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Groundwater Flow in Fractured Rocks: Models and Reality

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Abstract

In fractured aquifers the regional groundwater movement may be a very important factor for mass and energy transport. Interpretation of the chemical and isotopic composition of groundwater, understanding of the geothermal conditions (anomalies) and forecasting the possible effects of industrial waste disposals nearly always would require the knowledge of the regional, intermediate and local groundwater flow systems.

In most cases the regional groundwater flow field must be simulated by using numerical models. As the available data on the hydraulic parameters are very limited, the indirect estimation of the hydraulic parameter fields plays a very important role in modelling fractured aquifers. Besides geostatistical methods (kriging, etc.) or simple correlations with geological factors (lithology, etc.), the geometry of geological discontinuities is frequently used to indirectly estimate the hydraulic conductivity and effective porosity values.

The "imbricated" or nested structure of the geological discontinuities, the effect of this structure on the hydraulic parameter fields and the possibility to represent this structure in numerical models are some of the problems addressed by the author. Field studies on the space variability of fracture density will complete the paper, which throughout reflects the point of view of a hydrogeologist.

1 Introductory remarks.

1.1 Real system, abstract scheme, numerical model.

The reconstruction of a regional groundwater flow field, which is consistent with a given hydraulic conductivity field and with given boundary conditions, nearly always requires the use of numerical models. A model is not the reality, it is only the realization of a schematic and symbolic representation of the real system. The relations between "real system", "abstract scheme" and "numerical model" are represented in *figure 1*, which also shows the principal problems in modelling groundwater flow.

To begin with, a *schematic representation of the real system* has to be worked out. Generally, the flow of the goundwater is represented by differential equations, which may change depending on the type of problem to solve (saturated-unsaturated flow, constant or variable density flow, multiphase flow, etc.). The flow equations contain a few parameters depending on the aquifer properties (hydraulic conductivity, specific

Representation of the principal problems in modelling groundwater flow

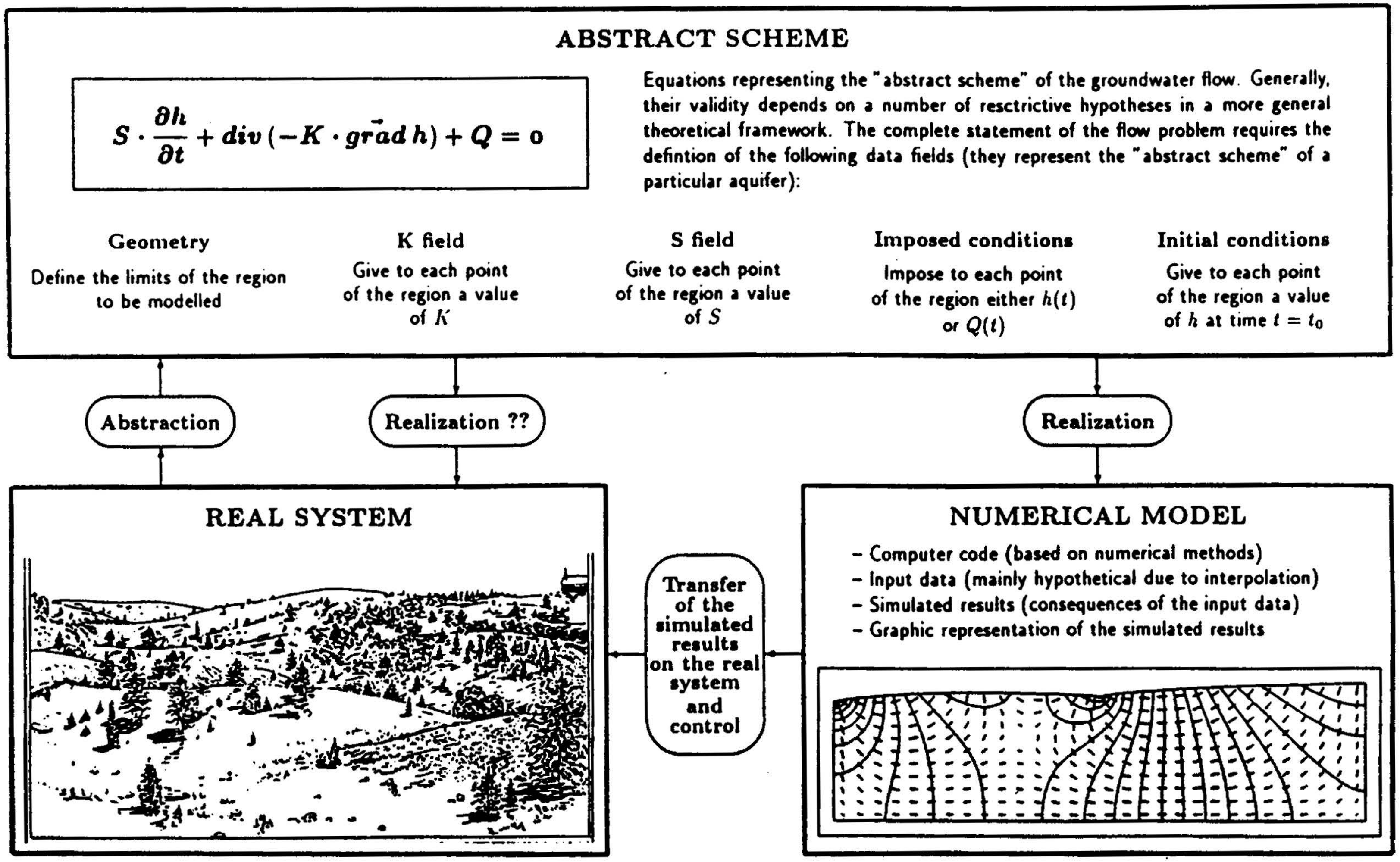


Figure 1: Relations between "Real system", "Abstract scheme" of the real system and "Numerical model".

storativity, effective porosity, etc.) and the real medium will be represented by the field of these parameters, i.e. by giving a parameter value to each point of the modelled region, even there where we have never made any observation. As the available data on the hydraulic parameters are very limited, it appears clearly that indirect estimation of the parameters and interpolation or extrapolation of the measured values will be unavoidable when modelling real aquifers. It must be emphasized that fractured media may present additional difficulties due to the strong local heterogenity of the parameter fields. Finally, the imposed and initial conditions complete the scheme, sometimes also termed the "conceptual model".

The second problem is related to the *realization of a computer code* based on numerical methods which allow to solve the equations defined in the abstract scheme. The problem is far from beeing simple for highly non-linear or hyperbolic differential equations in a heterogeneous 3-D space. As a matter of fact, the numerical model is only a more or less imperfect realization of the abstract scheme.

The third, very important problem in modelling groundwater flow is the *transfer of the simulated results onto the real system.* Strictly speaking, the simulated results are not "valid" but in the highly simplified scheme or numerical model, and their meaningful transfer onto the real system requires that simplifying assumptions and uncertainities on the data explicitly do appear as uncertainities on the results. This could help to avoid such situations as trying to simulate an observed piezometric head to within a few centimeters, even though the schematized hydraulic conductivity field "ignores" the strong local heterogeneities existing in the real system.

In the author's opinion many misunderstandings and unnecessary discussions about models could be avoided when keeping in mind the differences between real system, abstract scheme and numerical model, as well as some of the fundamental properties of a scheme (Suter, 1966):

- A scheme is established with a previously defined intention: to solve a problem. Depending on the problem to solve, the same real system may be represented by very different schemes.
- A scheme is summary, partial. Only certain elements of the real system are represented (generally by symbols) and only certain processes of the real system will be expressed by (generally quantitative) relations between these symbols.
- A scheme is always perfectible (by using more complicated equations and more detailed parameter fields), but it will never be identic (and it could never be identified) with the real system.
- Once established, the efficiency of a scheme must be judged with respect to the previously declared intention (aim). In itself, a scheme is neither "good", nor "bad". It becomes "good" or "bad" only when it is supposed to represent such and such real system or to solve such and such well defined problem.
- Each concrete realization of an abstract scheme will be called **"model"**. The numerical model, for example, is a realization of the scheme (see *figure 1*), but the real system, which motivated the creation of the schematic representation, ought to be a "model" of the abstract scheme, too.

