Partial examination

November 4, 1999

9:00 - 12:00 a.m.

room 234 Building ‘Mijnbouw’

ta4780

‘Flow and Transport in

Fractured Rock Masses’

The questions may be answered in any language

(English, Nederlands, Afrikaans, etc.)

Question 1

Fresh groundwater has to be protected against migration of pollutants. For aquifers consisting of fissured and porous rocks this is more complex than for unconsolidated aquifers.

1a.

- Mention four particular features of fissured aquifers that cause this additional complexity.

1b.

- Describe the protection area approach.

1c.

- Describe the residence time zones approach.

1d.

- What is the disadvantage of laboratory measurements of the rock permeability with respect to field measurements?
- Mention some field measurements.

1e.

- The ‘double porosity character’ of fissured porous rocks has a strong influence on the time-dependent heads observed in pumping well and recovery tests. It has also a strong influence on the time-dependent concentrations during the migration of solutes and/or tracers. Describe and explain the differences in response of head and of concentration with respect to ordinary porous media.

- **Question 2**

Let us consider a mixture of water and salt flowing through a fractured (or fissured) porous rock. The three basic equations describing the flow of the mixture and the transport of the dissolved salt are

(i) the equation of mass conservation of the water-salt mixture (continuity equation),
(ii) the momentum balance (Darcy's law), and
(iii) the mass balance of dissolved salt (advection-dispersion equation).

2a.

- Explain the equation of mass conservation of the mixture using the words 'inflow,' 'outflow' and 'storage.'
- Give the name of the parameter that occurs in this equation and a unit in which it is expressed. (Parameters are quantities expressing properties of the fluid and/or the rock.) Use the three-dimensional (3D) approach, not the two-dimensional (2D) 'aquifer-aquitard approach.'
- How many unknowns occur in this equation? (Unknowns are quantities expressing the state of the flow/transport process.) What are the names of the unknowns and give units in which they are expressed.

2b.

- In the momentum balance (Darcy's law), nine parameters occur. Describe these nine parameters and relate the unit in which they are expressed to the units of the other quantities that occur in Darcy's law.
- What are the names of the unknowns in Darcy's law and give units in which they are expressed.

2c.

- Explain the meaning of the following five mechanisms that play a role in the advection-dispersion equation: (i) 'storage,' (ii) 'advection,' (iii) 'diffusion,' (iv) 'longitudinal dispersion' and (v) 'lateral (transversal) dispersion.'
- What is the meaning of anisotropy related to dispersion?
- Give the parameters that occur in the advection-dispersion equation and give units in which they are expressed.
- Give the unknown quantity and its unit in the advection-dispersion equation.
- When considering transport on the scale of the pore space (the fluid-filled space between the solid grains), there are only three transport mechanisms: (i) 'storage,' (ii) 'advection' and (iii) 'diffusion.' Some persons therefore claim that 'dispersion does not really exist.' Explain the point of view from which dispersion does makes sense.

2d.

- What is the difference between heterogeneity and homogeneity?
- What is the difference between anisotropy and isotropy?
- Explain that an isotropic heterogeneous rock on the fine scale may be considered as a homogeneous anisotropic rock on the coarse scale.

Question 3

The basic equations governing groundwater flow and transport of dissolved mass are *partial differential equations* in *continuous* space and time.

3a.

- Why do we need numerical approximation methods?

3b.

- Into what type of equations do numerical methods transform the partial differential equations?

3c.

- What are direct methods, what are iterative methods, and why do we need them?

3d.

- What is the basic idea behind the Finite Difference Method?

3e.

- What is the basic idea behind the Finite Element Method?

3f.

- Make a picture of a finite element mesh and of a finite difference mesh, and show the refinement around a well in the two pictures.

3g.

- What is ‘upscaling,’ or ‘homogenization’ and why do we need this in the context of numerical methods?

Question 4

Let us consider an isotropic fissured (fractured) aquifer with fissure planes parallel to the horizontal x-axis. The four equations for the four unknowns q_x, q_y, q_z and h are given by

$$\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}=0, \quad q_x=-K_{//}\frac{\partial h}{\partial x}, \quad q_y=-K_{\perp}\frac{\partial h}{\partial y}, \quad q_z=-K_{//}\frac{\partial h}{\partial z}$$

The composite (upscaled) hydraulic conductivities are $K_{//}=1.0\, m/day$ and $K_{\perp}=0.001\, m/day$. The thickness of the aquifer is $b=50m$. A bedrock without fissures having a negligible hydraulic conductivity underlies the aquifer ($K=0.0\, m/day$). It is common practice to simplify the above-given 3D flow equations to a 2D approximation.

4a.

- This 2D approximation is sometimes stated as: “In aquifers the flow is two dimensional in the horizontal x and y directions, with zero vertical flux component $q_z = 0$.” Show that the thus-stated simplification ($q_z = 0$) results in three 2D equations for three unknowns. Is this a useful approximation when the aquifer is recharged by precipitation?

4b.

- Consider again the 3D equations and show that replacement of the third component of Darcy’s law, $q_z=-K_{//}\partial h/\partial z$, by $\partial h/\partial z = 0$ (Dupuit’s approximation) results in four equations for four unknowns.

4c.

- Show that in this system of equations a non-zero vertical flux component, $q_z \neq 0$, is possible.
- Is this a useful approximation when the aquifer is recharged by precipitation? Why?
- What could be the advantage of using the 2D approximate equations above the original 3D equations? What could be the disadvantage?

4d.

- Derive 2D equations for the ‘integrated flux’ q' (expressed in m^2/day) and introduce the transmissivity $T=Kb$.

4e.

- If the hydraulic head, h, is given by $h=h_0-x^2/L,\ L=3\,650\,000m,\ h_0=10m$, what is then the vertical flux at the top of the aquifer?
- If the water table is steady, what is then the recharge expressed in *mm/year* ?
- If there would be no recharge, what is then the velocity, expressed in *mm/year*, with which the water table goes down? The specific yield (effective porosity) is 0.2.