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APPROACHES FOR MODELLING TRANSIENT UNSATURATED-SATURATED GROUNDWATER FLOW DURING AND AFTER CONSTRUCTION

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ABSTRACT

Construction of underground research laboratories and geological disposal facilities has a significant transient impact on groundwater flow, leading to a drawdown in the water table and groundwater pressures, and groundwater inflow into shafts, access ways and tunnels accompanied by desaturation of the surrounding rock. Modelling the impact of underground facilities on groundwater flow is important throughout the construction and operation of the facilities, e.g. estimating grouting and water treatment facility requirements during construction, and estimating the rate of resaturation of the engineered barrier system and the establishment of steady-state groundwater flow after backfilling and closure.

Estimating the impact of these effects requires modelling of transient groundwater flow under unsaturated conditions at large scales, and over long timescales. This is a significant challenge for groundwater flow modelling, in particular because of the non-linearity in groundwater flow equations, which can have a marked effect on suitable timesteps for transient calculations. In addition, numerical grids need to be developed at appropriate scales for capturing the transition between saturated and unsaturated regions of the sub-surface, and to represent the features of complex hydrogeological structures such as heterogeneous fractured rock.

The Japan Atomic Energy Agency (JAEA) has been developing modelling techniques to overcome these problems as part of the Mizunami Underground Research Laboratory (MIU) Project in the Tono area of Gifu Prefecture, Japan. An integrated geological and hydrogeological modelling, and visualisation system referred to as GEOMASS has been developed, which allows for transient unsaturated groundwater flow modelling in the presence of dynamic underground excavation models. The flow simulator in GEOMASS, FracAffinity, allows for such modelling by the application of sophisticated gridding techniques, allowing for modification of hydraulic conductivity in key zones, and by suitable modification of water retention models (the relationship between saturation and pressure, and saturation and hydraulic conductivity).

The approaches that have been developed in GEOMASS have been tested through a series of models of increasing complexity, and the testing has demonstrated that there is no significant impact on estimates of regional groundwater flows or local estimates of flow into underground excavations. The tools and approaches that are described in this paper are of significance in all geological disposal projects, where a key requirement is to estimate and understand the hydrogeological regime and the transient response of groundwater flow to underground construction. Such understanding is important for construction, operation and post-closure phases of facility development.

INTRODUCTION

Understanding deep groundwater flow relies on a combination of geological knowledge, hydrodynamic testing and monitoring, geochemical characterisation and integration (e.g. Neumann, 2005; Eaton *et al*., 2007; Follin *et al*., 2008). Very often, the lack of integration introduces uncertainty in the hydrogeological models that is further transferred to the use of numerical models and to the decision based tools. Thus, the synthesis of research programmes requires software tools that facilitate the integration of the fundamental aspects of groundwater flow in the area of interest.

In this respect, the Japan Atomic Energy Agency (JAEA) has been investigating the Tono area (e.g. Mizunami Underground Research Laboratory (MIU) construction site) for many years to develop understanding of the fundamental processes affecting groundwater flow in deep crystalline rocks (JNC, 2003). The needs of integrating sophisticated geological characterisation of fractured and sedimentary rocks with multiple sets of conducting features families and specific faults with the site specific, local and regional hydrogeological boundary conditions and parameter zones to produce accurate predictions of the impacts of the shaft sinking in the nearby formations prompted JAEA to develop an integrated tool which serves their site-specific purposes and can also be applied worldwide in a number of different scenarios.

Estimating the impact of these effects requires modelling of transient groundwater flow under unsaturated-saturated conditions at regional scales, and over long timescales. This is a significant challenge for groundwater flow modelling, in particular because of the non-linearity in groundwater flow equations, which can have a marked effect on suitable timesteps for transient calculations. In addition, numerical grids need to be developed at appropriate scales for capturing the transition between saturated and unsaturated regions of the sub-surface.

The GEOMASS (GEOlogical Modelling Analysis and Simulation Software) system has been developed by JAEA since 1997 in order to improve their capability to evaluate groundwater flow at depth in a rock mass. The system provides an integrated simulation system environment for both geological and hydrogeological model development, and groundwater flow simulations. The capabilities of the GEOMASS system and the benefits of the system to general site characterisation activities have been described in previous conference publications (White *et al.*, 1998; Saegusa *et al.*, 2006; Guimerà *et al.*, 2008). This paper focuses on recent developments to the system which have focused on improving the modelling of transient groundwater flow under mixed unsaturated-saturated conditions, and which is a key requirement for underground research laboratory (URL) and repository site investigations.

MIZUNAMI UNDERGROUND RESEARCH LABORATORY

The MIU is now under construction by JAEA, in the Cretaceous Toki granite in the Tono area, central Japan (http://www.jaea.go.jp/). The MIU is a purpose-built generic URL that provides a foundation for multidisciplinary studies to build a firm scientific and technical basis for geological disposal of nuclear wastes. The main goals of the MIU Project are to establish techniques for investigation, analysis, and assessment of the deep geological environment and to develop a range of engineering techniques for deep underground application.

