Tetrahedral meshes to model discretely-fractured media: application to the Olkiluoto site (Finland)

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ABSTRACT

A new approach for hydrogeological modeling of discretely-fractured media has been developed by coupling three distinct software tools: the HydroGeoSphere numerical code (Therrien et al. 2007), the mesh generator LaGriT (Los Alamos National Laboratory) and the 3D geological modeling platform GOCAD (Mira Geoscience). The modeling approach is based on the use of tetrahedral meshes to discretize fractured geological media. The discretely-fractured bedrock of Olkiluoto Island (Finland) constitutes the case study presented here. The goal is to reproduce a pumping test conducted in the summer 2004. This study demonstrates that tetrahedral meshes provide a suitable spatial discretization and that the modeling approach is a new suitable way to investigate discretely-fractured media.

RÉSUMÉ

Une nouvelle approche pour la modélisation numérique en hydrogéologie des milieux à fractures discrètes a été développée en couplant trois outils informatiques: le code numérique HydroGeoSphere (Therrien et al., 2007), le générateur de maillage LaGriT (Los Alamos National Laboratory) et la plateforme de modélisation géologique 3D GOCAD (Mira Geoscience). L'approche est basée sur l'utilisation des maillages tétraédriques. Le massif rocheux fracturé de l'île d'Olkiluoto (Finlande) constitue l'étude de cas présentée ici. Le but de la modélisation est de reproduire un essai de pompage effectué en été 2004. Cette étude démontre que le maillage tétraédrique est approprié et que l'approche de modélisation constitue un nouvel outil pour l'étude des milieux géologiques fracturés.

1   INTRODUCTION

The mesh generation phase represents the connection between geological and numerical models. A geological model, or Geomodel (Mallet, 2002), is the 3D geometric representation of geological structures, such as layers, faults, folds or fractures. A numerical model is used to solve the governing equations over the discretized geological model. To provide a suitable discretization, the mesh should be chosen in an appropriate way.

A new modeling approach based on the combination of the geological modeling platform GOCAD (Mira Geoscience), the mesh generation software LaGriT (Los Alamos National Laboratory), and the numerical model HydroGeoSphere (Therrien et al., 2007) is developed. The combination of these three different software tools allows for a better discretization of complex domain geometries using tetrahedral meshes.

The application of the modeling approach to a case study is presented here. The subject of this study is Olkiluoto Island, which is located off the west coast of Finland. The crystalline bedrock of the island has been chosen to be a deep geological repository for high level nuclear waste. The rock is characterized by low permeability, crossed by few major fracture zones that control groundwater flow. Current investigations concern the safety of the future geologic nuclear waste repository. As a result, it is necessary to locate the hydraulically active fractures, define their geometry, and investigate the hydrogeological behavior of the fractured geological system. The purpose of this work is to build a Geomodel representing the fracture network, to provide a 3D discretization of the simulation domain, and to evaluate the groundwater flow field using the HydroGeoSphere numerical model.

2   SITE DESCRIPTION

Olkiluoto Island (12 km²) is located on the Bothnian Sea and is part of the Eurajoki municipality, 13 km north of the town of Rauma, in the south-west part of Finland (Figure 1). In this area, the coast is characterized by shallow bays surrounded by small archipelagos. The average annual temperature is 5.8 °C, the annual precipitation is 555 mm, and the snow thickness in winter is usually less than 20 cm. Seawater around Olkiluoto has a maximum depth of 30 m (Posiva Oy, 2003).
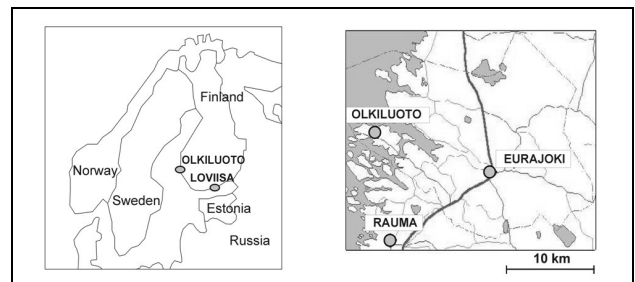

Figure 1. Location of Olkiluoto (adapted from Posiva Oy, 2005)

The average island topographic height is about 5 m a.s.l., with the highest point being at 18 m a.s.l. The soil, mainly stony moraine, is no more than 1.5 m thick and

usually less than 0.8 m. An overburden layer made of till, sand, and silt is found between the organic soil and the bedrock. The overburden has an average thickness of 3 m, with a maximum value of 10 m. The crystalline bedrock, which is part of the Precambrian Fennoscandian Shield, lies deeper. Rocks have undergone metamorphism and tectonic deformations and are mainly represented by metasedimentary migmatic mica gneiss.

