is adopted. The hydraulic conductivity of the wall elements is then increased by the ratio of numerical to actual wall thickness (typically a factor of 10) to be hydraulically equivalent to the actual cutoff wall thickness.

4.4 Model Calibration using PEST

Calibration of a flow model refers to the iterative process whereby a set of parameters, boundary conditions, and stresses that produce simulated heads and fluxes are adjusted to achieve a reasonable match between model values and observed values (i.e. field measured values). The accuracy of model calibration is evaluated through statistical methods. Typically, these involve the correlation coefficient (r^2) and the normalized RMS (root mean squared) as defined by ASTM Standard D 5918-96. A model is commonly considered calibrated when the correlation coefficient is about 0.95 and the normalized RMS is under 10%.

Model calibration can be performed to steady-state or transient data sets. Transient model calibration is necessary if the model is to be used to predict time-dependent response of the groundwater regime to future imposed stresses (i.e. tailings infilling or mine dewatering). Only under transient calibration can the storage properties assigned to the groundwater model be adjusted to fit the measured aquifer storage properties determined from a pump test and the model estimated drawdowns calibrated to the field measured values.

Model calibration can often be the most time-consuming step in the model development. Advantage can be taken of programs that perform the inverse algorithm, i.e. that vary hydraulic parameters in the model to achieve a match between model calibration targets and field measured targets (typically water level data and surface water flows). Automated calibration also increases the likelihood that the objective function (difference between model and field values) is minimized. Inverse algorithms report on the sensitivity of various parameters to the objective function and help to focus attention on those parameters most important to minimizing the calibration error.

PEST® is an inverse algorithm software developed by John Doherty and is offered as freeware. The software takes control of the Feflow model and executes hundreds of model runs to minimize the objective function through the use of sophisticated mathematical procedures. The application of this software has greatly increased the efficiency of the calibration process and results in a greater confidence in the calibration results.

PEST is also intelligent in that it allows the user to assign prior information on parameters, or on relationships between parameters, that can be incorporated into the estimation process. For example, if the ratio between hydraulic parameters for aquifers and aquicludes is understood then this can be set as a constraint in the calibration process.

PEST has been successfully applied on several complex Feflow groundwater models developed for SMS design in the oilsands, both for steady-state pre-mine calibration and transient calibration to pump tests conducted to establish storage parameters.

5 MODEL SIMULATION OF THE SMS

Once the groundwater model is calibrated then model runs are undertaken to represent the mine plans including advance of the open pit and infilling of the tailings pond. Since the ponds are often sited close to the open pit the effect of drainage of aquifers caused by pit development impacts the direction of groundwater movement and hence movement of PAW.

5.1 Numerical Representation of Tailings Ponds

Detailed numerical representation of the tailings pond and containment dykes is undertaken with 2D seepage models. This work is conducted in support of internal drainage of the dyke structure. This level of detail is not possible with the 3D groundwater model due to model size constraints. Instead the top model layer is revised to reflect the tailings pond geometry and the layer hydraulic properties revised to represent the tailings hydraulic properties. Time dependent constant head boundary conditions are then assigned to represent the tailings staging. A typical set of tailings staging curves is illustrated in Figure 2.

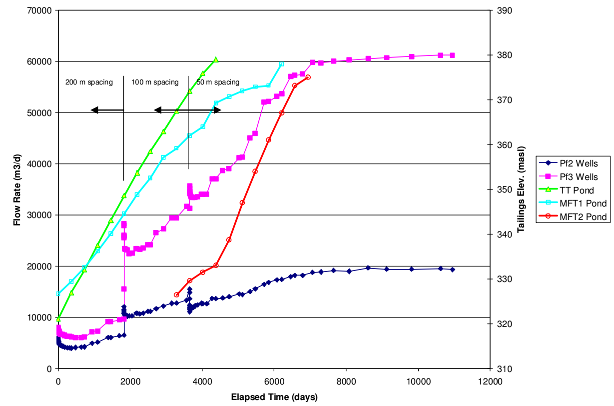

Figure 2. Example of Tailings Staging Curves

As indicated in Figure 2, the spacing of interception wells around the perimeter of the tailings pond decreases as the pond levels rise. This is done to effectively capture PAW exiting the foundation of the tailings pond and to reduce piezometric heads at the downstream toe of the tailings dykes for geotechnical stability reasons. Interception wells are also necessary to reduce the hydraulic gradient through the cutoff wall to minimize the potential for hydraulic fracturing of the well. For these reasons the interception wells are located upstream of the cutoff wall and downstream of the tailings dyke toe.

6 EXAMPLES OF SMS DESIGNS

The optimum SMS for a particular site is established by investigating a number of possible solutions assessed using the numerical groundwater model. The effectiveness of each SMS option is then evaluated and ranked, usually in the context of a risk analysis. The goal is to minimize environmental impacts of the tailings facility within the technical and financial constraints associated with each option. Often regulatory requirements will preclude permanent forms of containment (i.e. cutoff walls) across major buried channels as the expectation is these channels need to remain open to groundwater flow under closure scenarios. Removal of cutoff walls to depths in excess of 40 m to re-establish regional groundwater flow patterns may not always be technically feasible.

The methodology for developing the SMS for tailings facilities has been successfully applied at several large tailings ponds in active use. Model estimates of interception well flows (both passive and active wells) agree well with actual measured flows from the installed system. Drawdown levels necessary for geotechnical stability of the tailings dykes are also closely approximating field measured values.

The modelling methodology has been successful in support of the regulatory permitting process and has been favourably reviewed by external reviewers well recognized in the geotechnical/hydrogeology community.

The intent is to use the models developed as an operational and mine closure tool for the SMS. As environmental monitoring well water level data and interception well flows are collected from ongoing performance monitoring this data will be used to re-calibrate the groundwater model using PEST and utilizing the re-calibrated model to confirm the system as installed is meeting performance targets established by the numerical model predictions.

7 PERFORMANCE MONITORING

In order to establish whether the SMS design is meeting design targets a comprehensive performance monitoring system is implemented including environmental compliance wells, monitoring of interception well flow rates with time and monitoring of pore pressures within the foundation of the tailings dykes. This data can be used for further model calibration to improve the predictive capacity of the model.

This approach is similar to the "observational approach" adopted by the geotechnical community wherein tailings dyke performance is assessed through-out the design life of the structure and design changes implemented, as required, to meet the design goals of the containment structure. The use of interception wells as a component of the SMS allows a relatively agile response to changes in system behaviour through the addition of wells or increases to well flow rates and drawdowns.

8 FUTURE WORK

Independent reviewers of the SMS systems developed by KCB have commented on the uncertainty related to the long-term fate of the PAW contained within the tailings facility and outlying SMS. Further research is required to understand the rate of decomposition of the PAW constituents in the environment and this is a key piece of information since it determines when the SMS can be de-activated and the tailings structure reclaimed. Several research initiatives are currently underway in the oilsands to address this issue.

Once a better understanding of the processes related to transport of PAW due to dispersion, diffusion, etc. is achieved then contaminant transport analyses using the groundwater model could be undertaken to address the uncertainty related to the long-term fate of PAW from the tailings facility.

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