Chapter 2
Water Flow in Rock: Geometry of Water Conducting Paths and Lugeon-Values

Each rock mass has its own pattern of water bearing paths. In Germany, in the 1970s the term "Wasserwegsamkeit" was in common use to describe this individual setting. An equivalent term is unknown in English and the direct translation is not concise—the term '*conductivity*', for instance, does not precisely meet the meaning. At first the term '*hydraulic routeing*' was suggested for this subject; but probably '*water routeing*' seems to be more adequate for the arrangement of the water-percolating paths: which paths exist, what is their geometry (size, shape and length) and how are they arranged along the discontinuities. Both the joint pattern and the degree of weathering determine this routeing. Figure 2.1 illustrates extreme cases, actual rock masses range in between:

- Vertical fissures crossing sandstone bands are completely open, they form a network of communicating water conducting openings; piezometer hydrographs run parallel.
- The discontinuities are still latent, some contain open veins of very thin apertures, they are connected only locally; hydrographs show largely independent courses.

The size and the shape of the paths are relevant for defining both the permeability of a rock mass and the penetrability of the grout slurry.

Textbooks deal with hydrogeological features mainly in terms of the 'productivity' of aquifers while the details of the water paths are not considered. Details need to be studied in assessing the permeability of a dam site. Very small geological features can create an anisotropic permeability across the foundation, and the often disregarded groundwater regime. The interaction between groundwater and reservoir is also quite significant for the under-seepage. Eventually, the groutability of a given rock type is very much influenced by the size and the shape of the individual paths. WPT's usually do not explore these details. Thus, the hydrogeological details of the foundation need due consideration.

Wolters et al. in 1972 published the results of specific investigations concerning the percolation behaviour of a Cretaceous marlstone in Westphalia (Germany):

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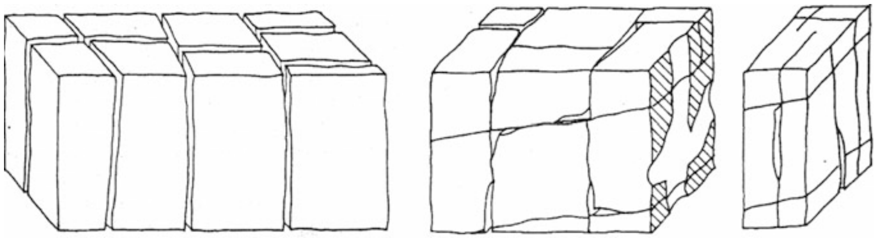

Fig. 2.1 Schematic illustration of typical arrangements of water paths: interconnected open fissures versus partly opened joints

In that rock the water flows along channels of mostly small diameters and extensions. The paths are arranged along discontinuities. They are often not connected with each other.

Ewert extended this research to several other rock types where a similar routeing was found. Weaver also gives examples of such channels encountered in Venezuela. Meanwhile many observations made in various rock types and regions all over the world support the idea that water preferably flows through veins developed along discontinuities, except those rock types where tension tectonics caused a splitting of whole joints which directly produces open fissures. The size and the shape of the veins depend on the development reached at the time; very small nearly circular paths of <1 mm in diameter may prevail or may exist side by side with wide ones, >10 cm in diameter. As the paths are getting wider, the previously circular or elliptical shape turns into flat fissures following the discontinuities and covering an increasing portion of the joint. This type of water routeing is principally the normal one.

Rock mechanical engineers often base their models used for computation on the assumption that joints are open throughout—at least the joints of one set. However, such cases are seldom, the opposite prevails: most joints are not completely open but are furnished with local water paths. They exist in form of veins of many very different sizes; they are irregularly distributed along the joints whose major parts are still closed.

Depending on the type and degree of both jointing and weathering we observe different arrangements of the water conducting voids. '*Voids*' mean any form of water conducting path. We have to distinguish between latent discontinuities, isolated paths, locally open joints and fissures (Fig. 2.2):

A Latent discontinuities are still closed, (bedding planes, for instance)

B Isolated paths (veins) are arranged along discontinuities. Very small veins have a quasi-circular shape, getting larger and following the joint they evolve first into quasi-elliptical and then longish paths.

C Joints opened 'throughout' have a rather limited extension and their widths are usually very small (order of magnitude: ≤ 1 mm).