The most dominant infrastructure is a nuclear power plant, which is characterized by two commercial reactors with auxiliary facilities. Another Finnish power plant is located in Loviisa (Figure 1). The construction of an underground research laboratory started in 2004. It is called ONKALO, which is an acronym based on the Finnish language expression for Olkiluoto Rock Characterization for Final Disposal. In fact, ONKALO is planned to be used to dispose of waste generated by the Finnish nuclear power plants.

2.1 Nuclear waste geological disposal

The preferred, and internationally recommended, option for the long term management of long lived and high level radioactive wastes consists in their disposal in deep geological repositories (IAEA, 2001). Four host geological formations are being widely considered for disposal: crystalline rocks, salt formations, argillaceous formations and tuff (IAEA, 1999).

ONKALO is being excavated in crystalline rocks, which have high mechanical strength, such that stable shaft, tunnel and gallery openings can be excavated at depths appropriate for geological disposal. In general, they are poorly transmissive and flow predominantly takes place through interconnected networks of fractures. They frequently have low matrix permeability and matrix porosity, as well as very low solubility. Finally, crystalline rocks normally have good thermal conductivity.

2.1.1 The ONKALO underground research facility

Characterization work performed in Underground Research Laboratories (URLs) plays an important role in the development of deep geological repository systems (IAEA, 2001). The ONKALO Underground Research Laboratory is planned to become a final deep geological repository for high-level nuclear waste. The construction of ONAKLO started in July 2004 and consists of a system of exploratory tunnels accessed by a spiraling tunnel and a ventilation shaft. The final disposal facility will be excavated at a depth of about 500 meters in the Olkiluoto bedrock. The total underground volume of ONKALO is approximately 330000 m^3 and the combined length of tunnels and the shaft is 8500 m.

The Swedish company SKB is hosting the secretariat of the Äspö Task Force, which is a forum of international organizations with the objective to interact in the area of conceptual and numerical modeling of groundwater flow and solute transport in fractured rock. Since 2005 the Task Force has initiated its Task 7, which focuses on Olkiluoto Island and modeling teams from Finland, Sweden, Canada, France, and Japan are participating. The Canadian modeling team is represented by the Nuclear Waste Management Organization (NWMO). In particular, Task 7A focuses on modeling a pumping test conducted at ONKALO in 2004, to understand the major features of the groundwater system at Olkiluoto. Specific goals are to determine proper means of incorporating the open boreholes in the hydrogeological model to simulate flowrates between fractures and boreholes, which are the main flow conductors.

3   GEOLOGICAL MODEL

The use of the discrete fracture conceptual model is justified by the fact that the fracture zones identified at the Olkiluoto site constitute the majority of the flow in the lower parts of the bedrock (Vidstrand and Ahokas, 2005a). The fractures are represented by irregular triangulated surfaces, whose modeling is based on the definition of structural intersections.

Vaittinen et al. (2003) defined an intersection as a fixed point that represents a core interval having properties that are important from a rock engineering and/or hydrogeological point of view and that differ from the average borehole properties. The core sample from the borehole KR09 constitutes an example of these intersections. The structural intersections identified in the boreholes were oriented according to the mean orientation of fractures measured in the borehole intersection (Vaittinen et al., 2003). The continuity of structures was estimated on the basis of the observed responses in long-term pumping tests, the geological and hydraulic properties of borehole intersections, and the compatible orientations of VSP-reflectors. Intersections are then correlated between boreholes, assuming that they represent parts of quasi-planar structures in 3D.