The last proposition is somewhat unusual, but it simply shows the formal condition for the possibility to transfer the simulated results onto the real system: the transfer is possible only if both the numerical model and the real system may be considered as beeing, to some extent, the "models" of the *same* abstract scheme. The central role played by the scheme may be surprising, but it is the only thing we actually and exactly know, because we have created it.

The above listed propositions also indicate, that starting from incomplete informations on the real system, we are free to invent any inevitably hypothetical and schematic representation, which helps to solve a problem (this is a question of "inspiration"). But after this, we have to control the consistency of the scheme in a theoretical framework, we have to deduce the verifiable consequences of the more or less hypothetical parameter fields (in most cases precisely by using numerical models) and we have to check, by direct or indirect experimental methods, whether the real system may (or may not) be considered as a realization (a "model") of the proposed scheme (this part of the work requires "transpiration").

The usual model concept declares that something we exactly know (the schematic representation) is a model of something we don't know so well (the real system). The above proposed "upside-down" definition suggests an action: how to show, by direct or indirect experimental methods, that a system which we don't know exactly may (or may not) be considered as a realization (a "model") of a schematic representation we have created from incomplete informations. In the first case the battle takes place mainly in the abstract scheme, very often without any new information on the real system. In the second case, we have to go back to the real system and look for new findings using direct or indirect experimental methods. And presently this is what we need the more.

1.2 Indirect estimation of the hydraulic parameters.

If we could measure the value of the hydraulic parameters everywhere in the Earth's crust, we ought not to bother about fractures, faults, lithologies and other geological factors: we could simulate and predict the groundwater flow systems without geology. Unfortunately this not the case. Hydraulic conductivities, for example, are "measured" mostly in isolated boreholes (sometimes located far apart from each other) and the obtained values have to be interpolated between the boreholes or extrapolated as far as the aquifer boundaries. The interpolation techniques may be based on geostatistical methodes, on causal relationships or simply on the experience and intuition of a hydrogeologist, but the fundamental fact remains: *the hydraulic parameter fields have to be determined mainly by indirect methods.*

Additional difficulties arise in fractured rocks where the hydraulic conductivity is both heterogeneous and anisotropic: we simply do not have enough empirical data on the anisotropy. Theoretical relationships allow to estimate the anisotroic hydraulic conductivity tensor by using certain parameter fields of the geological discontinuities, such as the orientation, the spacing, the aperture and the connectivity. Now the

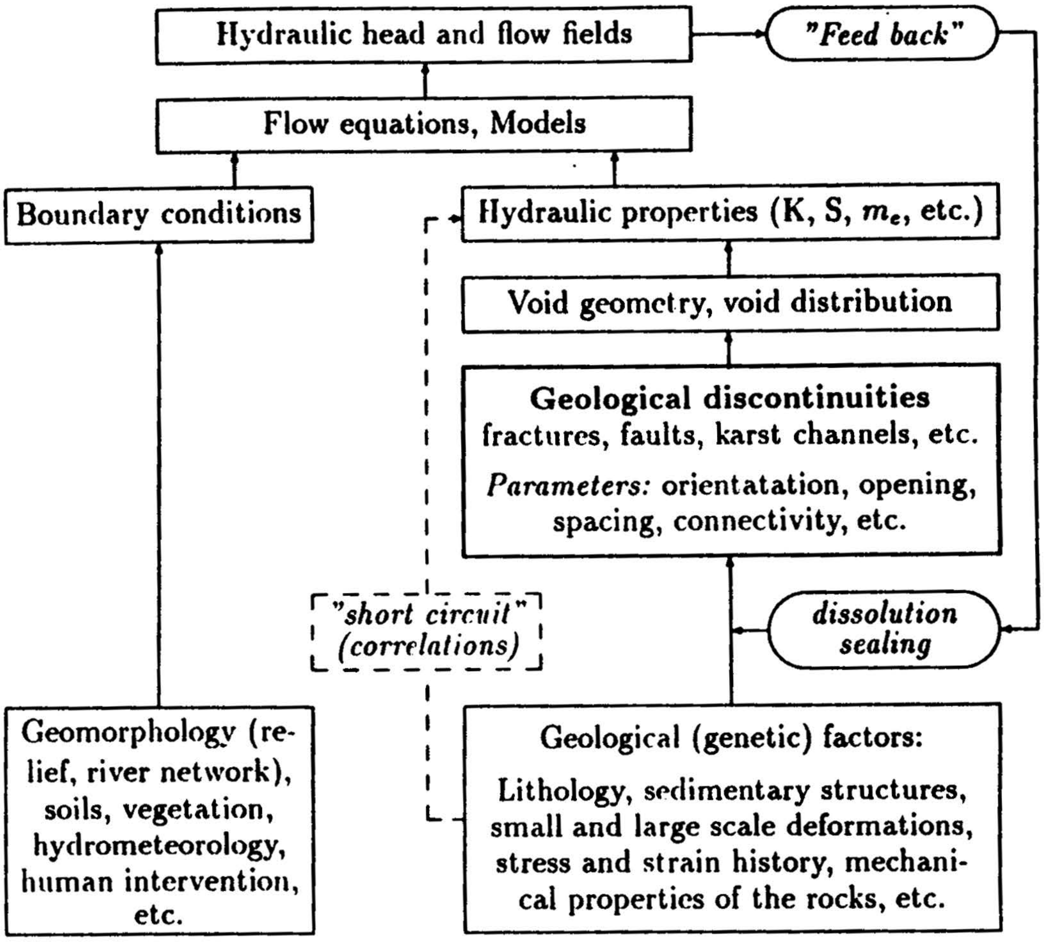


Figure 2: Conceptual relationships between groundwater flow field, geological discontinuities and other geological factors in fractured and karstic aquifers (after Kiraly, 1975).

problem re-appears at another level: how to determine the parameter fields of the geological discontinuities? Direct measurement on isolated outcrops and interpolation or extrapolation of the measured values between the outcrops and in depth will be unavoidable. In other words, the fracture parameters must be indirectly estimated over wide areas and in huge volumes.

As geologists are used to make more or less sound hypotheses on the geological structures, on the spatial distribution of lihtological series, on the strain and stress history of the Earth's crust, we wonder if there is a possibility to use this geological knowledge to indirectly estimate the spatial distribution of the geological discontinuities and their more important parameters. The "chain" of conceptual relationships between geological factors, discontinuities, hydraulic parameters and groundwater flow field is represented in *figure 2*, and perhaps it could be used to indirectly estimate the parameters of the "higher" level from the parameters of the "lower" level.

The diagram of *figure 2* shows that even the groundwater flow field plays an active role in the development of the hydraulic conductivity field: direction of flow and flux density will influence the dissolution or sealing in geological discontinuities, thus modifying their aperture. The "feed-back", which is a long-term action, is particularly important in carbonate aquifers, where exists a pronounced autoregulation between groundwater flow field and hydraulic conductivity field (known as the "karstification"). Up to a point, the "feed-back" plays a very important role in nearly all rock-water interaction, even in non-carbonate aquifers.

Of all the problems represented in the diagram of *figure 2*, only two will be addressed here more in detail: the estimation of the hydraulic conductivity tensor for fractures or intersections of fractures, and the spatial distribution of fracture density.

2 The nested structure of the geological discontinuities.

2.1 Qualitative observations in the field.

Geological discontinuities exist at all scales: intragranular cracks not longer than a few microns, microfractures of a few millmeters or centimeters, fractures (in the usual sens) of metric or decametric length, faults of a few hectometers, kilometers or tens of kilometers, and big fault zones extending over several hundreds of kilometers. In sedimentary rocks the bedding planes (stratification) represent very persistent, closly spaced (from a few centimeters to a few meters) discontinuities of considerable lateral extension (several kilometers). The definition and the detailed description of the enumrated discontinuities may be found in most textbooks of structural geology (see, for example, Davis, 1984). Geologists have developed a rather complicated genetic terminology of their own to designate rock discontinuities, but this terminology will not be used here. Following the International Society of Rock Mechanics *Suggested Methods for Quantitative Description of Discontinuities in Rock Masses* (Brown, 1981), we use only the generic term **discontinuity** and the somewhat more specific term **fracture**, to designate discontinuities of metric or decametric length.

