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DETERMINATION OF REGIONAL ROCK-MASS PERMEABILITIES

CLASSIFICATION DES PERMEABILITES DE MASSIFS ROCHEUX

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Summary

Permeabilities of Paleozoic and Mesozoic rocks in the western mountain areas of Germany have been tested and observed on a large scale basis for applied engineering purposes during the last 10 years.
Data of fracture-measurements, water pressure tests, pumping tests, dye tests, run-off measurements (springs, rivers, tunnels) and seepage losses of dams have been evaluated and compiled in a synoptic nomogram, classified in decimal steps of permeability-coefficients and attributed to the different rock types.

Résumé

Pendant les dix dernières années, un grand nombre de perméabilités ont été mesurées dans les roches paléozoïques et mésozoïques des régions montagneuses de l'ouest de l'Allemagne.
Les données provenant de mesures de fracturation, d'essais d'injection, ou de pompage, de traçages, de mesures des pertes d'eau dans les barrages etc..., sont présentées dans un abaque, reliant une échelle décimale des coefficients de perméabilité aux différents types de roches.

1. Introduction

Data on rock-mass permeabilities of areas or zones of various size are required for water– and waste– management purposes as well as for planning and operation of open-pit mines, quarries, underground mining, tunnelling, dam construction and all kinds of foundation excavations.

For the determination of mean permeability values of soils, with their typical porosity, well established laboratory– and *in situ* testing methods are available. A good example for the classification of soil permeabilities is represented by the nomogram (fig. 1) which has been introduced by Breddin (1956).

It is based upon grain size distribution, i.e. finally upon the effective porosities of the different soils. The permeability classes are graduated by different colours from blue (high permeability) over violet-blue, violet-red and pink to orange (low permeability).

An appropriate semi-quantitative classification for rock-mass permeabilities is very difficult to establish due to the obvious inhomogenuities in rocks. Here the water follows discontinuity planes and distinction has to be made between pore– and open– crack– permeabilities.

In connection with water management projects, research studies and site investigations a great number of different permeability tests in a large variety of rock types has been performed in the Western Rhenish Mountains in Germany during the last 10 years. The results are discussed with respect to their reliability and comparability.

2. Regional Geology

The Western Rhenish Mountains in Germany are built-up of Palaeozoic clastic and subordinately carbonitic rocks which are regionally covered by young-Palaeozoic and Mesozoic formations (Permian to Cretaceous). In some areas also Tertiary and Quaternary volcanic intercalations occur. The Cambrian phyllites and quartzites were subjected to the Caledonian orogenesis. Their thickness is greater than 1.000 m. The schists and quartzitic sandstones of the Ordovician amount to about 800 m. The greatest part of the region is occupied by clastic series of the Lower Devonian with up to 5000 m thickness. The occurence of Middle– and Upper-Devonian clastic-carbonitic rocks is bound to a N-S oriented flexure zone and to the vicinity of Aachen. Carboniferous limestones and coal beds are restricted to the northern rim of the Rhenish Mountains. The total Palaeozoic sequence was folded in the Variscan orogenesis and is characterized by a distinct NW-vergence. In the region of the Triassic triangle of Mechernich and around Aachen more or less flat lying carbonitic-clastic beds of the Mesozoic are represented which mostly appear as solid rocks, but partly also as unconsolidated soft rocks. In the Central and Southern Eifel mountains and in the Bergisches Land volcanic plugs as well as basaltic and tuffitic beds of Neozoic age are intercalated.

3. Geological, hydrogeological and geotechnical parameters

The variety of petrographically and diagenetically different rock types in the respective area and the great number of tests performed allow a comparative evaluation of the permeability properties of rock-masses. A prior condition for any realistic evaluation is a diligent observation of the primary and secondary rock parameters which depend on the sedimentary and tectonic history during diagenesis and orogenesis as well as on atectonic features, weathering, glacial influences, morphological exposition etc... The evaluation covers jointing, weathering and near surface–