For modeling purposes the geometry had to be simplified and modified to give a transparent and understandable framework while retaining all the important features at the site scale (Posiva Oy, 2003). The volume modeled in this case study covers 17.5 km^2 (3.5 km x 5 km) and its limiting coordinates are 6791000 - 6794500 Northing and 1523000 - 1528000 Easting (Figure 2).
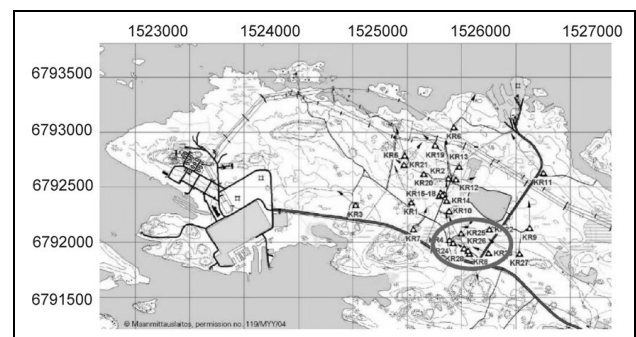

Figure 2. Plan view of Olkiluoto Island, where the location of ONKALO is circled (adapted from Vidstrand and Ahokas, 2005a)

The geological model considered here contains 13 fractures and 14 boreholes. The fractures are HZ1, HZ2, HZ3, HZ4, HZ8, HZ19A, HZ19C, HZ20A, HZ20AE, HZ20B_ALT, HZ21, HZ21B, and BFZ99, where HZ is the acronym for Hydrogeological Zone and BFZ for Brittle Fault Zone (Andersson et al., 2007). The boreholes integrated in the discretized geological model are KR4, KR6, KR7, KR8, KR9, KR10, KR12, KR14, KR22, KR23, KR24, KR25, KR27, and KR28.

Each fracture is built and triangulated independently from the structural intersections previously mentioned. The objective is to obtain a homogenous triangulation, with a resolution appropriate for the modeling objectives. The geometry and the triangulation of fractures are modeled using the *Pset*, *2DGrid* and *Surface* GOCAD tools, as well as the *Fit Surface to Pset* option. For this specific application, triangular edges on fracture surfaces are about 25 m long. Edge length is chosen in relation to the desired nodal distribution around the fractures.

Moreover, triangular surfaces are refined around borehole intersections. The boreholes are characterized by inclined axes, except KR24, and are discretized by tetrahedral edges 6 m long.

Intersecting fractures are then selected and the *Mutual Cut Among Surfaces* tool is executed to create the intersection lines. It should be noted that all intersecting fractures must be selected together and only one global cut is executed. The resulting intersection line holds concurrently the mesh of both the intersecting surfaces, but one side effect is that long and skinny triangles are created (Euler et al., 1999).

The GOCAD *beautify* algorithm is required to minimize the number of nodes, to optimize the size of the segments and to obtain the best fitting line (Euler et al., 1999). Thus, the *Simplify All Surface Borders* command is used to improve the triangulation at intersection lines and to create a conforming triangular mesh. The resulting network of intersecting fractures and boreholes is shown in Figure 3, where the longest borehole reaches a depth of 870 m.

Once the Geomodel is built, an external boundary should be defined (Figure 4) and the space discretized with 3D finite elements, which will represent the porous rock matrix surrounding the fractures and boreholes.
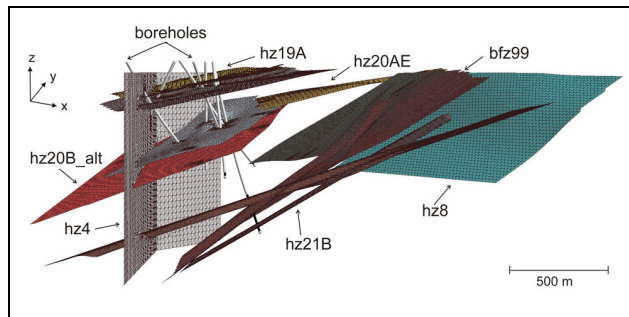

