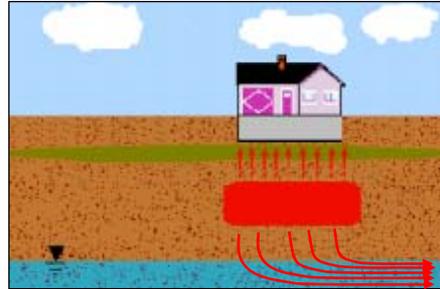


Note A5:
Dispersion in aquifers

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Introduction

This note contains information on dispersion and selection of dispersivity values in aquifers. The note assumes basic knowledge on transport in aquifers including the advection/dispersion equation and Darcy's law (see for instance Waterloo Hydrogeologic, 2001).

Transport and dispersion

Transport processes in porous media are well described in literature. The classical advection/dispersion equation describes the transport in sandy aquifers with high to moderate hydraulic conductivity ($1.0 \cdot 10^{-3}$ - 10^{-5} m/s) very well. Several examples exist in literature where observations in field injection experiments or field studies are simulated by 3 dimensional transport models (Broholm et al., 2001; Højberg et al, 2005; Prommer et al., 2006).

The flow velocity is basically governed by Darcy's law, where the determination and variation in hydraulic conductivity are a challenge as it can vary several orders of magnitude within short distances. Porosity variation is much smaller compared to variation in hydraulic conductivity (typically a factor of two). Determination of hydraulic gradients is fairly straightforward from measurements of hydraulic heads in piezometers, however, in field studies poor identification of flow field is very common due to a poor geological model, temporal or spatial variation in hydrogeology or a limited number of piezometers.

The transport (seepage) velocity describes the mean velocity, while the dispersion describes the variation in velocity causing spreading of contaminants. This is well known from 1 D tracer experiments in columns where breakthrough is smoothen due to dispersion. In 3 D the dispersion coefficients are defined mathematically as:

$$D_x = \alpha_x v, \quad D_y = \alpha_y v, \quad D_z = \alpha_z v$$

- D_x is the dispersion coefficient in the flow direction, D_y is the transverse dispersion coefficient, and D_z is the vertical dispersion coefficient
- α_x is the dispersivity in the flow direction, α_y is the transversal dispersivity, α_z is the vertical dispersivity
- v is the seepage velocity in the flow direction, which corresponds to the Darcy velocity divided by the porosity (effective), θ , (see note A3 for details).

The basic parameters are the dispersivities, which characterise the aquifer. The challenge is to identify realistic dispersivity values in order to describe the spreading of contaminants properly.

Longitudinal dispersivity values

The longitudinal dispersivity governs the spreading of contaminants in a 1 D system e.g. a column experiment. The longitudinal dispersivity affects only to a small degree the spreading of a continuous source leaching into an aquifer (Liedl et al., 2006). Most contaminant sources will with a life time of decades resemble a continuous source. This behavior is opposite to a pulse release (typically an accidental spill or a tracer study), where the longitudinal dispersivity has a significant effect. The effect of the longitudinal dispersivity is also crucial in order to describe first arrival or breakthrough of contaminants to a point of compliance or a drinking water supply well.

In the eighties and early nineties dispersion was subject to significant research efforts. The interpretation of dispersion in aquifers was improved both theoretically and practically (see Neuman, 2006 and references in here). A number of large scale field tracer experiments were conducted in North America, the most famous being experiments in the sandy aquifers at Borden and Cape Cod (Freyberg et al., 1986, Garabedian et al., 1991). Also the experiments at the Columbus site were a land mark as the first example of a site with a significant geological heterogeneity (Boggs et al., 1992). In Denmark a large scale field tracer experiment was carried out in the sandy Vejen aquifer (Jensen et al., 1993).

The experiments and theoretical developments revealed some important findings:

- The magnitude of the longitudinal dispersivity is scale dependent.
- The longitudinal dispersivity reflects the spatial variation in hydraulic conductivity, which can be described by use of geostatistical tools.
- The longitudinal dispersivity is significantly larger than the transversal dispersivity (Gelhar et al., 1992).

These general findings are still valid although additional studies have refined the understanding of the processes and the database with high quality observations (Schulze-Makuch, 2005; Neuman, 2006). Some examples of findings in relevant field studies are provided in Table 1.

Table 1: Examples of dispersivity values obtained from field tracer experiments and field observations at contaminant plumes.