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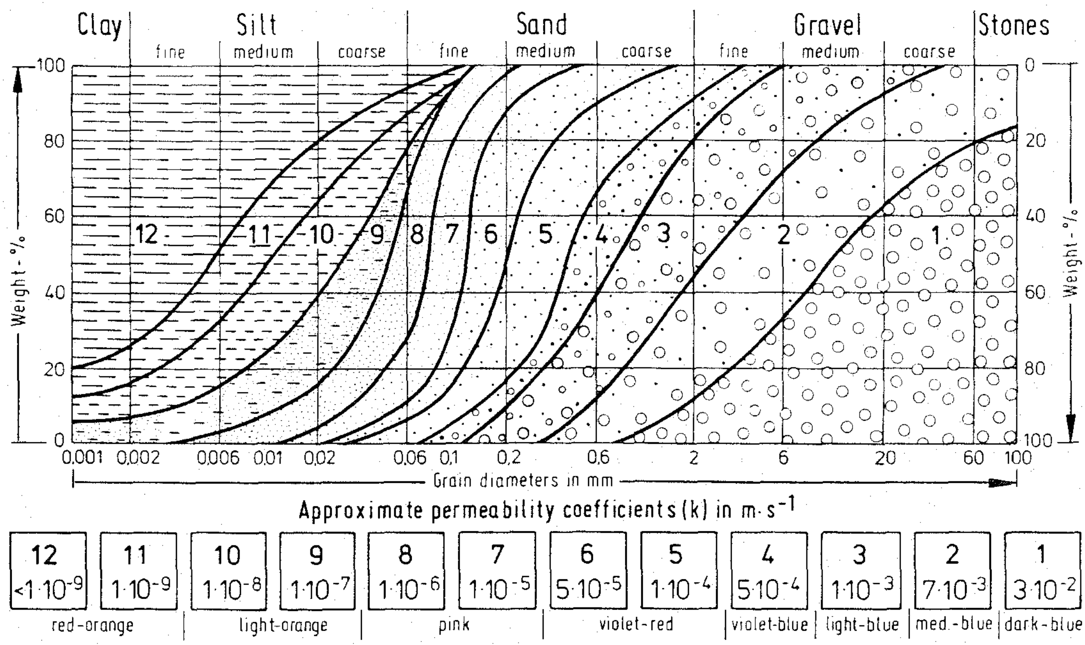

Fig. 1: Grain size distribution and permeability classes of soils.

loosening, standard permeability tests, water ingress in tunnels, water level fluctuations in observation holes, mean well capacities, tracer tests and dry-weather run-off.

3.1. Jointing, weathering, near surface– loosening

Rock-mass permeability is generally governed by water seepage through discontinuity planes, because the original pores have been closed by diagenesis. The same applies, more or less, for minor consolidated Mesozoic rocks with preserved porosities of up to 20 per cent (mostly < 10 per cent). Considerably higher values, mentioned in some publications, resemble soil properties.

The open-crack volume of rocks has been determined by different methods. Measurements in quarries have normally produced excessive values, since number and width of fissures are increased by blasting–, ice– and gravity-actions. A very reliable method is provided by modern television and optical sounding of boreholes which allows direct inspection and detailed evaluation by means of magnetic tape recording.

Relatively good results are obtained by grouting operations, especially when the grouted zone is exposed later on. In petrographically and tectonically well established aquifers the effective open-crack volume can be derived also from run-off measurements (Udluft 1972).

A general observation is that the number of discontinuity planes, their extension and width depend on the hardness of the rocks and their diagenetic-tectonic development as well as on stress-relief and weathering phenomena, the effectiveness of which decreases with depth. Observations and measurements in borings and wells and during dam and underground constructions have established that, generally, a near-surface loosening zone is typical of mountainous areas. In this zone water circulation is greatly increased by additional and enlarged fissures as compared with the conditions at greater depths. The extent of this zone varies greatly and depends on the age and development of the surface, the erosional conditions, the exposition (valley floor, slope, plateau), and last but not least on lithology, stratification, degree of jointing and weathering.

Water circulation in rock-masses is largely restricted to this near-surface loosening zone which may be approximately compared in its hydrodynamic behaviour with water percolation in porous aquifers. In any case preferred flow directions are defined by the dominant joint system.