The conceptual design of the MIU consists of two circular 1,000 m-long shafts, and horizontal research galleries at depths of 500 m and 1,000 m (Figure 1) (Sato *et al*., 2003). The MIU Project has three overlapping phases: Surface-based Investigation (Phase I), Construction (Phase II) and Operation (Phase III), with a total duration of 20 years. The project began in 1996.

Surface-based (Phase I) investigations were conducted stepwise at the MIU Construction Site. The main aims of the investigations were to develop conceptual models of the geological environment and to enhance the understanding of the undisturbed deep geological environment before excavation of the shafts and research galleries. The approach adopted for the investigations involved iteration of the following steps:

- develop an investigation concept,
- plan the investigations,
- undertake the planned investigations,
- interpret the investigation results,
- model and simulate the investigation results,
- assess the consequences of modelling and simulations,
- evaluate uncertainties within the consequences,
- specify the main items for further investigations.

Field-based investigations began with fault mapping at and around the MIU Site, following a literature survey. Work continued with reflection seismic and vertical seismic profile surveys. In addition, a large programme of borehole investigations was carried out in several boreholes ranging from 100 to 1,300 m deep, in order to extensively characterise the sub-surface geological environment. Cross-hole tomography and hydraulic tests were carried out using these deep boreholes.

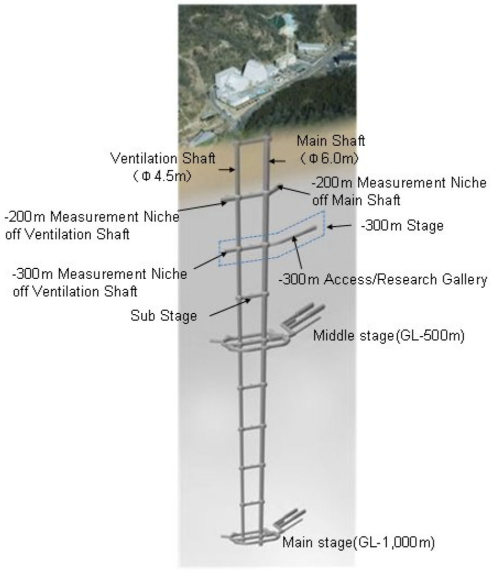

Figure 1: Layout of the MIU (layout subject to change).

The results of the field-based investigations were synthesised in geological, hydrogeological, hydro-chemical and rock mechanical conceptual models. The main items for further investigation were specified through evaluation of model uncertainties (JNC, 2005).

Excavation of the shafts commenced in July 2003. By the end of May 2009, the Main Shaft had reached a depth of 327m and the Ventilation Shaft had reached a depth of 355m. A range of geoscientific investigations is also being carried out during the construction of the underground facilities.

GEOMASS

The GEOMASS system is currently based on two software applications, EarthVision® and FracAffinity. EarthVision® is a commercial geological modelling system that is being used for the construction of geological models and visualisation. FracAffinity is a proprietary code that uses a hybrid medium model for simulation of groundwater flow. The linking between EarthVision® and FracAffinity in the GEOMASS system is illustrated in Figure 2.

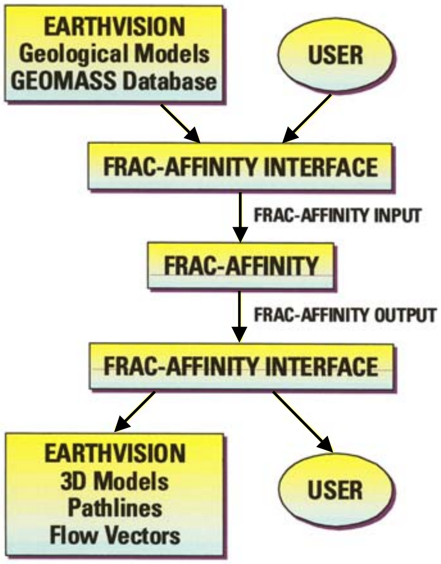

Figure 2: Workflow used in the GEOMASS system.

GEOMASS provides a powerful, efficient and flexible modelling system for modelling of the geological and hydrogeological environment. EarthVision® provides flexible geological modelling to allow complex faulted and non-faulted interpretations of geological data. EarthVision® uses a grid-based system for modelling and combines these grids into an integrated geological model through operations defined in a Sequence File. The Sequence File and grids are passed to FracAffinity via an automatic transfer script. With GEOMASS, the process of exporting a 3D geological interpretation and constructing a hydro-geological grid is reduced to a few hours or less, even for relatively complex models, which allows for much greater flexibility in testing the impact of geological structures on the results of groundwater flow simulations.