Figures 3, 4, 5, 6 and *7* give an idea how the discontinuities of different magnitudes may appear in real systems. In most cases they are not randomly oriented, but form families, even if the orientation of a family may change from place to place (see *figure 6.* for example). This is quite normal given the fact that the orientation of the discontinuities must somehow be related to the rather complicated, past or present, regional and local stress fields (Chinnery, 1965; Gramberg, 1965). If the lateral extent of the discontinuities is greater than their spacing, it seems reasonable to suppose that families with different orientations will form more or less connected ***networks of discontinuities***, with "meshes" of different magnitudes (Jamier and Simeoni, 1979; Rouleau, 1985). As the networks of different magnitudes coexist in the real systems, the fractured medium should be characterized by its **nested structure of discontinuities** (see *figure 8* which illustrates the concept).

Even if the nested structure concept is a qualitative mental picture only, it allows

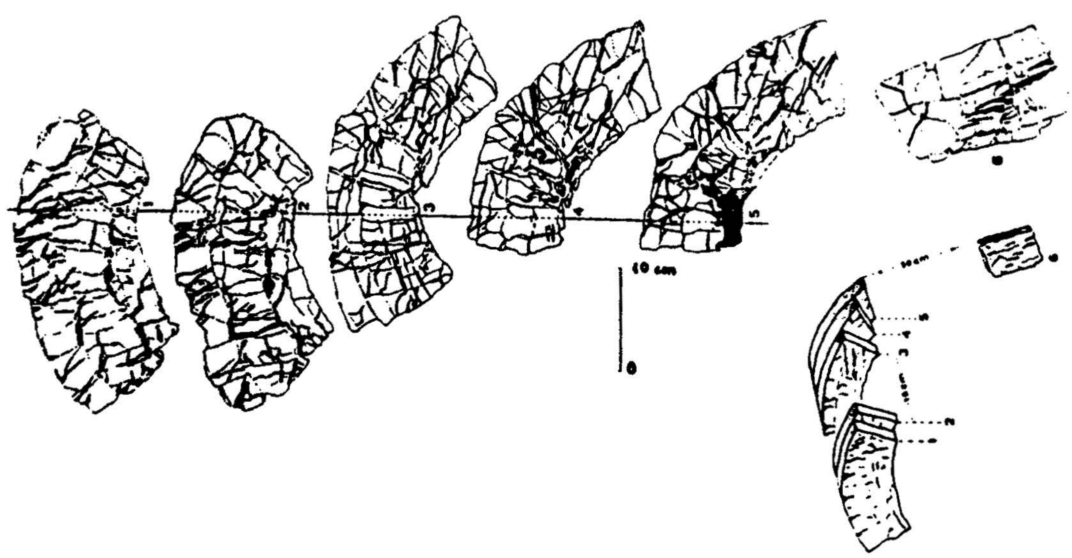


Figure 3: Microfractures in limestone (Droxler and Schaer, 1979.)

Figure 4: Aerial view of discontinuities in limestone (Razack 1978). Diameter of the circle: about 350 m. Observe a higher order fault zone in the right of the photograph.

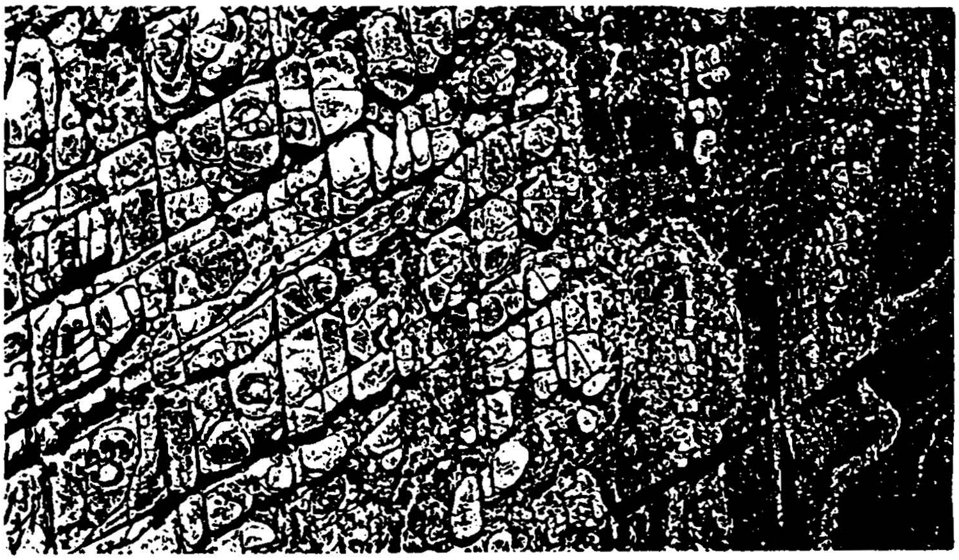


Figure 5: Aerial view of discontinuities in sandstone (photograph by George E. McGill). The length of the photograph is about 700 m.

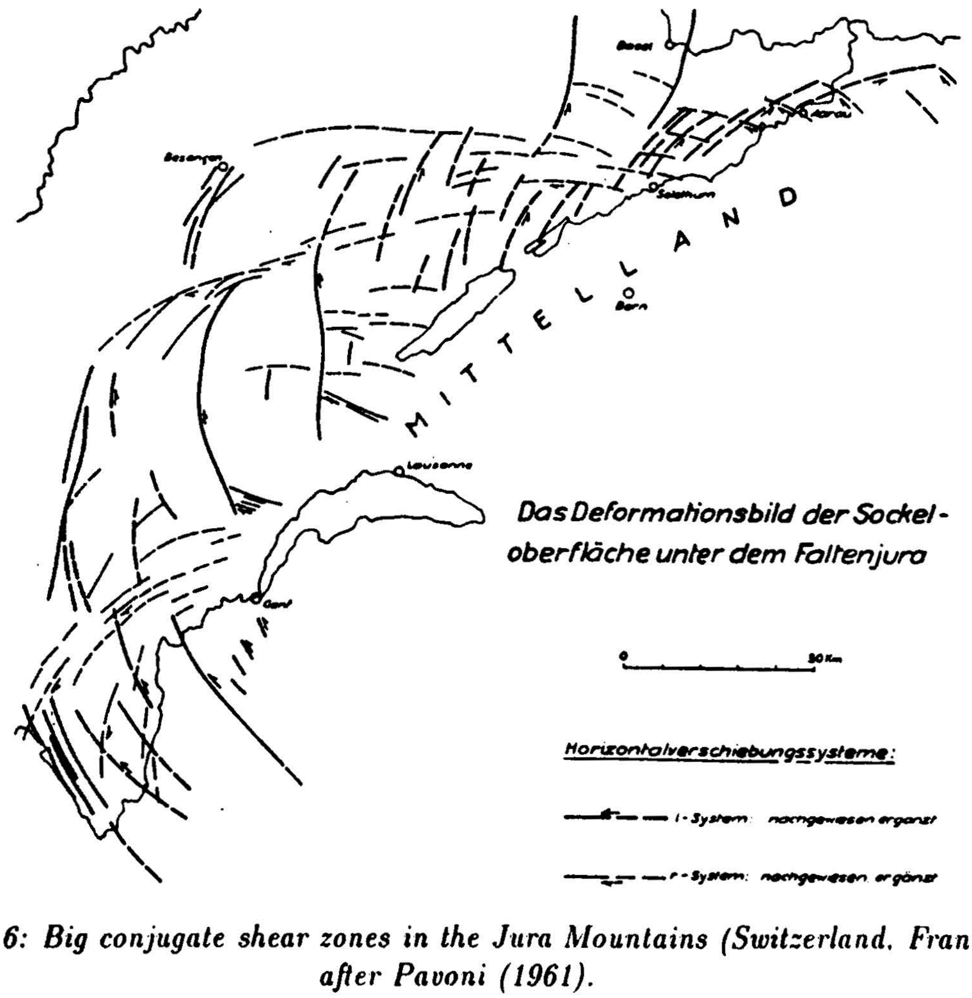


Figure 6: Big conjugate shear zones in the Jura Mountains (Switzerland, France) after Pavoni (1961).