In highly consolidated clastic rocks, in magmatites and metamorphites loosening depths between 5 and 80 m have been observed, with normal values between 30 and 50 m.

Different, of course, are the flow-condition in karstic aquifers, where great solution cavities follow one or two joint directions and/or the bedding planes. The near-surface loosening zone is here overlapped and highly permeable rock zones can extend to several 100 m below plateaus and more than 100 m below present valley floors.

In Mesozoic sandstone areas loosening depths of about 100 m have been observed.

Investigations in tunnels and in deep mines have proved that water circulation below the loosening zone is restricted to singular faults and jointing zones. Outside of these zones the rock-mass is wet only or appears rather dry.

3.2. Results of permeability tests

The various tests to establish rock-mass permeability (pumping tests, infiltration tests with falling or constant head, recharge tests, etc.) are primarily intended for the investigation of soils. They can, however, also be applied in the loosened and karstic-zones of solid rocks, and may provide good results.

A test, specially developed to investigate solid rocks (also above groundwater level) is the water-pressure test after Lugeon. The scientific background of this standard test has been revised during the last years by the German Geological Survey (H.J. Schneider 1979) and at the Technical University, Aachen. The revision has made obvious that the evaluation of the test results is much more complicated than hitherto assumed. A transformation of Lugeon-values into permeability coefficients is possible only for long-term tests, performed below the groundwater level. Testing techniques with constant water quantities in the different test stages have proved to be preferable to the application of constant pressures. Pressure/time-diagrams are better suited for the interpretation of crack-phenomena than the usual quantity/pressure-diagrams. The values obtained by the conventional testing method can, consequently, no longer be used for the determination of permeability coefficients, but only for their original purpose, the assessment of necessary grouting depths.

3.3. Water ingress in tunnels

Observation and measurements of water ingress in tunnels and other underground structures offer another important criterion for the assessment of rock-mass permeabilities. The 'yield figure' (Ergiebigkeitsziffer), introduced by Stini (1950), is defined as the amount of water ingress (l/s) for a tunnel length of 100 m. This figure, although originally intended to distinguish permeabilities of different rock types, is mostly calculated as a mean value for the entire tunnel with all its different formations. The initial water ingress is normally 3- to 5-times greater than the constant ingress and, generally, a distinct dependency on rainfall can be observed.

In carbonitic formation the possibility of mud-water ingresses has always to be expected with frequently observed quantities of 10 to 20 l/s. In most cases, however, flows diminish within hours or days. In limestone masses the ingresses can be far greater. Values of 100 to 200 l/s have been published.

3.4. Groundwater fluctuations in observation holes

Groundwater fluctuations in observation holes after rainfall depend on the open-crack volume of the surrounding rock-mass. Rock types with high open-crack volumes, for example karstic volumes, react far less to rainfall than those with small volumes. The fluctuations in soils, with their great porosity, amount to a few metres maximum, while values of up to 20 m have been observed in poorly permeable rock-masses.

3.5. Mean well capacities

The yield of water wells depends directly on the effective open-crack volume of the neighbouring rock-mass and connections with the prevailing system of discontinuities. The evaluation of a great number of well tests in the Rhenish Mountains indicates a significant correlation between well capacities and different rock types, that is their effective open-crack volumes. In individual cases the lithologically dominated phenomena can be superposed by local tectonic features, such as faults and flexures.

The 'mean well capacity' (Brunnenergiebigkeit) is defined as the yield of a well (l/s) divided by the total drawdown.

This division reduces random influences of pump capacities and different drawdown to a large extent (Hilden & V. Kamp 1974). The figures vary between 0,0003 l/s.m for relatively watertight claystones to 4, 16 l/s.m for karstic dolomites.

3.6. Apparent flow velocities

Apparent flow velocities in rock-masses are determined by various tracer tests. The results allow a further assessment of the rock-mass permeability. Tracer tests are preferably performed in highly permeable rock types, such as karstic limestones, and for the detection of hydraulic connections via fault- and shear- zones. A diagram with measured apparent flow velocities in different rock types (fig. 2) has been suggested by Heitfeld (1966).