Groundwater flow modelling in FracAffinity is based on the concept of a hybrid medium in which a volume of fractured rock is represented as two main components: discrete features and intact rock (this is shown schematically in Figure 3, and using an example from the Tono area in Figure 4). Discrete features are linear objects such as faults, fractures, unconformities or dykes that introduce linear/surface variations in the properties of the rock. A distinction is made between deterministic discrete features (DDFs), whose geometry might be determined accurately by a regional geological investigation (e.g. large-scale faults), and stochastic discrete features (SDFs), which are smaller-scale features about which only partial information is available (e.g. fractures or sub-seismic faults). The intact rock is the remaining rock which is either completely intact or contains only “micro-fractures”.

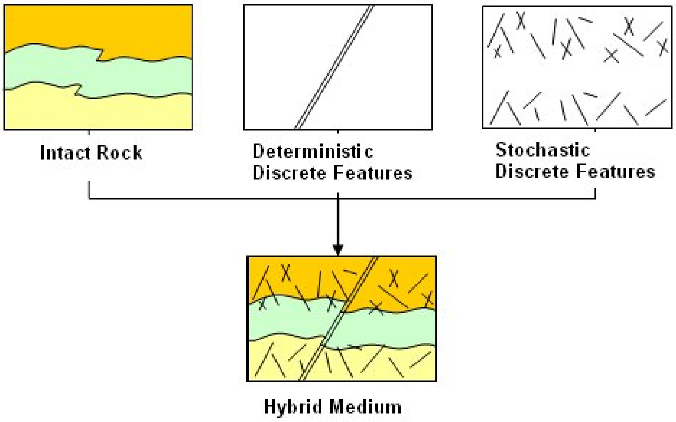

Figure 3: Schematic diagram of the constituent components of the FracAffinity hybrid medium: intact rock, deterministic discrete features and stochastic discrete features.

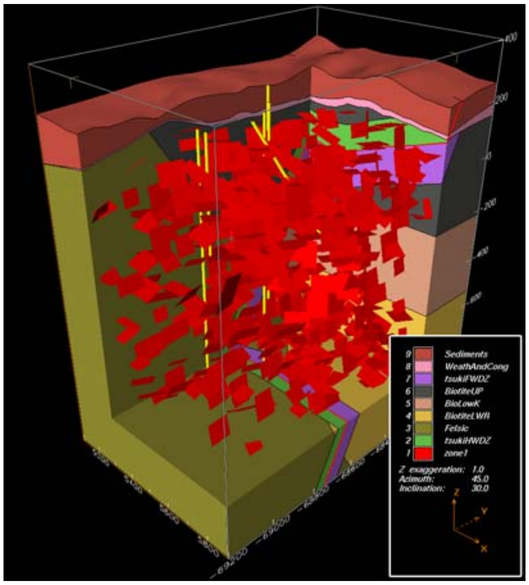

Figure 4: Illustration of a hybrid medium model based on data from the Tono area. The geological structure is developed in EarthVision®, and is shown by the coloured zones representing intact rock and the thin red line representing a DDF, in this case the Tsukiyoshi Fault. The red rectangles are a set of SDFs generated in FracAffinity, which represent fractures within the Toki Granite.

FracAffinity solves for the pressure head on a flow network, based on finite-difference principles. Steady-state and transient models can be run for either saturated or unsaturated conditions.

Key features of FracAffinity are:

- the ability to consider heterogeneity at all scales,
- the ability to model engineering features including dynamic excavation of shafts in transient calculations and modelling of boreholes for pump test modelling,
- the ability to model unsaturated flow at regional scale, which is facilitated by sophisticated grid refinement techniques.

In addition to traditional techniques for analysing and interpreting model results, there is full interactivity between EarthVision® and FracAffinity, allowing the calculations in FracAffinity to be viewed alongside the geological models on which the flow network is based. Key aspects of this interactivity include:

- visualisation of the flow network (including visualisations of fracture networks developed in FracAffinity),
- visualisation of property distributions,
- visualisation of modelling results (3D head, pressure and saturation, and pathlines).

APPROACHES TO MODELLING TRANSIENT GROUNDWATER FLOW UNDER MIXED UNSATURATED-SATURATED CONDITIONS USING FRACAFFINITY

Flow Equations and Flow Solution

In FracAffinity, the domain is discretised as an unstructured network (Figure 5). The nodes of the network represent regions of space that have head and saturation values, while the connections between nodes represent flow paths. Groundwater flow is modelled by solving for the head at each node and by balancing the groundwater flows along the connections, with consideration of storativity effects. This network is equivalent to a finite-difference discretisation of the governing equations.

For saturated flow calculations, the discretised equations on a FracAffinity network are written as:

$$\sigma_i \frac{\partial h_i}{\partial t} = \frac{1}{V_i} \sum_{\text{conn i-j}} C_{i,j}(h_j - h_i) + q_i \qquad (1)$$

where the i and j subscripts indicate nodes, and:

h is the head (m),
σ is the specific storage coefficient (m^{-1}),
t is the time (s),
V is the volume (m^3),
C is the conductance (m^2/s), and
q is a source of water, usually zero ($m^3/s/m^3$).

The conductance is calculated from the hydraulic conductivity and geometric data:

$$C_{i,j} = \frac{K_{i,j} A_{i,j}}{d_{i,j}} \qquad (2)$$

where:

K is the hydraulic conductivity (m/s),
A is the cross sectional area (m^2), and
d is length (m).