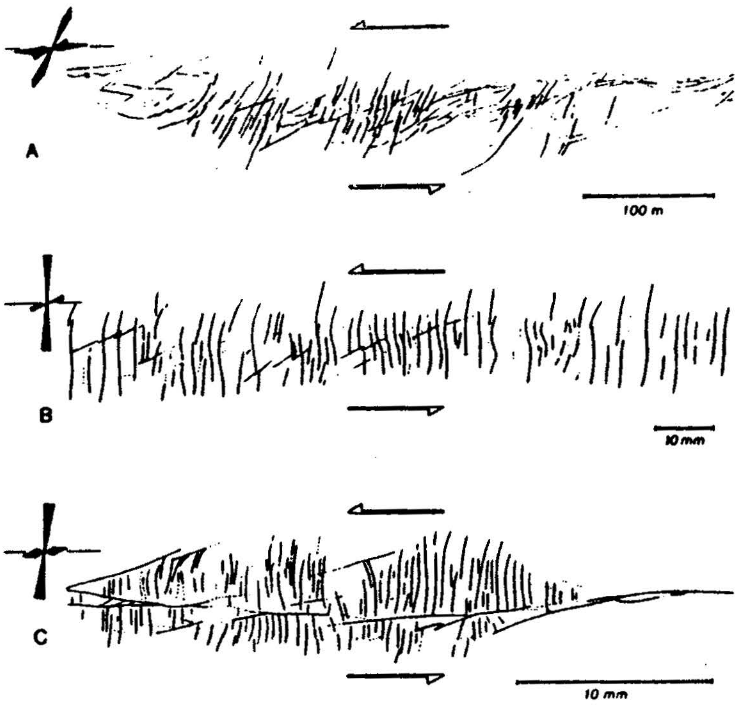


Figure 7: Similarity in the orientation of discontinuities at different scales (Tschalenko, 1970.)

Figure 8: Illustration of the concept of "nested structures": coexistence of "big meshes" and "small meshes" (in: "Feuille d'Avis de Neuchâtel").

to ask some important questions when we are investigating flow and mass transport in fractured media:

- Which magnitudes of the discontinuities are of interest for the investigated phenomena and which may be neglected.
- Which magnitudes could be averaged and which not (is it possible to combine the "discret fracture" approach with the continuum approach).

How could we quantify the nested structure of the discontinuities (if required).

- How do the presently used quantitative methods respect the existence of nested structures in the real systems (in randomly generated fracture networks, for example).
- And finally, the most important question: could the nested structure of the geological discontinuities determine a ***nested structure of the hydraulic conductivity field?***

Many of these questions will remain unanswered here. In spite of this fact, they deserve attention from a heuristic point of view.

2.2 The scale effect in nested structures.

There is an abundant scientific literature on scale effect in fractured media. The interested reader will find the more recent references in Bear et alii (1994) or in Lee and Farmer (1993). In most of these papers the scale effect is investigated by applying the percolation theory or the renormalization theory to a schematic representation of the fractured aquifers. As the above theories don't apply to nested structures, all the schematized discontinuities are of the same order of magnitude, even if there is a certain statistical distribution allowed about the mean frature length, the mean fracture orientation and the mean fracture opening. The obtained scale effect is related to the clustering of the interconnected discontinuities in randomly generated networks.

A different kind of scale effect could appear in the above described nested sctructures. The idea was developed for fractured and karstic limestone aquifers in the early seventies (Tripet, 1972: Kiraly, 1973, 1975), but the principle might well apply for non-carbonate aquifers, too. Anyhow, it could have a heuristic value.

In karstic aquifers, besides the common fracture network with "meshes" of a few meters, there is a high-permeability channel network with wide, kilometric intervals, which is well connected to a discharge area (the karstic spring). Between the channels, the fractured rock mass has a low hydraulic conductivity, about 10^{-6} to 10^{-7} $[m/s]$, values obtained by pumping tests in 300 to 400 m deep boreholes. Regional numerical models showed, that at a basin-wide scale the overall hydraulic conductivity must be 2000 to 5000 times higher than the "local" conductivity values measured in the boreholes (see *figure 9*). This important scale effect is due to the very high hydraulic conductivity of the widely spaced karst channel network. As most of the boreholes are located between the karst channels, the locally measured hydraulic conductivity values don't give any information on the existence of this scale effect. Basin-wide

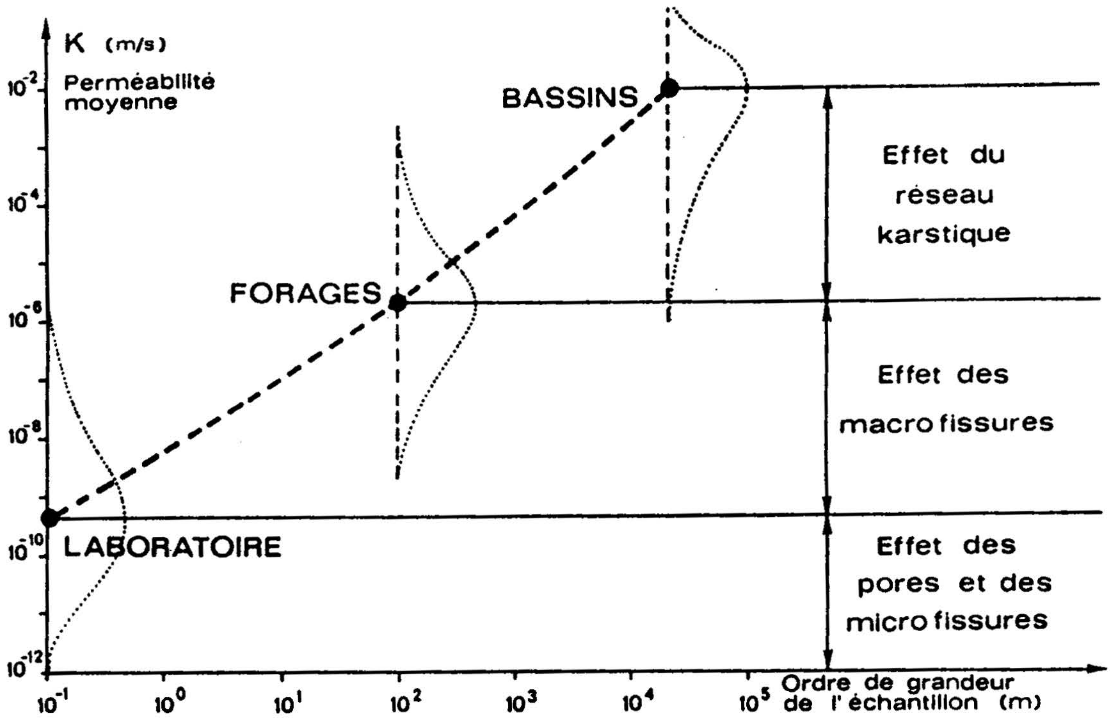


Figure 9: Scale effect on the hydraulic conductivity in fractured and karstic aquifers (after Kiraly, 1975).

water balance studies and the use of regional numerical models are necessary to put forward the phenomenon.

In non-carbonate fractured aquifers there is no karstic network. Neverthless, it could happen that large discontinuities with a wide spacing have a higher hydraulic conductivity than closely spaced smaller ones, and in this case there will be a certain scale effect on the hydraulic conductivity: local values will not be the same as the overall regional values. This kind of scale effect is very different from what we obtain with the percolation or renormalization theory: it is the consequence of the nested structure of the hydraulic conductivity field inferred from the nested structure of the fractured medium.

The idea on the *nested structure of the hydraulic conductivity* suggests to go back to the real systems and check it. Instead of doing statistics on anonymous conductivity values, it would be far more interesting to obtain information about the spacing of the high-permeability zones, about the lateral extent of the high-permeability zones and about the connectivity of the high-perneability zones. Then it would be possible to compare the structure of the hydraulic conductivity field with the structure of the geological discontinuities. Because presently we are not yet able to answer such fundamental questions as how to predict actually water conducting zones from statistical information about geological discontinuities.