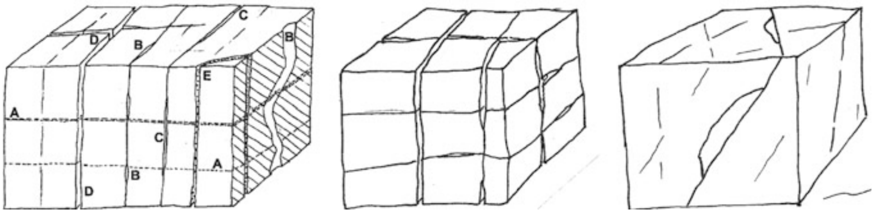

Fig. 2.2 Arrangement and course of most water conducting paths in rock (schematic illustration), *left* Regular rock, *middle* Fissure karst, *right* Cave karst

D Open joints of a considerable width are classified as fissures (order of magnitude: >1 mm).
E Fissures can be filled with a sandy or loamy material.
F Cavities in karstic limestone differ very much in shape and size: planar fissures to huge caves from a few centimeters to many kilometers—fissure karst and cave karst, respectively.

In order to accomplish an optimal result of a grouting program we should know the type of the water routeing. Of course, a rock mass contains mostly a variety of different forms and sizes of water routes. Nevertheless, depending on the geological environment the same types of water paths prevail, e.g. planar of tubular ones. This should be taken into account since their penetrability for the grout suspension can differ very much, although they may even produce similar LU-values. In deciding on the appropriate impermeabilization criteria the penetrability of the paths, their size and shape are really important.

Since the water take of 1 LU played such a key role in deciding on the execution of a grouting program it was interesting to find out the size of the respective path. Lab tests using geologically defined models showed that a circular path of ≤ 1 mm in diameter and 300 mm in length absorbs at a pressure of 10 bar 1 l/min, i.e. 1 LU. An elongated joint of an area of 0.2 mm $\times$ 20.8 mm and 700 mm in length yields a similar water take. Water takes ≤ 1 LU signify even smaller entrances or longer extension of the paths. From these tests it can be inferred that small LUGEON-values originate always from isolated little paths (Type B) or from narrow joints of limited extension (Type C). Large veins, joints or even fissures produce much larger LUGEON-values. A water take of 1 LU reflects a rock which is practically impervious.

Besides the effect of the rock permeability regarding water losses their head losses have to be considered as well. If the hydrogeological setting could be assessed beforehand, an economical approach could be made concerning all aspects relating to groundwater. This has not been achieved so far and the situation concerning the effect of groundwater at construction sites is determined more by chance than by clear results of a hydrogeological investigation. Although it remains impossible to predict a given situation with accuracy, a substantial improvement could possibly be achieved if more systematic research was done. Unfortunately, investigation programs for individual projects covering all these details are expensive, and hence are not carried out. It may possibly help to improve our situation in the long run if hydrogeologists, wherever doing research work, would also observe the characteristics of this water routeing. The findings should be related to the various types of the rock masses including all the individual factors which influenced the development of water routeing and permeability. Presumably, a classification could be established after some time. On that basis, it should be possible to assess the type of the routeing and the permeability for new projects beforehand.

In order to relate WPT-values to the relevant hydrogeological features and to understand better the individual groutability, this water routeing has been examined in open pits and tunnels. The available space does not allow to present details which are described elsewhere. The results were valuable for practical purposes. This justifies the suggestion that this research should be done in as many rock masses as possible. Thus, colleagues involved in this matter are encouraged to make their contributions.

The frequency and distribution of water flowing out of rock walls varies considerably. In tunnels or other pits there are sometimes completely dry sections, several hundred meters in length, while in other water seepages are quite frequent at a spacing of a few centimeters. Studying the frequency and distribution of water seepages at rock surfaces confirms that the pattern of seepage corresponds to the type of water routeing described before. Water flows mostly along smaller or wider openings developed along discontinuities. The arrangement, course and size of the water carrying openings justify the old idea of 'water veins'. Only in a minority of cases and in tunnel sections near to the surface is the water flow along fissures open throughout.