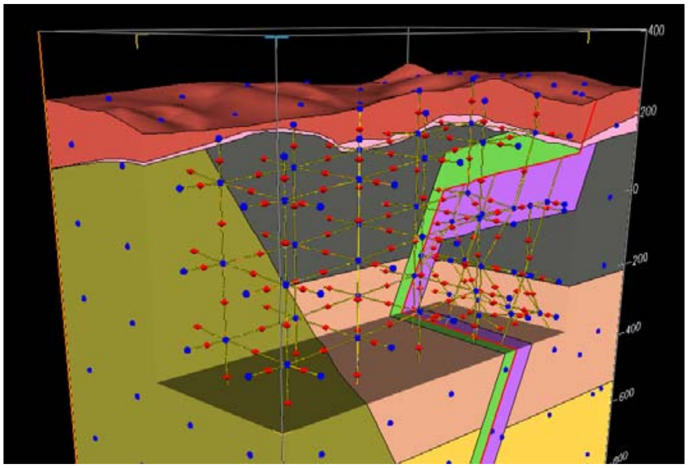

Figure 5: Illustration of a hybrid medium flow network, visualised against the geological model from which it has been derived. In the figure, blue spheres represent nodes and red diamonds mark the centre of connections. Note that in the model, the grid spacing is deliberately coarse to allow for visualisation of nodes and connections.

For unsaturated flow, the situation is similar to saturated flow, and the nodal equation, which is based on the mixed form of Richards' equation, is:

$$\phi_i \frac{\partial s_i}{\partial t} + \sigma_i \frac{\partial p_i}{\partial t} = \frac{1}{V_i} \sum_{\text{conni-j}} C_{i,j}(p_i, p_j)(p_j - p_i + z_j - z_i) + q_i \qquad (3)$$

where:

p is the pressure head (m),
z is the vertical coordinate (m),
s is relative saturation (-),
ϕ is the porosity (-),
σ is the specific storage coefficient (m^{-1}),
t is the time (s),
V is the volume (m^3),
C is the conductance (m^2/s), and
q is a source of water, usually zero ($m^3/s/m^3$).

For this equation, there are additional relationships between p and s that have to be determined to derive the conductance given the nodal pressure heads (actually the dependence is on the saturation). These relationships are commonly referred to as the water retention model, and, in FracAffinity, these are most typically modelled using the van Genuchten relationships (van Genuchten, 1980). The relationship between conductivity, suction and saturation in the van Genuchten relationship is illustrated in Figure 6.

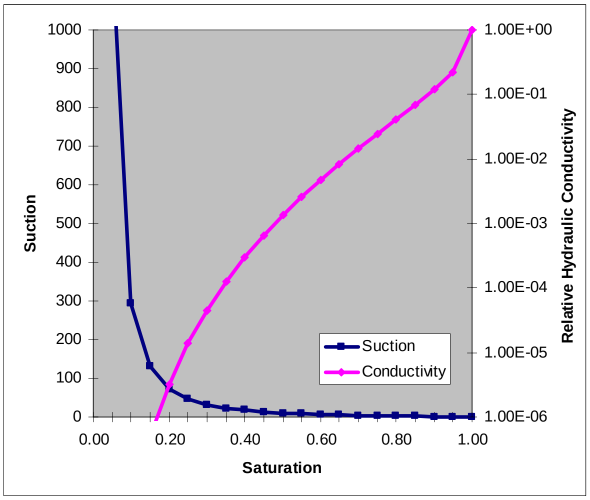

Figure 6: Graph of the relative hydraulic conductivity and suction against saturation for the van Genuchten relationship.

FracAffinity employs a range of schemes for solving for the flow for the different types of flow problems addressed:

Steady-state saturated flow: This system is linear and requires the solution of a symmetric matrix equation. This is solved using an iterative approach that employs a preconditioning matrix.

Steady-state unsaturated flow: This system is non-linear because of the dependence of conductance on saturation, and is solved by an iterative approach utilising two schemes, a Picard scheme based on a linear approximation to the non-linear problem, and a Newton scheme that uses a full Jacobian matrix for the non-linear system, where the Jacobian represents the best linear approximation to a differentiable function near a given point.

Transient flow: Transient flow is calculated using the DYLAN solver which employs a variable-order predictor-corrector method based on an algorithm published by Byrne and Hindmarsh (1975). At each timestep, DYLAN performs the following calculations:

- Predict the solution at the end of the step.
- Correct the prediction, using Newton non-linear iterations.
- Determine the error, and decide whether to accept the step.
- Determine the duration of the next timestep (or for a re-taken step if the error was unacceptable).
- Determine the order of the method for the next timestep.

Objectives of Groundwater Flow Modelling for URLs Under Investigation in the MIU Project

Considering the approach to groundwater flow requires consideration of the objectives of the modelling. The following objectives are recognised for the hydrogeological modelling undertaken in the MIU Project.