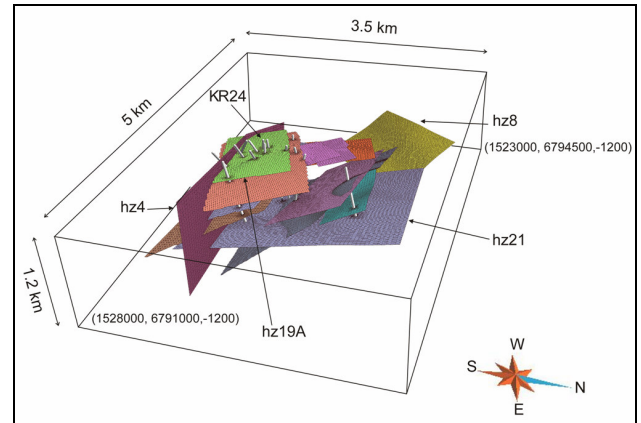Figure 3. Close-up of fractures and boreholes

Figure 4. Geomodel built with GOCAD: global view with simulation domain boundary

4   GEOMODEL DISCRETIZATION

Two main types of meshes exist, structured and unstructured. The fundamental difference between structured and unstructured meshes is the ordering of the nodes to form the elements, or cells, within the grid (Thompson et al., 1999). Structured meshes have a simpler geometry and they require less computer memory. In fact, they are characterized by a foreseeable rule that describes nodal connectivity and that can be used to find the neighbors to any node in the mesh. In contrast, unstructured mesh connectivity needs to be explicitly stored, because there is not a repeatable pattern describing nodal connectivity, as the index of neighbor nodes changes all over the domain. Structured meshes lack the flexibility in fitting a domain with a complicated shape, while unstructured meshes can provide multiscale resolution and conformity to complex geometries (Shewchuk, 1999). Therefore, unstructured meshes are generally preferred to discretize complex domains, such as discretely-fractured geological media. Well-studied geometric constructions such as Delaunay triangulation are central to unstructured mesh generation (Bern and Plassman, 1996). The Delaunay triangulation is a well-known algorithm to build a tetrahedral mesh. The particularity of the Delaunay mesh is that it has a dual mesh, the Voronoi diagram, which is useful to apply the Control Volume Finite Element numerical method (see Section 5).

The Geomodel discretization is performed with the mesh generator LaGriT. GOCAD surface files and borehole nodal coordinates are imported into LaGriT. As a result, 14 triangular Mesh Objects, which describe the 13 fractures and the topography of the domain, and 14 linear Mesh Objects, which represent the boreholes, are now the current Mesh Objects of a LaGriT session.

A hexahedral Mesh Object is generated to create the background nodal distribution on the simulation domain. A nodal spacing of 100 m is chosen to obtain a suitable mesh resolution, which includes refinement near fractures and around boreholes. Hexahedral elements near fractures and boreholes are selected for refinement. After two refinement steps hexahedral edges are 25 m long

around fractures. The same two-step procedure is used to refine near boreholes and obtain a nodal spacing of 6 m around the boreholes.

Once the mesh is properly refined, the hexahedra that are too close to fractures and boreholes are removed. Once the hexahedral mesh is refined around fractures and boreholes, all its nodes are copied to a tetrahedral Mesh Object, where they are connected using a Delaunay algorithm. Fracture surfaces are then extracted from the tetrahedral mesh just created. Finally, indexes of the tetrahedral nodes that correspond to fractures and borehole nodes are identified. These tetrahedral node indexes will be used by the numerical code to define the fracture and well elements.

The local refinement is clearly visible in the center of the domain, where fractures and boreholes are located (Figure 5). The refinement on the right extremity of the domain corresponds to fracture HZ8. An interior and central portion of the mesh located at z = - 300 m is shown in Figure 5b, where the refinement around fracture traces and boreholes is evident. The mesh generation procedure ensures that inclined borehole axes will preserve their real geometry in the discretized Geomodel.
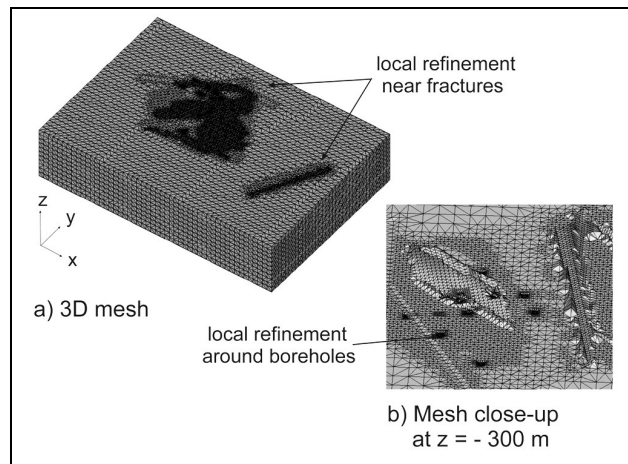

Figure 5. Tetrahedral mesh for the Olkiluoto site

5   HYDROGEOSPHERE

HydroGeoSphere is a numerical simulator specifically developed for supporting water resource and engineering projects pertaining to hydrologic systems with surface and subsurface flow and contaminant transport components. The development of an enhanced HydroGeoSphere version was motivated by the objective to reach a seamless combination between geological and numerical models.