Although based on qualitative observations and on inferences, the general ideas developed in these first pages will help to critically evaluate the techniques presented without much comment in the next sections. Every subject should be replaced in the general diagram of *figure 2*, which shows the conceptual relationships between flow fields, hydraulic parameters, geological discontinuities and other geological factors.

3 Hydraulic parameters and geological discontinuities.

3.1 Effect of the anisotropy on the flow field.

The anisotropic hydraulic conductivity is a second rank tensor, which transforms the vector field of the driving forces (for example, the hydraulic gradient field, if the hydraulic potential does exist) into the vector field of the volume fluxes or specific discharges, according to Darcy's law:

$$\vec{q} = -\frac{[k]}{\mu}\,(\vec{grad}\,p - \rho\,\vec{g}) \qquad (1)$$

$$\vec{q} = -\frac{\rho g}{\mu}[k]\,\vec{grad}\,h = -[K]\,\vec{grad}\,h \qquad (2)$$

where $\vec{q}$ = volume flux ($m^3/s\,m^2$); ρ = density of fluid (kg/m^3); g = acceleration due to gravity (m/s^2); μ = dynamic viscosity ($kg/m\,s$); $[k]$ = geometric or intrinsic permeability tensor (m^2); p = pression ($kg/m\,s^2$); h = hydraulic head or potential (m).

Equation (1) is more general and is also valid for variable density flow, where the hydraulic potential is not defined. Equation (2) is valid for constant density flow only (in which case the hydraulic potential is defined) and is more familiar to hydrogeologists who call the volume conductivity $[K]$ (m/s) simply "permeability". In the following pages only the second form of Darcy's law will be used, together with the shorter term "permeability" to designate the volume conductivity $[K]$.

The effect of anisotropic permeability on the flow field is illustrated by *figures 10 and 11*, obtained by a simple finite element model using 303 quadratic elements and 984 nodal points. As it can be seen in *figure 10*, the effect of a regionally homogeneous, anisotropic permeability field is very impressive. In *figures 10b, 10c and 10d* the principal permeabilities have exactly the same value, only their orientation varies. Depending on the orientation of the principal permeabilities, the local and regional flow systems (in the sens of Toth 1961, 1962) may become important or nearly disappear.

Figures 11a and 11b show the effect of a heterogeneous, completely random anisotropic $[K]$ field on the distribution of the hydraulic potentials h and the flux vectors $\vec{q}$. The results should be compared to *figures 11c and 11d*, which illustrate the effect of a heterogeneous, random, but isotropic $[K]$ field. Even if there are considerable differences between the local values, the general aspect of the potential field in the heterogeneous *anisotropic* case is not fundamentally different from the general aspect of the potential field in the heterogeneous *isotropic* case. This results from the fact, that the orientation of the principal permeability K_{max} may vary in a range of 90°.

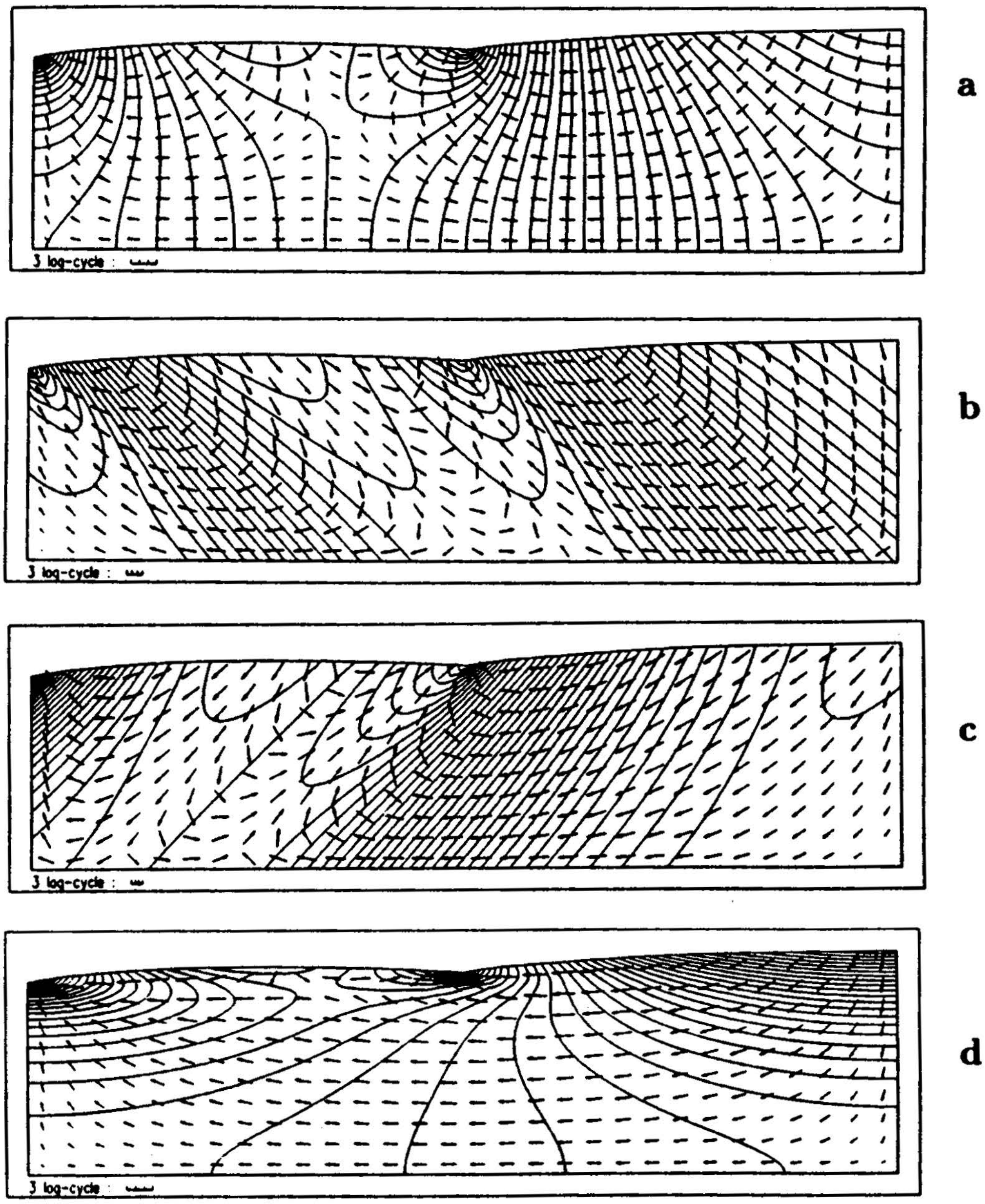
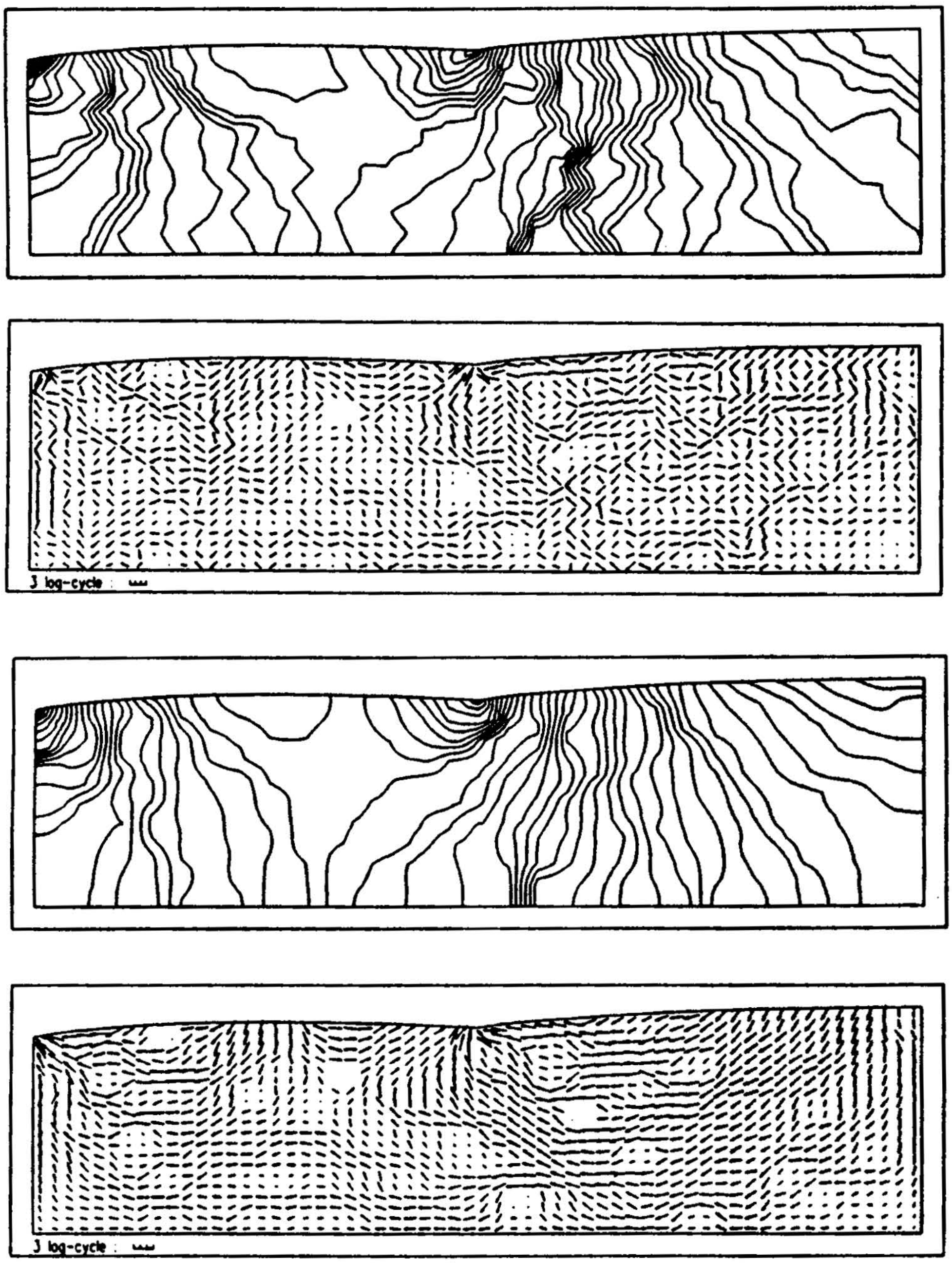