Estimating the flows into the MIU shafts and access galleries. Currently, an important focus of the hydrogeological modelling is supporting the construction of the shafts by providing estimates of groundwater flow into the facility. This information is being used to support grouting of the host rock and design of the water treatment facility.

Modelling the response of the water table to excavation of the MIU. This is important for considering the impact on the hydrological environment around the MIU construction site.

Modelling heads at, and flows into, boreholes across the region. There are many boreholes across the Tono area, including boreholes related to public resources including leisure activities, and scientific boreholes developed as part of the Tono Natural Analogue Project, the Regional Hydrogeological Study and the MIU Project, and understanding the impact on flows into these boreholes as a result of MIU URL excavation is an important aspect of the hydrogeological modelling.

Development of an approach to site characterisation. A key objective of the MIU Project is to develop site characterisation technologies and methods for application at future repository investigation areas (at both the Preliminary Investigation Area (PIA) Stage and the Detailed Investigation Area (DIA) Stage (NUMO, 2007)).

This modelling requires consideration of both saturated and unsaturated flow conditions. For example, the flow into the shaft will be closely controlled by the relative hydraulic conductivity, which, as can be seen from Figure 6, reduces markedly as the rock desaturates. Therefore, JAEA has concluded that modelling of unsaturated-saturated transient flow is required to adequately understand hydrogeological processes occurring in the Tono area. JAEA wishes to undertake unsaturated transient groundwater flow modelling at regional scale, and the challenges of such modelling are discussed in the next section.

Difficulties in Modelling Transient Flow at Regional Scale with Partially Unsaturated Conditions

The van Genuchten relationship used in FracAffinity is known to cause difficulties with flow solvers reaching convergence (Vogel *et al*, 2001; Ippisch *et al.*, 2006). This is due to the highly non-linear nature of the relationships, as illustrated in Figure 6.

In particular, for a small change in saturation, there is a large change in pressure for the van Genuchten model. The practical effect of this is that the timesteps required for convergence of flow solutions using the variable-order predictor-corrector method applied in FracAffinity are reduced to small values and the solution does not proceed at a sufficient rate for the calculations to be practicably undertaken. This effect is particularly problematic during excavations where the pressure field is constantly changing.

In addition, the distance across which the saturation of rock changes from regions that are fully saturated to regions that have only residual saturation are small compared to the scale of the problem but are large enough to impact regional flow (i.e. centimetre-scale). Typically, it is considered necessary to model this transition region due to the large changes in conductivity associated with small changes in saturation.

Modelling of the features described above could be undertaken by very detailed model grids but these would exceed the limits of current computing capability. Therefore, modelling of unsaturated flow at regional scale using FracAffinity requires a reduction of the model complexity.

Options for Reducing Modelling Complexity

There are a variety of ways that one can imagine reducing the complexity of hydrogeological modelling at regional scale to understand groundwater flow, even under transient unsaturated flow conditions:

Use of the saturated solver: Flows into boreholes will occur where the groundwater is saturated. Therefore, it may be sufficient to model these issues using the saturated solver.

Estimation of transient effects using the steady-state solver: The unsaturated flow solver is relatively quick to calculate the steady-state solution and it may be possible to estimate transient effects at certain times by use of the steady-state solver.

Simplification of water retention models: Water retention models, such as the van Genuchten relationship, are highly non-linear (Vogel *et al.*, 2001; Ippisch *et al.*, 2006), with significant changes in pressure for small changes in saturation. The objectives of the regional-scale modelling at Tono are focused on understanding the location of the water table and flows into boreholes and the shaft. Therefore, if the water retention models can be simplified to focus on the medium being either saturated or unsaturated, it might be the case that the timestepping solver will run faster.

Understanding gridding impacts and identifying optimum gridding approaches: It is frequently assumed that modelling of unsaturated flow requires a detailed grid so that the behaviour across the transition between saturated conditions and unsaturated conditions can be adequately represented. Typically, this would require modelling on the sub-metre scale, which is clearly not possible for regional models at the kilometre-scale. Therefore, any approach to reducing the complexity of groundwater flow models at Tono needs to consider appropriate grid scales for different types of problem.

TESTING OF APPROACHES

The options for reducing modelling complexity discussed above were tested by running a series of small scale test models using FracAffinity. The modelling used a series of simple 2D and 3D models designed to run quickly but to represent significant unsaturated transient flow conditions to allow detailed comparison of results and to test the capabilities of model and against difficult problems. The geometry of the models is illustrated in Figure 7, and key parameters are provided in Table 1. The model establishes unsaturated conditions across the model by reducing the heads on the side boundaries from topographic to lower values after one second. Modelling of this condition identified the timescale for the transient response to be of the order of 10,000 years.