The Control Volume-Finite Element method, CVFE, constitutes the basis of the numerical solution. In this method, a finite volume subgrid is constructed as a complement to the finite element grid (Geiger et al., 2004). The Control Volume technique produces discretized equations by applying physical conservation laws to control volumes surrounding mesh nodes. Thus, two meshes are considered, a finite element grid and a

dual mesh, which is the control volume mesh. The CVFE method applied to numerical modeling in hydrogeology is discussed in Forsyth (1991) and Letniowski and Forsyth (1991).

Simulation results presented here consider fully-saturated subsurface flow. The governing equation for transient subsurface flow in fully-saturated porous media characterized by hydraulic conductivity K and specific storage S_s is:

$$\nabla\left(K_{ij}\nabla h\right)\pm\Gamma = S_s\frac{\partial h}{\partial t} \qquad [1]$$

where Γ is a volumetric flux representing a source (positive) or a sink (negative) to the porous medium system. The analogous equation for fully-saturated flow in a discrete fracture of aperture $2b$ is:

$$\nabla(2b)\left(K_{f_{ij}}\nabla h\right)+q_{n|_{I^+}}+q_{n|_{I^-}}\pm\Gamma = (2b)S_{sf}\frac{\partial h}{\partial t} \qquad [2]$$

Eqs.[1] and [2] are linked via the fluid leakage fluxes $q_{n|_{I^+}}$

and $q_{n|_{I^-}}$ across the two surfaces I^+ and I^-, respectively, of a fracture.

With the discretely-fractured medium representation, each fracture is explicitly represented by specifying its own geometry, areal extent, dimensions and position in the 3D space. The numerical approach is based on continuity of hydraulic head and concentration at the fracture/matrix interface, which corresponds to instantaneous equilibrium between the two domains. This method is also called the common node approach and it is essentially based on superposition of 2D fracture elements onto the elements of the porous matrix (Therrien and Sudicky, 1996; Therrien et al., 2007). Thus, nodes at fracture locations are common nodes that receive contributions from both the rock matrix elements and the fracture faces.

The original HydroGeoSphere code used only block and prism finite elements, while tetrahedral finite elements are introduced here. The development presented here represents an extension of the work of Graf (2005) for the representation of irregular networks of fractures. A new relationship between 2D triangular and 3D tetrahedral elements considered here to represent the porous rock matrix and the discrete fractures, respectively (Figure 6).
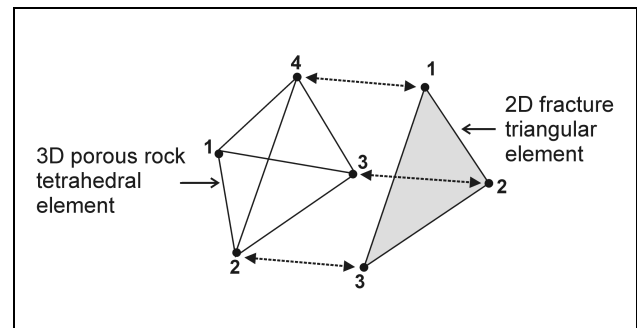

Figure 6. Relation between 2D and 3D finite elements

6 SUBSURFACE FLOW SIMULATIONS

To predict the effects on the groundwater and to characterize hydraulic connections in the scale of 100 m - 1 km, a long-term pumping test was carried out in deep borehole KR24 in 2004 (Vaittinen and Ahokas, 2005). The pumping test started on March 25 and finished on June 2. The borehole is 540 m deep and had a casing section down to 20.13 m. A one meter packer with bypass tube was installed at the borehole depth of 80.60-81.60 m. As a result, the lower part of KR24, partially isolated by the packer, experienced a smaller drawdown than the upper section during the pumping (Vidstrand et al., 2006).