This is no novelty and was known already to miners in ancient times. Thus, one could conclude that research on this subject is not required anymore. Nevertheless, the analysis is quite helpful:

- For hydraulic calculations, we need the coefficient of permeability k_f. The permeability is investigated by means of WPT's. The direct conversion of $Q_{WP'T}$ into k_f is impossible; Q_{WPT} does not disclose whether the water is absorbed by many thin or a few wide paths, producing different k_f values as discussed below. Examining the setting of the paths allows us to recognize the prevailing type of the paths in view of their width and shape which is helpful to appraise k_f.
- Impermeabilization measures at dam sites are usually based on the results of WPT's. However, the tests only disclose the permeability of the rock around the borehole. WPT-results reflect the permeability of the foundation more or less appropriately if the rock tends to be homogeneous (Fig. 2.3a). If to the contrary, the rock mass encompasses impervious intercalations, WPT-results do not reflect the actual permeability (Fig. 2.3b); in such cases an impermeabilization scheme is not required.
- It is usually assumed that a rock mass below the groundwater level is filled throughout with communicating groundwater. This is not always true. There

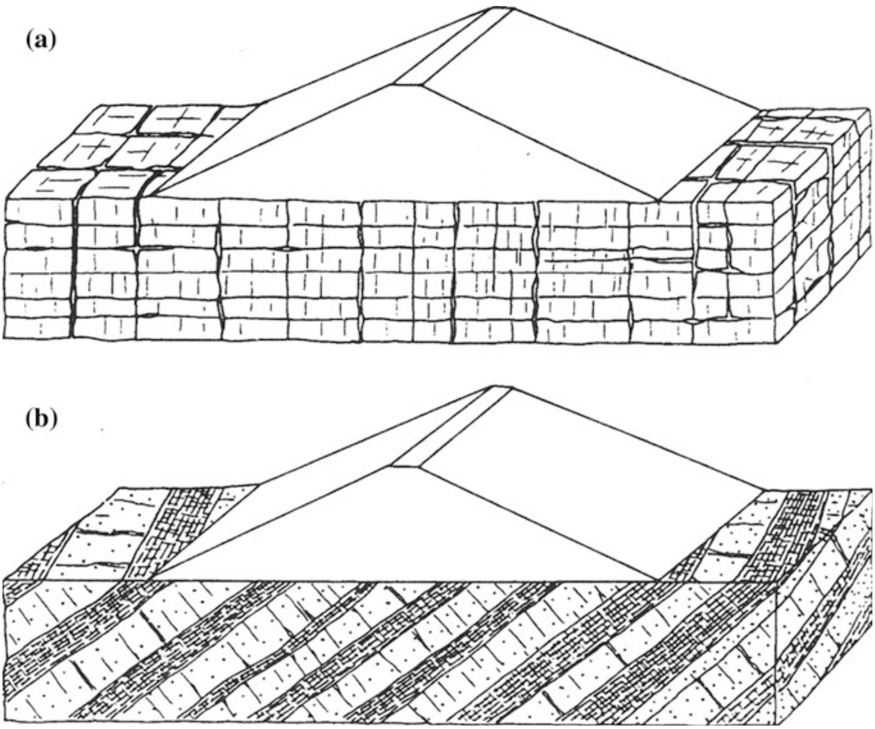

Fig. 2.3 Dam foundation of approximately isotropic (*above*) and anisotropic permeability (*below*); the latter is not reflected by WPT-results

often exist large areas of completely dry rock and such areas can extend over many hundreds of meters, particularly in deeper zones. Piezometer hydrographs sometimes indicate not only different groundwater levels but also independent fluctuations which discloses separate groundwater systems side by side. Thus, it is not always appropriate for static calculations to consider the full hydraulic head. A different approach would be expedient.

- Driving tunnels through permeable rocks can cause a regional lowering of the groundwater table with serious consequences for buildings or for agriculture and forests above the tunnels. It is highly desirable to predict such an impact and to find out whether this is a permanent or temporary one and what should be the appropriate counter measures.
- Papers and discussions often reveal that hydrogeological facts verified by practical observations are not appreciated by everybody involved. Several scientists base their conceptions on models not completely in harmony with the real hydrogeological situation. If the facts were taken into account, a more realistic—and more valuable—result could be achieved. This is discussed in detail later.

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