Figure 10: Effect of the anisotropic hydraulic conductivity [K] on the flow field.
a: *homogeneous, isotropic, reference solution.*
b: *homogeneous, anisotropic [K] field (K_{max}/K_{min} = 15; the angle between K_{max} and the x axis is 135°).*
c: *homogeneous, anisotropic [K] field (K_{max}/K_{min} = 15; the angle between K_{max} and the x axis is 45°).*
d: *homogeneous, anisotropic [K] field (K_{max}/K_{min} = 15; the angle between K_{max} and the x axis is 0°). The boundary conditions are the same for all diagrams.*



a

b

c

d

Figure 11: Effect of the anisotropic hydraulic conductivity [K] on the flow field.

a *and* **b**: *equipotentials and flux vectors for a heterogeneous, random anisotropic [K] field (K_{max}/K_{min}: from 1 to 1000; the angle between K_{max} and the x axis may vary from 45° to 135°).*

c *and* **d**: *equipotentials and flux vectors for a heterogeneous, random isotropic [K] field (the isotropic K values represent the trace of the random [K] tensors in the above example). The boundary conditions are the same as in figure 10.*

The above examples indicate, that the estimation of the anisotropic permeability may be very important. But they also indicate, that it would be as much important, or even more so, to estimate the degree of heterogeneity (mainly local or mainly regional) of the hydraulic conductivity field.

3.2 Permeability tensor for fractures and intersections of fractures.

The estimation of the hydraulic conductivity tensor from fracture geometry was proposed by Romm and Pozinenko (1963). Snow (1969) presented a general method for individual fractures and Kiraly (1969) proposed to estimate the permeability tensor for both fractures and intersections of fractures. We have to emphasize that using the hydraulic conductivity tensor transforms the discontinuous real aquifer into an equivalent continuum.

Let us define N families of fractures in the δ-neighbourhood of a point. The mean plane of i-th family is characterized by $\vec{n}_i$ = unit normal of the plane; f_i = avarage number of fractures in the direction of the normal $(1/m)$; d_i = avarage aperture of the i-th family (m)

The volume flux or specific discharge for the i-th family is given by

$$\vec{q}_i = \frac{\rho g}{12\mu} f_i d_i^3 \cdot \vec{J}_i \qquad (m^3/s\,m^2)$$

where $\vec{J}_i$ is the projection of the general gradient $\vec{J}$ onto the i-th mean plane (see the diagram of *figure 12*). As $\vec{J}_i = [I - \vec{n}_i \otimes \vec{n}_i] \cdot \vec{J}$, we may write

$$\vec{q}_i = \frac{\rho g}{12\mu} f_i d_i^3 \cdot [I - \vec{n}_i \otimes \vec{n}_i] \cdot \vec{J} = [K]_i \cdot \vec{J}$$

where $[K]_i$ is the permeability tensor for the i-th family. Summing the $[K]_i$ we obtain the global permeability tensor for the N families of fractures:

$$[K] = \frac{\rho g}{12\mu} \sum_{i=1}^{N} f_i d_i^3 \, [I - \vec{n}_i \otimes \vec{n}_i] \qquad (3)$$

Obviously, the "tensor character" results from the geometric operation of projecting the general gradient vector $\vec{J}$ onto the fracture planes. The geometric or intrinsic permeability $[k]$ is easily identified: it depends only on the fracture parameters f_i, d_i and $\vec{n}_i$.

Let us idealize the intersections of two families of fractures by a bundle of tubes, characterized by $\vec{m}_i$ = unit vector parallel to the i-th bundle; F_i = number of tubes per unit surface perpendicular to $\vec{m}_i$ $(1/m^2)$; D_i = average diameter of the tubes in the i-th bundle (m). Making use of the Hagen-Poiseuille formula and projecting the general gradient $\vec{J}$ onto the tubes, we write the specific discharge for a bundle as

$$\vec{q}_i = \frac{\rho g \pi}{128\mu} F_i D_i^4 \cdot [\vec{m}_i \otimes \vec{m}_i] \cdot \vec{J} = [K]_i \cdot \vec{J}$$

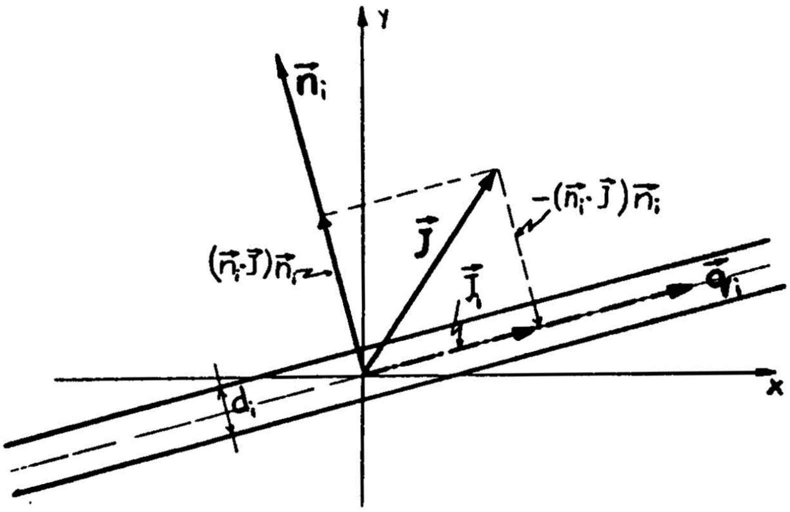


Figure 12: Projection of $\vec{J}$ in the fracture plane (after Kiraly, 1969).