Borehole KR24 is intersected by fractures HZ19A, HZ19B, HZ20A, and HZ20B_alt. The porous rock is divided into two sections characterized by different hydraulic conductivities. This division is supported by measured transmissivity values and by calibration during subsurface flow modeling. Hydraulic conductivity equal to 7.8×10^{-8} m/s is attributed to the top 70 m of the bedrock, while the deeper bedrock is assigned a lower conductivity equal to 1×10^{-12} m/s. Fracture apertures are calculated from the geometric mean transmissivity values given by Vidstrand et al. (2006). Nevertheless, the values of the four fracture apertures intersecting KR24 are slightly modified from the calculated value to obtain a better calibration of the drawdown at the pumping well (Table 1).

Table 1. Fracture transmissivity values and apertures

Fracture name	Transmissivity [m^2/s]	Aperture [m]
HZ1	-7.9	2.6×10^{-5}
HZ2	-6.0	1.1×10^{-4}
HZ3	-6.2	9.6×10^{-5}
HZ4	-6.8	6.1×10^{-5}
HZ8	-5.0	1.3×10^{-4}
HZ19A	-5.8	1.0×10^{-5}
HZ19C	-5.5	1.6×10^{-4}
HZ20A	-5.1	3.9×10^{-4}
HZ20AE	-6.0	1.1×10^{-4}
HZ20B_ALT	-5.5	5.0×10^{-4}
HZ21	-7.8	2.8×10^{-5}
HZ21B	-6.1	1.0×10^{-4}
BFZ99	-7.8	2.8×10^{-5}

6.1 Steady-state flow field

Before simulating the pumping test, a steady-state flow field is evaluated to obtain the initial hydraulic head distribution for successive transient simulations. A first type boundary condition is imposed on the top boundary of the domain. Hydraulic heads are available from groundwater table measurements, which vary from 0 at the sea level to 9 m in the center of Olkiluoto Island. Open boreholes are disconnected from the surface, by defining their top node 10 m below the topographic surface. Otherwise the hydraulic head would not change

in the boreholes, since constant heads are imposed on the top boundary. This choice is justified by the fact that all boreholes have a casing section that prevents groundwater at the surface from flowing to the boreholes (Vidstrand and Ahokas, 2005b). Heads on the lateral boundaries are all equal to sea elevation, while the bottom boundary is assumed impermeable. Observation points are located at open deep boreholes KR04, KR07, KR08, KR10, KR14, KR22, KR27, and KR28. The hydraulic heads measured at those boreholes are listed in Table 2 together with the corresponding simulated heads. Observed heads are calculated as the average between March 16th and March 24th measurements. This choice is motivated by two main reasons. First of all, no values are available at KR4 on March 24th. Moreover, the average is intended to balance water table fluctuations during the ten days separating the measurements, since the heads imposed on the top boundary are the long term groundwater table mean values. The maximum absolute difference between observed and simulated heads obtained here is less than 0.9 m. The biggest difference is observed at boreholes KR7 and KR27 (Table 2).

Table 2. Observed and simulated hydraulic heads

Borehole name	Observed head [m]	Simulated head [m]
KR4	6.03	6.00
KR7	5.31	6.04
KR8	6.28	6.06
KR10	5.98	6.16
KR14	6.82	6.7
KR22	6.17	6.02
KR27	6.72	5.85
KR28	5.69	6.00