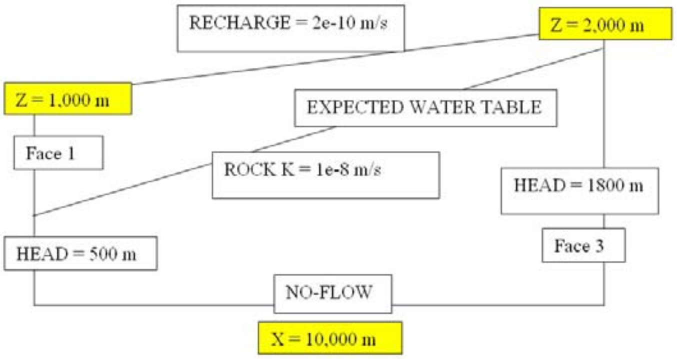

Figure 7: Geometry and related parameters for the 2D Test Model. Figures in yellow boxes indicate length scale of model boundaries. The head conditions on the side boundaries are applied 1 second after the start of the simulation – the model starts at full saturation (i.e. topographic head).

Table 1: Key model parameter values for the Test Model.

Parameter	**Value**
Porosity	10%
Specific Storage Coefficient	1e-05
Water Retention Model	Van Genuchten, A = 0.33, B = 0.2
Grid Size	X=50m, Y=1m, Z=50m

Use of the Saturated Solver

A comparison of heads predicted at steady-state (i.e. following full recovery from the transient conditions) obtained through use of the saturated solver with those obtained using the unsaturated solver are illustrated in Figure 8. As can be seen from the figure, in the regions where there is a significant unsaturated zone, the heads are significantly different, and this calculation illustrates that use of a saturated solver to calculate heads for transient unsaturated flow is not appropriate.

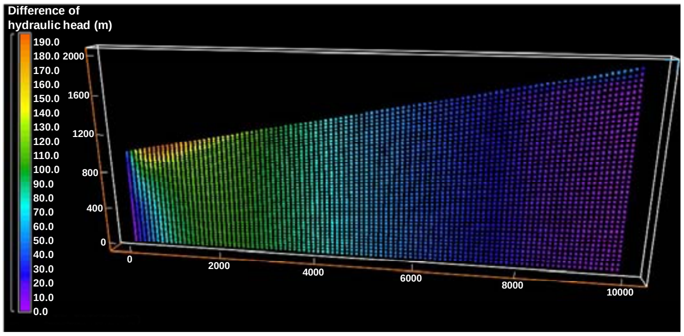

Figure 8: Difference of hydraulic head between steady-state run using unsaturated solver and saturated solver. The difference is illustrated in head in metres (yellow nodes ~ 200 m, green nodes ~ 100 m and purple nodes ~ 0 m head difference), which was calculated by subtracting the nodal heads from the model calculated using the unsaturated solver with the nodal heads calculated using the saturated solver.

Use of the Unsaturated Steady-State Solver

As noted above, the transient effects for the test model are long lasting; the steady state is reached after ~10,000 years, which is partially due to the large drawdown imparted across the model. This long time means that the model calculation also takes a long time if run in the transient mode; about ten times slower than if the calculation is run in the steady state mode. Therefore, the effect of using the steady-state solver was tested, and the result is illustrated in Figure 9.

The results are similar, with calculated flows in to and out of the side boundaries less than 1% different, and with heads below the water table different by up to 1-2 m, which are insignificant for flows across the side boundaries. Therefore, it can be concluded that the steady-state unsaturated flow solver and the transient unsaturated flow solver produce consistent results for the test model.

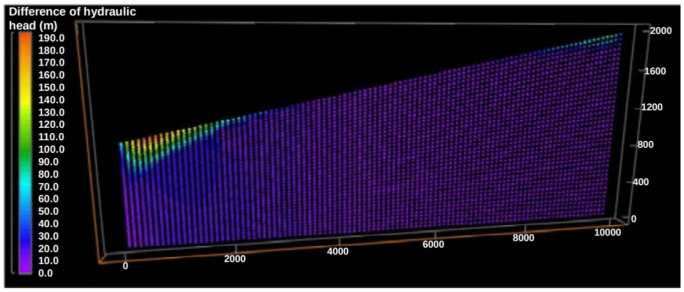

Figure 9: Difference of hydraulic head between steady-state run using unsaturated solver and saturated solver. The difference is illustrated in head in metres (yellow nodes ~ 15 m, green nodes ~ 10 m and purple nodes ~ 0 m head difference).

Simplification of the Water Retention Model

As illustrated in Figure 6, the van Genuchten water retention model imparts a strong non-linearity on the model calculations. This can lead to difficulties with convergence as the water responds to transient effects. In particular, as the water table falls, individual nodes may become very dry and block groundwater flow due to the relationship between relative conductivity and saturation.