Summing the $[K]_i$ we obtain the global permeability tensor for the M bundles of intersections:

$$[K] = \frac{\rho g \pi}{128 \mu} \sum_{i=1}^{M} F_i D_i^4 \, [\vec{m}_i \otimes \vec{m}_i] \tag{4}$$

Again, the tensor character results from the projecting of $\vec{J}$ onto the tubes. Knowing the fracture parameters for N families of fractures allows to estimate the parameters for the M bundles of intersections:

$$M = \frac{N(N-1)}{2} \qquad \text{(number of bundles)}$$

$$\vec{m}_k = \frac{(\vec{n}_i \times \vec{n}_j)}{|\vec{n}_i \times \vec{n}_j|} \qquad \text{(orientation)}$$

$$F_k = f_i \cdot f_j \cdot |\vec{n}_i \times \vec{n}_j| \qquad \text{(density of intersectons)}$$

where $\times$ is the vector product; $i \leq j$; $i = 1...(N-1)$. Obviously, the most ticklish problem is to estimate D_k when $d_i \neq d_j$.

The above described schematic representation of the geological discontinuities, which allowed to estimate the permeability tensor, is never totally realized in the real systems. Real fractures are not evenly spaced, their aperture is not constant in the fracture plane, they are not strictly parallel to each other even in the same family, their lateral extent ("length") may vary, in a word: the fractured medium is not only anisotropic, but heterogeneous, too. If the δ-neighbourhood for which we estimate the permeability tensor is "big" with respect to the local heterogeneities, the $[K]$ tensor will not correctly describe the behaviour of the real system. This is shown in *figure 13*: the distribution of the directional permeabilities in a randomly generated heterogeneous and anisotropic fractured medium is not the same as in a homogeneous

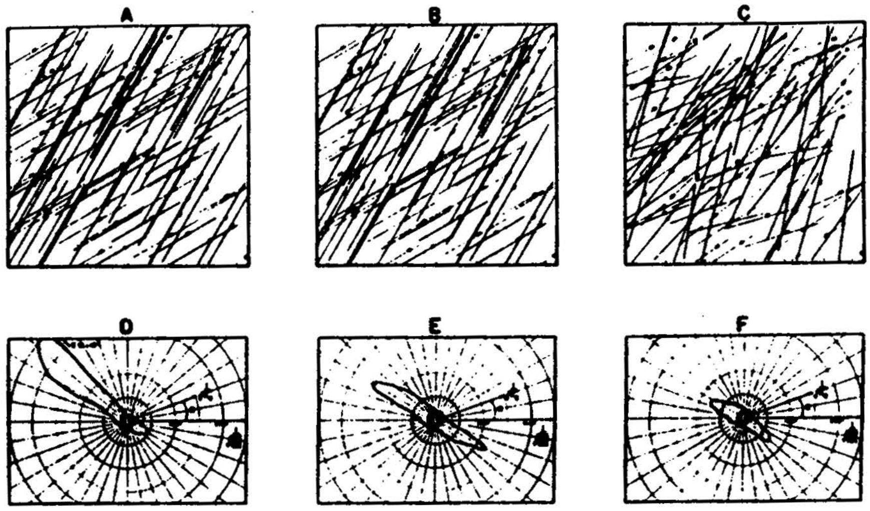


Figure 13: Directional permeabilities in a randomly generated heterogeneous and anisotropic fracture network (after Long et al. 1982).

anisotropic medium. This simply shows that one $[K]$ tensor alone cannot describe the whole region and the δ-neighbourhood has to be diminished. In this case the heterogeneities would appear clearly in the interior of the region and nobody would hope to find an "ideal" distribution of the directional permeabilities. Last, but not least: the continuity of the fractures is required only in the δ-neighbourhood, not over the entire region.

3.3 The "serial type model" of the void geometry in fractured rocks.

In three orthogonal and equally developed fracture families, or intersection bundles, the permeability is isotrope and its magnitude depends on the spacing $x = 1/f$ (or $X = 1/\sqrt{F}$) and the aperture d (or D). In a diagram $\log d$ versus $\log x$ (or $\log D$ versus $\log X$) constant permeabilities or constant porosities appear as straight lines (see the diagrams of *figure 14*). These diagrams allow to rapidly estimate the permeability value for more or less connected networks and discontinuities, with "meshes" of different magnitudes. The dark zones represent spacing and aperture values which seem reasonable in real fractured or karstic aquifers.

In the swiss Jura Mountains we have field measurements on the permeability (about 10^{-6} m/s), on the efficient porosity (about 1% the fracture spacing (about 0.6 m). If we represent these values on the diagrams of *figure 14* (see points K and n), we cannot find a unique fracture aperture or channel diameter which could "explain" both the permeability value and the efficient porosity value. In other words, the void geometry which determines the permeability is not the same as the void geometry which determines the efficient porosity. The efficient porosity value requires large openings in the fracture planes (up to 1 mm aperture) but the permeability value shows that

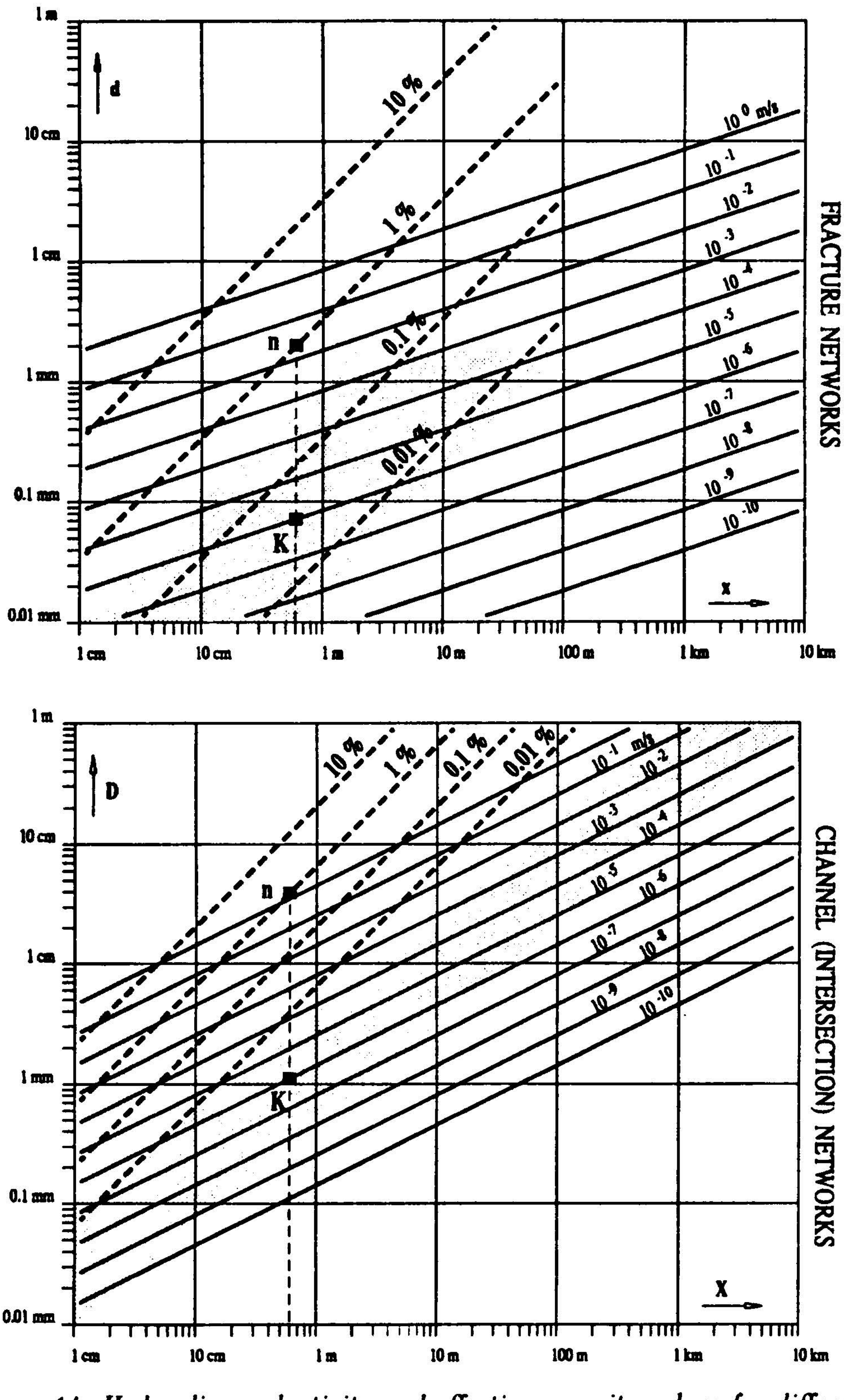


Figure 14: Hydraulic conductivity and effective porosity values for different networks of discontinuities.