A quantitative relation between apparent flow velocity (V_a) and permeability coefficient (K) is based upon the effective open-crack volume (c_v) and the hydraulic head (i) under laminar flow conditions:

$$V_a = K \cdot i \cdot c_v^{-1}$$

3.7. Dry weather run-off

The evaluation of run-off measurements in dry seasons in a great number of small catchment areas has revealed that the data are in practice not influenced by morphology and plant cover. Also the annual rainfall can be neglected in wide ranges, because the relatively small open-crack volume of most rock types can be filled by small rainfall quantities. The dry weather run-off is thus rather completely determined by the effective open-crack volume, i.e. indirectly by the primary and secondary properties of the different rocks. Relations between different rock types and dry weather run-off have been established in various investigation programms.

4. Synoptic nomogram and conclusions

All the data which have been observed, collected and evaluated up to now during different geological, hydrogeological and engineering geological studies provide indications for rock-mass permeabilities. Always it became obvious that the reliability of the results depends greatly upon the kind, number and combination of tests and observations and, last but not least, upon diligent consideration of all geological features, especially the sedimentary and tectonic history of the area. It must always be kept in mind that the tests provide point of linear results only, and that the results obtained are far less representative in rock-masses than in soils. In spite of all advancements in testing-, registration- and evaluation- techniques of permeability tests the fact remains that a rock-mass which has been irregularly deposited, folded, faulted, weathered and loosened by atectonic and climatic influences finally prohibits an exact description.

All calculations, therefore, can only be approximations which depend to a great degree on the reliability of the geological and geotechnical parameters. The calculated results must always be reconsidered by general and regional experience.

To be rejected in any case is a schematic application of a single test method. All observations during an investigation and project study have to be considered and compared.

Many authors have established relations between the results of single testing methods in different rock types. In the attached nomogram (fig. 3), an attempt is now made to interrelate all parameters discussed with respect to lithology.

The main obstacle to such a synopsis is the wide range of data for individual rock types. For instance, the permeability coefficient of limestones varies from 0 to $> 10^2$ cm/s.

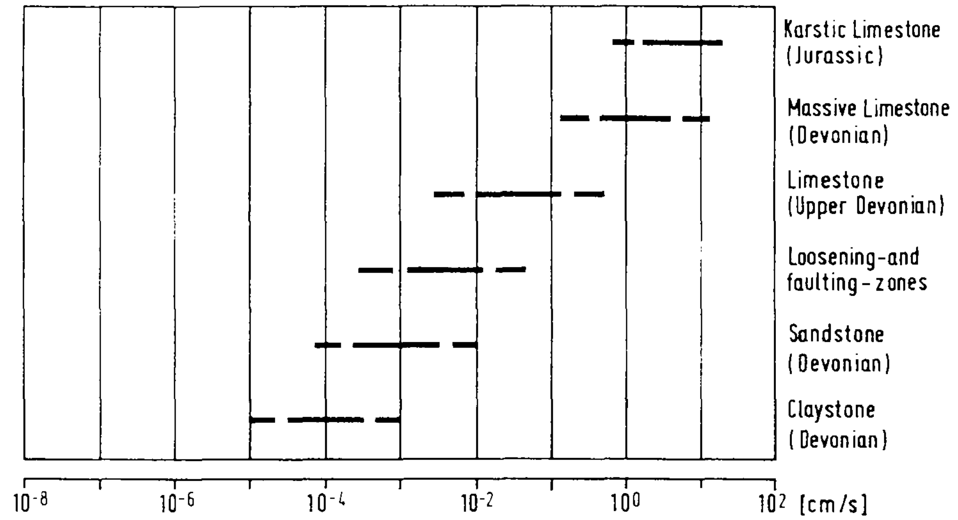

Fig. 2: Apparent flow velocities (Heitfeld 1966).