In order to simplify the modelling approach, a method to reduce the non-linearity in the water retention model was introduced. This is referred to as the Non-Linear Fraction (NLF) and modifies the van Genuchten (or other) relationship. The NLF (f_{nl}) modifies the pressure-dependent conductivity ($K(p)$) as follows:

$$K(p; f_{nl}) = \frac{K_{sat}}{K_{red}}\left(f_{nl} + (1 - f_{nl})K_{red}\right) \tag{4}$$

where K_{red} is the reduction factor for the full non-linear water retention model

$$K_{red} = \frac{K_{sat}}{K(p)} \tag{5}$$

This reduces the non-linearity and constrains the minimum conductivity, for example, with a non-linear fraction of 0.98, the minimum conductivity is 1/50 of the saturated value. Figure 10 shows the effect of the NLF on the relative conductivity (the reciprocal of the reduction factor) across the full range of saturation for a Van Genuchten model. A logarithmic scale is used to emphasise the effect. Each figure shows the full value and the 99%, 95%, 90% and 75% values (that is f_{nl} = 1.0, 0.99, 0.95, 0.9 and 0.75).

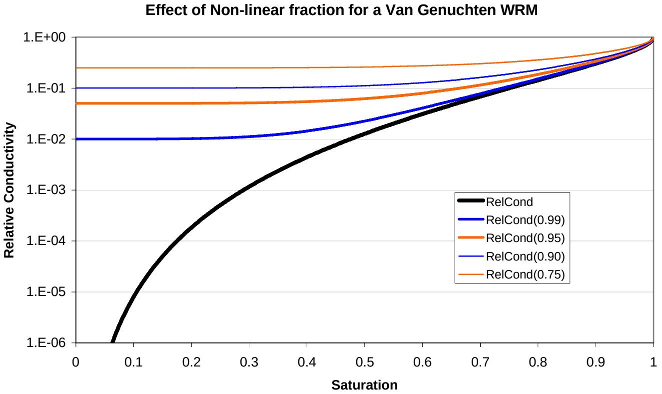

Figure 10: The effect of the non-linear fraction on the relative conductivity for a typical Van Genuchten retention model.

Investigation of the impact of using a NLF was investigated in combination with the effects of grid size, and are discussed below.

Identifying Optimum Gridding Approaches

For modelling at regional scale, with a hybrid medium groundwater flow model the flow network has to be focused on the regions of most importance. These include the areas where features control groundwater flow processes (e.g. the water table) and regions where key modelling outputs are required (e.g. shafts or boreholes).

Reduction of the number of network nodes can save significant modelling time, and allow for greater investigation of modelling uncertainties (by running more sensitivity case models). To investigate the effect of the number of nodes, the 2D test model was run with node spacings (grid size) of 50m, 10m and 1m.

The model was run using the transient unsaturated solver, and took 4 minutes, 26 minutes and 32.5 hours to run respectively. Differences in flows into and out of the model were less than 2% different for all models. This illustrates that, for the test model, the grid size can have a significant effect on model run times, but not on the results for regional flows.

However, for unsaturated regions such as shaft walls, there is likely to be a requirement to understand local effects and FracAffinity has a variety of schemes available for modifying the grid close to engineering features:

- Dynamic excavation model.
- Refinement of the grid size in cuboid regions (local grid).
- Refinement of the grid size around boreholes.
- Refinement of the grid size around 2.5D features (e.g. grids with a similar geometry to the expected the water table).

In order to investigate the requirements for gridding around the shaft, the test model was extended to 3D, a shaft was introduced (with transient excavation of the shaft as the calculation progressed). Using the transient unsaturated model, a grid size of 100m x 100m x 50m, and an NLF of 0.9 the model took 28.5 hours to run. This time was reduced to 14 minutes for the steady-state run using the unsaturated solver. Both models calculated an identical flux into the shaft of $7x10^{-4}m^3/s$, and 3D head fields (Figure 11).

However, the long time required for the transient calculation illustrates the need to simplify the model. Therefore, the model was re-run with a larger grid size (200 x 200 x 100 m) and with the NLF reduced to 0.75. This reduced the run time to 1.7 minutes for the steady-state run and 27 minutes for the transient run. However, the results were not consistent with the smaller grid size models, with flows into the shaft reduced to $4x10^{-4}m^3/s$.

Therefore, a series of sensitivity tests were undertaken to identify how the model could be simplified, without significantly affecting the shaft inflows. These were run with the steady-state solver.

Initially, it was assumed that the NLF would have the greatest impact on model results. Therefore, the modelling plan for the sensitivity tests (Table 2) envisaged running the model with the large grid spacing (designated as COARSE in Table 2), with increasing NLF in steps of 0.05.

Table 2: Summary of results for the 3D Test Model. See text for explanation.

MODEL ID	NLF	Grid Size	Shaft Inflow (m^3/s)	Run Time (minutes)
FINE	0.9	100x100x50	7.0e-4	14
COARSE	0.75	200x200x100	4.5e-4	1.7
COARSE A	0.8	200x200x100	4.5e-4	2
COARSE B	0.85	200x200x100	4.6e-4	23
COARSE C	0.9	200x200x100	NOT RUN	
FINE D	0.75	100x100x50	7.0e-4	14
FINE E	0.8	100x100x50	NOT RUN	
FINE F	0.85	100x100x50	NOT RUN	
COARSE LOCAL	0.9	200x200x100 with local grid size of 100x100x50 around shaft	6.8e-4	2