Field site and type	Aquifer and scale	Longitudinal dispersivity	Transversal dispersivity	Vertical dispersivity	References
Borden air force base, tracer test	Homogeneous sandy aquifer, 90 m	0.43 m	0.04 m	Not reported	Freyberg (1986)
Cape Cod, tracer test	Homogeneous sandy aquifer, 250 m	0.96 m	0.018 m	0.0015 m	Garabedian et al. (1991)
Vejen, tracer test	Homogeneous sandy aquifer, 125 m	0.45 m	0.001 m	0.0005 m	Jensen et al. (1993)
Columbus site tracer test	Heterogeneous sand and gravel aquifer, 200 m	7.5 m	Not reported	Not reported	Adams and Gelhar (1991)
Contaminant plume with chloride, field observation	Sand and gravel aquifer, 5500 m	Not reported	0.10 m	Not reported	van der Kamp et al. (1994)
Grindsted landfill, field observation	Homogenous Sandy aquifer, layered, ~150 m	3 m	0.05 m	Not reported	Lønborg et al. (2006)
Sjølund Landfill, field observation	Sandy aquifer, layered, ~300 m	Not reported	Not reported	0.003 m	Prommer et al. (2006)

The scale and the aquifer type are important in order to identify a relevant longitudinal dispersivity. The following general equation is reported by Schulze-Makuch (2005):

$$\alpha_x = c(L)^m$$

c is a parameter characteristic for a geological medium

m is the scaling exponent

L is the flow distance

For unconsolidated media (e.g. a sandy aquifer) c and m has been identified by Schulze-Makuch (2005) using the most reliable data:

$$\alpha_x = c(L)^m = 0.20(L)^{0.44}$$

For a distance of 100 m, the longitudinal dispersivity will be estimated to a value of 1.6 m. Similar equations exist for other types of aquifers. The equations may have some limitations on L.

Transversal and vertical dispersivity values

The knowledge about the transversal and vertical dispersivities is much less than for the longitudinal dispersivity. This is a serious problem as:

- The transversal and vertical dispersion primarily govern the spreading of contaminants for a continuous source in a horizontal flow system.
- The mixing in the capillary fringe is governed by the vertical dispersivity (Klenk and Grathwohl, 2002).
- The magnitude of the vertical dispersivity has a significant impact on degradation in stationary contaminant plumes governed by degradation processes at the fringe of the plume (Liedl et al., 2005; Cirpka et al., 2006).

The magnitude of the transversal and vertical dispersivity values has been subject to debate over the years. Today most researchers agree that dispersivity values observed in the most reliable field studies and identified under well controlled laboratory conditions are in the range of millimeters to a few centimeters (Table 1). This is close to be at the same order of magnitude as diffusion coefficients. The small transversal dispersivity has two significant practical implications for site investigations:

- Contaminant plumes will be very narrow – cigar shaped
- Boreholes in monitoring networks should be placed very close in order to catch a spill or a contaminant plume with a high certainty.

The small vertical dispersivity has the same implications as the transversal dispersivity. It is often difficult to recognize the limited vertical spreading in traditional borehole, where the screens are 1-3 m long. However, observations at several contaminant plumes characterized by multi level sampling systems with short screens (few cm) placed with small vertical increments have showed very steep vertical concentration gradients. A feature which affects mixing of reactants and thereby degradation processes at plume fringes (Tuxen et al., 2006; Prommer et al., 2006).

In modeling of solute transport the selection of appropriate transversal and vertical dispersivities is a key issue. It is recommended to perform simulations with very small numbers and if possible quantify dispersivity values by comparison with observations. Use of small dispersivity values demands a fine model discretization in order to recognize the effect from numerical dispersion.

It should be mentioned that several relationships between the longitudinal and the transversal dispersivity have been suggested, however, Cirpka et al. (2006) states:

“At the pore scale, transverse dispersion coefficients are considerably smaller than longitudinal ones. On typical plume scales of tens to hundreds of meters, the difference is more pronounced because the transverse dispersivity is hardly affected by the heterogeneity of the aquifer, whereas the longitudinal coefficients increase by orders of magnitude.”

This implies that use of rules of thumb (fixed ratios) for relationships between the longitudinal and the transversal dispersivity are misleading. Several relationships have been used and are still used in application of transport model (see for instance Waterloo Hydrogeologic, 2001), especially by modelers in consulting companies. This is very problematic as the relationships generally overestimate the transversal dispersivities. Thus the spreading will be overestimated causing overestimation of the contaminant concentrations.

Under field conditions the apparent transversal and vertical dispersivities can be enhanced due to:

- Variations in geology or hydrogeology
- Water table fluctuations (smearing of gasoline compounds, Light Non-aqueous Phase Liquids)
- Density flow (e.g. at landfills sites with dense leachate), transport of separate phases (e.g. for chlorinated solvents)

These factors can blur the picture, but not the fact that transversal and vertical dispersivities are small!

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