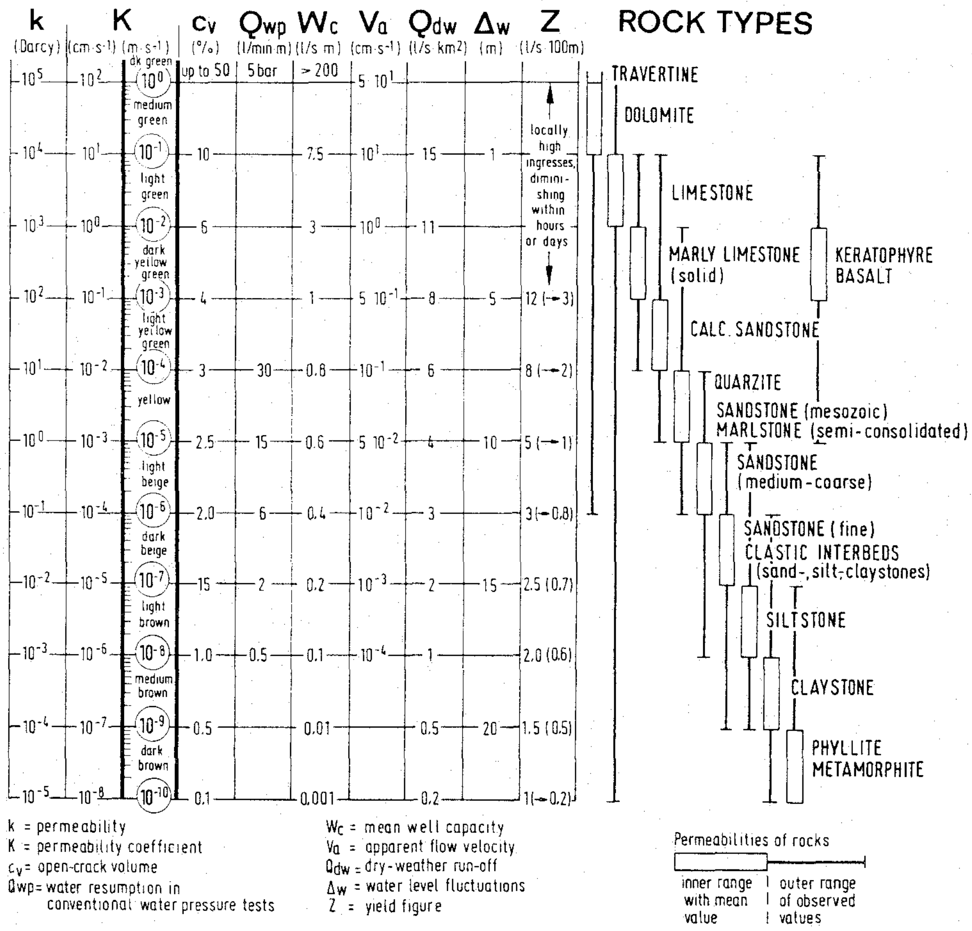

Fig. 3: Nomogram for the classification of rock-mass permeabilities.

The ranges can essentially be reduced if the classification is restricted to the near surface loosening zone and to karstic zones. In these zones the main water circulation occurs, and thus they are of primary interest for water- and waste-management projects as well as for dam and underground construction. Below these zones the permeability of practically all rock types is very low.

The dominant factor for rock-mass permeability is the effective open-crack volume. The evaluations have given values between 0.1 per cent for very tight phyllites and 10 - 15 per cent for highly karstic limestone and dolomites, with extreme values of up to 50 per cent for lime-tufa and travertines.

These are limiting values and a graduated scale can be attributed roughly to permeability classes in decimal steps.

In order to enable a planar presentation of permeabilities on maps an association of colours with these permeability classes and rock types is suggested, wherein every rock type or formation is classified according to its mean permeability. The colour-scale reaches from green (high permeability) over light-green, yellow, light brown to dark brown (low permeability). This colour-scale differs from the grain-size/porosity-scale for soils in order to indicate the principal differences between pore- and open-crack permeabilities.

The attribution of rock types is, of course, not valid for all areas, but must be adapted to regional conditions. Since, however the effective open-crack volume is used as the central parameter or rock-mass permeability the relations in other morphological and climatic zones will not differ in principle from the situation in the Western Rhenish Mountains.

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