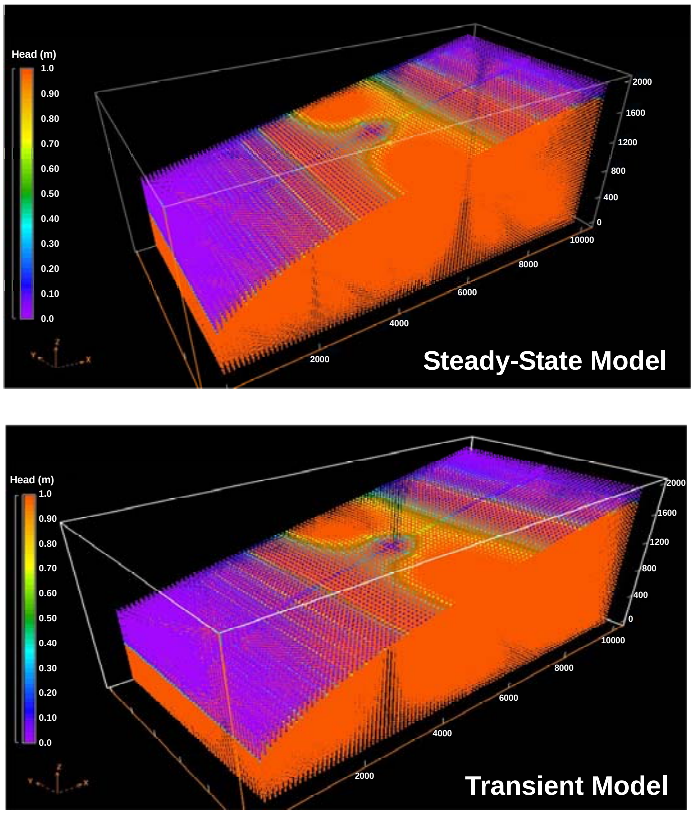

Figure 11: 3D head field for the 3D head field illustrating the similarity in results calculated using the steady-state unsaturated solver and the transient steady-state solver.

However, this had little impact on the results, other than increasing the time required for performing the calculation. Therefore, rather than run all of the planned calculations, the model with the smaller grid size (100m x 100m x 50m) and low NLF (0.75) was run (model FINE D). This model gave the same results as the model with the smaller grid size and high NLF (model FINE), indicating that, for the test models, the NLF does not significantly impact shaft inflows and that the grid size does.

However, the 2D Test Model had indicated that grid size did not impact on location of the water table and external boundary flows, so a further calculation was undertaken to determine whether a local grid could be developed for the COARSE model that would match the flows for the FINE model.

A local grid was implemented using a grid refinement of 100m x 100m x 50m for the first group of nodes around the shaft. The flows were very close to the results for the FINE model (flow into shaft $6.8\times10^{-4}m^3/s$), with the difference probably due to small differences in the precise location of the nodes with respect to the shaft.

DISCUSSION AND FORWARD WORK

Modelling of the impacts of unsaturated flow at regional scale is necessary for projects associated with radioactive waste disposal, including those associated with URLs and repositories. Underground excavations will remain open for several decades, leading to significant desaturation around the excavations and drawdowns to the regional water table.

Unsaturated flow processes typically occur at local scale and are therefore problematic to model at regional scale. JAEA has developed the GEOMASS system for integrated modelling of unsaturated flow at regional scale. The flow solver in GEOMASS, FracAffinity, provides special routines for modelling at regional scale, and the introduction of the NLF and grid refinement techniques for transient modelling are particularly significant.

The following conclusions regarding the modelling of unsaturated-saturated groundwater flow at regional scale are drawn from the test modelling:

- The choice of parameters is complex and requires testing for specific models.
- For unsaturated conditions, the unsaturated-saturated solver can be used to give an approximation of the water table location but does not provide realistic heads in regions where there is a significant unsaturated zone.
- Calculations of the steady state for unsaturated-saturated conditions are not affected by approach, i.e. use of transient or steady-state solver.
- The modelling indicates that steady-state solution is reached in >10,000 years for regional models (km scale) with a specific storage coefficient of 1×10^{-5}, hydraulic conductivity of 1×10^{-8}m/s and grid size on the order of 100m.
- Calculation of the fluxes at external boundaries and the topography of the water table are insensitive to grid spacing.
- Introduction of the NLF for transient calculations allows complex unsaturated-saturated models to be calculated without significantly affecting the results; care should be used to confirm that use of the NLF is appropriate for specific models.
- Calculations of the fluxes into a shaft are affected by the grid spacing around the shaft; this is a highly-local effect, possibly restricted to the first one or two nodes (depending on the grid size for these nodes).

More testing is required to understand the impact of local gridding and water retention model sensitivities to calculations of shaft inflows. In particular, the testing using the 3D test model focused on implications for the steady-state solver, and implications for the transient solver need to be investigated further. The use of a simple test model to understand how certain key parameters affect modelling efficiency and modelling results is useful and can provide insights, however, the results of the study also need to be proven against the more detailed and complex models developed for the MIU Construction Site.

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