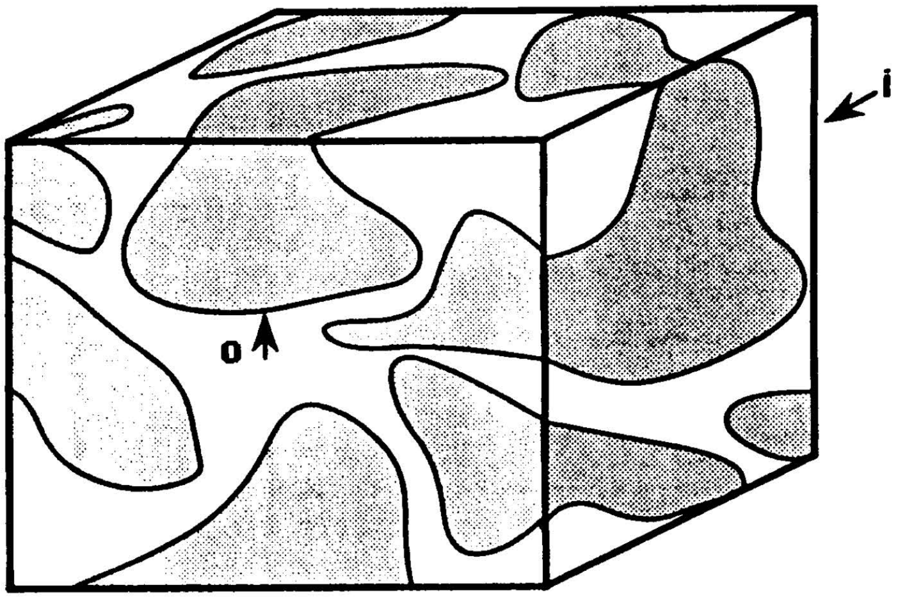


Figure 15: "Serial type model" of the void geometry in fractured rocks: large voids in the fracture planes (o), well connected to the intersections (i) or channels.

these large voids are not well interconnected.

Combining the "fracture model" with the "intersection model" may represent a solution to the problem: the permeability is determined by the intersections of fractures (required diameter: about 1 *mm*) and the efficient porosity is determined by the larger voids in the plane of the fractures (required aperture: about 1 *mm*). The large openings are well connected to the intersections where the groundwater flows, but are poorly connected to each other. The above described void geometry is schematically represented in ***figure 15***, which is not more than the "serial type model" of Scheidegger (1963) adapted to the three-dimensional fractured medium. Interestingly enough, the "serial type model" of the void geometry could explain all particularities of the empirical break-through curves observed in fractured rocks, without adsorption and desorption phenomena, and without molecular diffusion into the "immobile water".

The above presented example shows that even theoretical and very schematic representations may be useful, provided they are confronted with the observations made in the real system.

References

[1] Bear J., Tsang C.F., de Marsily G., Flow and contaminant transport in fractured rock. *Academic Press, 1993*

[2] Beucher H., Blanchin R., Feuga B., Application des méthodes géostatistiques à la prévision de la fracturation d'un massif granitique. *In: Journé sur le granite, Orléans-la-Source, 1984*

[3] Billaux D., Feuga B., Etude comparée des méthodes de modélisation de la fracturation des roches. *Documents BRGM N° 149, 1989*

[4] Bles J.L., Feuga B., La fracturation des roches. *BRGM, Manuels et méthodes N° 1, 1981*

[5] Bles J.L., Distribution de la fracturation en surface et en profondeur dans les granites. *In: Journé sur le granite, Orléans-la-Source, 1984*

[6] Chinnery M.A., Secondary faulting 1. Theoretical aspects. *Canadian Journ. Earth Sci., 3, pp 163-174, 1965.*

[7] Davis G.H., Structural geology of rocks and regions. *John Wiley, 492 p., 1984.*

[8] Droxler A., Schaer J.P., Déformation cataclastique plastique lors du plissement, sous faible couverture, des strates calcaires. *Eclogae Geol. Helv., 72/2, pp 551-570, 1979*

[9] Gramberg J., The axial cleavage fracture 1. Axial cleavage fracturing, a significant process in mining and geology. *Engineering Geology, 1/1, pp 31-72, 1965*

[10] Jamier D., Etude de la fissuration, de l'hydrogéologie et de la géochimie des eaux profondes des massifs de l'Arpille et du Mont Blanc. *Thèse, Université de Neuchâtel, 1975*

[11] Kiraly L., Statistical analysis of fractures. *Geol. Rundschau, 59/1, pp 125-151, 1969*

[12] Kiraly L., Anisotropie et hétérogénéité de la perméabilité dans les calcaires fissurés. *Eclogae Geol. Helv., 62/2, pp 613-619, 1969*

[13] Kiraly L., Rapport sur l'état actuel des connaissances dans le domaine des caractères physiques des roches karstiques. *in: Hydrogeology of karstic terrains, A. Burger and L. Dubertret (eds), pp 53-67, Paris, 1975*

[14] Kiraly L., Les unités hydrogéologiques. *Bull. Centre d'Hydrogéologie de Neuchâtel, pp 83-216, 1978*

[15] Kiraly L., Large scale 3-D groundwater flow modelling in highly heterogeneous geologic medium. *in: Groundwater flow and quality modelling, E. Custodio et al. (eds), pp 761-775, NATO ASI series Vol.224, 1988*

[16] Lee C.H., Farmer I., Fluid flow in discontinuous rocks. *Chapman and Hall, 169 p., 1993*

[17] Long J.C.S., Remer J.S., Wilson C.R., Witherspoon P.A., Porous media equivalents for networks of discontinuous fractures. *Water Resources Research, vol.18, No.3, pp 645-658*

[18] Muller L., Der Felsbau. *Stuttgart, 624 p, 1963*

[19] Nelson, R.A., Geologic analysis of naturally fractured reservoirs. *Gulf Publishing Company, Houston, 320 p., 1985.*

[20] Pavoni N., Faltung durch Horizontalverschiebung. *Eclogae Geol. Helv., 54, pp 515-534, 1961*

[21] Rouleau A., Gale J.E., Baleshta J., Fracture mapping in the ventilation drift at Stripa: Procedures and results. *1981, Report SAC-42*

[22] Rouleau, A., Statistical characterization and numerical simulation of a fracture system - Application to groundwater flow in the Stripa granite. *Ph.D. thesis, University of Waterloo, 416 p., 1984.*

[23] Scheidegger A.E., On the statistics of the orientation of bedding planes, grain axes, and similar sedimentological data. em U.S. Geol. Surv. Prof. Paper 525-C, pp 164-167, 1965

[24] Scheidegger A.E., The physics of flow through porous media. *University of Toronto Press, 313 p., 1963*

[25] Snow D.T., Anisotropic permeability of fractured media. *1969, Water Resources Research, 5/6, pp 1273-1289*

[26] Stearns D.W., Friedman M., Reservoirs in fractured rock. *AAPG Mem. 16, pp 82-106, 1972*

[27] Suppe, J., Principles of structural geology. *Prentice-Hall, 537 p., 1985.*

[28] Tchalenko J.S., Similarities between shear zones of different magnitudes. *Geol. Soc. Amer. Bull., 81, pp 1625-1640, 1970*

[29] Tchalenko J.S., Ambraseys N.N., Structural analysis of the Dasht-e Bayaz (Iran) earthquake fractures. *Geol. Soc. Amer. Bull., 81, pp 41-60, 1970*