Simulated hydraulic heads on the domain boundary are shown in Figures 7 and 8. The flow is directed from the topographic high areas of the island toward the sea, where the hydraulic head is equal to zero. The impact of the open boreholes on the groundwater flow field is analyzed by simulating flow and comparing hydraulic head distribution with and without the boreholes. The differences in the flow field are clearly shown for three vertical sections inside the simulation domain. Since the open boreholes intersect the fractures, a complex network of major flow conductors is created. As a result, when the open boreholes are included, the global hydraulic conductivity of the domain increases and hydraulic heads are higher at greater depths. The difference in hydraulic heads is particularly noticeable toward the North, in the direction of increasing y coordinates, around borehole KR6, which intersects fractures HZ1, HZ21B, and HZ21. In particular, top and bottom nodes of this borehole are located at coordinates y=6793050 m and y=6793350 m, generating greater hydraulic heads in this portion of the domain. Thus, the boreholes drilled at the site have a considerable influence on the groundwater field in the discretely-fractured medium.
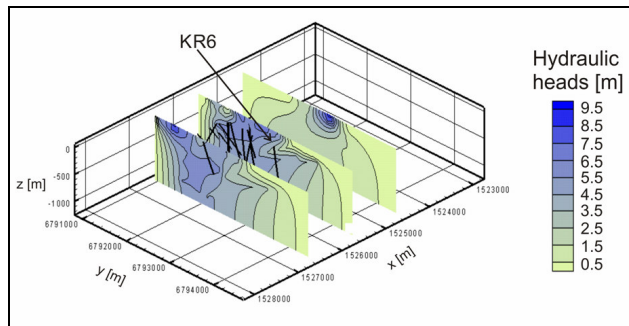
Figure 7. Simulated steady-state hydraulic heads: view inside the domain with open boreholes
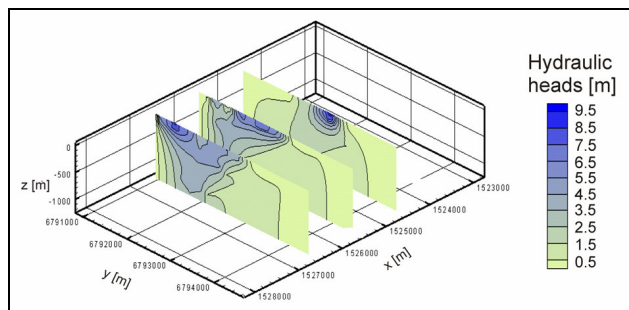

Figure 8. Simulated steady-state hydraulic heads: view inside the domain without boreholes

6.2 Transient flow field: KR24 pumping test

The main purpose of the modeling of the Olkiluoto site is to reproduce the pumping test conducted at borehole KR24. Few manual head measurements are available above and below the packer, while automatic measurements, taken every 15 minutes, are conducted from March 26 to July 22. The maximum drawdown observed in the upper section of KR24 is 19.25 m, while it is 1.94 m in the lower section. A difference between water levels before and after pumping is observed and is assumed to be caused by the natural decrease of groundwater surface in the island (Ahokas and Vidstrand, 2005).

The packer is represented in the model by splitting the borehole into two separated sections: the upper section extends from ground surface to -86 m, while the lower starts at -92 m from the surface and extends down to -540 m. The upper section only intersects fracture HZ19A and is discretized by 15 nodes. This intersection with HZ19A also coincides with the withdrawal node, where a pumping rate equal to 6570 m^3/y is imposed. In contrast, the lower section is discretized by 76 nodes and intersects fractures HZ19C, HZ20A, and HZ20B_alt at depths of about -105 m, -296 m, and -390 m, respectively. A pumping rate equal to 2891 m^3/y is imposed at the top of this lower section. The model is calibrated by adjusting hydraulic parameters of the discretely-fractured medium to match observed and simulated drawdown at both observation points and pumping well.

A good match between automatic measurements and simulated heads at the pumping well is obtained using the apertures listed in Table 1. The porous rock hydraulic conductivities are the same as those used for the steady state simulations and equal to 7.8 x 10^{-8} m/s and 1 x 10^{-12} m/s for the top layer and for the bedrock, respectively. The quick recovery at the end of pumping is accurately reproduced, as well as the minimum hydraulic head reached during pumping (Figure 9). A slight difference can be noticed at the end of the simulation, after 110 days, when the observed heads are lower than the simulated heads. This difference is explained by a natural decreasing trend, which has been observed on Olkiluoto Island (Ahokas, 2007).
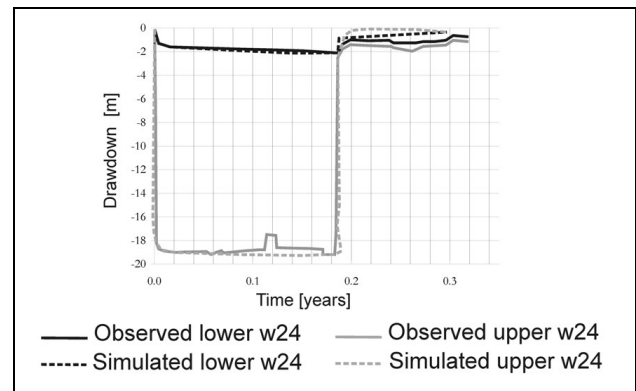

Figure 9. Calibrated drawdown at pumping well KR24

Simulated drawdown at observation points is also compared to that observed. However, observed drawdown contains not only the decreasing of hydraulic heads due to pumping at borehole KR24, but also the natural decreasing trend observed on Olkiluoto Island. Ahokas (2007) described some historical relationships between observed heads near surface and deeper in the bedrock. Decreasing trends have been analyzed for summers 1991, 1994, 1996 and for the longer period January 2002 - May 2003. An average trend of 1 cm/day is observed between mid-July and mid-September 1991. This natural decreasing trend is considered here to correct the observed drawdown at boreholes KR04, KR07, KR08, KR10, KR22, KR27, and KR28, which are chosen as observation points. The resulting observed "detrended" drawdown is compared to the drawdown simulated at observation boreholes (Figures 10 and 11). The corresponding drawdown at borehole KR24 has been presented in Figure 9.

Boreholes KR4, KR7 and KR27 show the largest difference between observed and simulated drawdown. For borehole KR4 this difference is probably due to the fact that KR4 is the nearest borehole to pumping well KR24 (about 60 m) and, therefore, the effect of pumping may be greater than the natural decreasing trend. Concerning boreholes KR7 and KR27, the differences have already been observed with the poor calibration in the steady-state simulation (Table 2). Moreover, the decreasing rate depends on local properties, such as the

topography, location either on an outcrop or on overburden, and porosity (Vaittinen and Ahokas, 2005). Thus, it may be too simplistic to correct all observed heads by the same quantity.
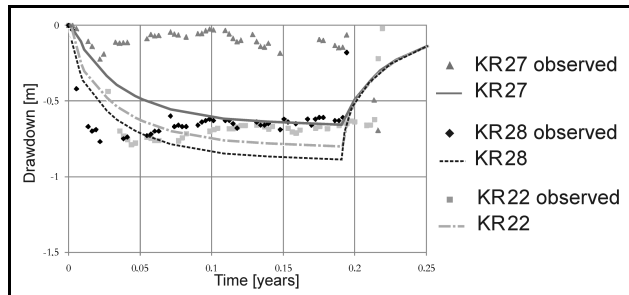

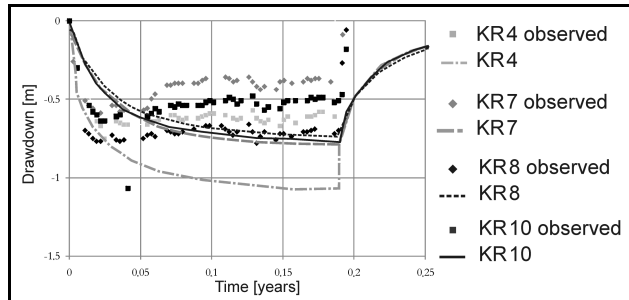Figure 10. Simulated and observed "detrended" drawdown at observation boreholes – part 1

Figure 11. Simulated and observed "detrended" drawdown at observation boreholes – part 2

7   CONCLUSION

This case study demonstrates that the developed approach is a suitable tool for hydrogeological modeling of complex fractured media. The geological modeling platform GOCAD is particularly suitable to build the 3D fracture network using available field data. The geological modeling platform allows for a more realistic representation of the fracture network, which is modeled and visualized before discretizing the 3D simulation domain. The tetrahedral mesh is appropriate to discretize this complex domain and it constitutes a good compromise between high mesh resolution and computational time. The enhanced HydroGeoSphere version can now identify tetrahedral faces and define them as fracture elements. Moreover, inclined boreholes are represented with their real geometry. Flow simulations aim at reproducing the pumping test conducted at the Olkiluoto site in 2004. Steady-state and transient simulations are executed and a satisfactory agreement between simulated and observed hydraulic head is obtained. Thus, this case study shows that the modeling approach based on tetrahedral meshes and on the coupling of the geological modeling platform with the numerical code is a supportive tool to investigate discretely-fractured geological media.

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