Rock Mechanics and Rock Engineering
https://doi.org/10.1007/s00603-019-01954-x

ISRM SUGGESTED METHOD

ISRM Suggested Method for the Lugeon Test

Philippe Vaskou[1] · Eda F. de Quadros[2] · Milton Assis Kanji[3] · Tom Johnson[4] · Mehmet Ekmekci[5]

Received: 8 July 2019 / Accepted: 19 August 2019

List of Symbols

P	Pressure at the pressure gauge (MPa)
P_{eff}	Effective water pressure in the centre of the test interval (MPa)
$P_{\min}$	Minimum test pressure (MPa)
$P_{\max}$	Maximum test pressure (MPa)
L	Length of the test window (m)
H	Length between surface pressure gauge and bottom of (upper) packer (m)
H_1	Height of pressure gauge above ground level (m)
H_2	Depth of the water table in borehole below ground level (m)
FL	Friction losses in pipe (MPa)
Q	Water injection flow rate (ℓ/min)
T	Transmissivity (m^2/s)
K	Hydraulic conductivity (m/s), often referred to as permeability coefficient
D	Borehole diameter (m)
r	Radius of the borehole (m)
R	Radius of influence (m)
e	Hydraulic aperture of fractures (mm)
E	Mechanical (or physical) aperture of fractures (mm)
S	Mean fracture spacing (mm)
LU	Lugeon unit or Lugeon value
JRC	Joint roughness coefficient

1 Introduction

The most commonly used in situ test to estimate permeability in rock engineering works is the Lugeon test, which is also known as the "packer test" or the "water pressure test". It has been designed as a means of assessment of rock mass permeability and the need for grouting at dam sites.

The Lugeon unit (LU) was introduced later on in reference to the "water loss coefficient" with the objective of characterising the water absorption in the rock mass.

A Lugeon unit (LU) is defined as the loss of one litre of water per minute per metre of the borehole test section, at an excess injection pressure of 1 MPa in the centre of the test interval.

The estimation of equivalent rock mass permeability values (hydraulic conductivity K in m/s) was not proposed in the original publication by Maurice Lugeon (Lugeon 1933). However, converting Lugeon values into equivalent rock permeability has become common practice all over the world. Conversion formulae or factors are applied to estimate the permeability coefficient derived from the constant injection pressure and flow, assuming the media are continuous and porous. This is normally done using an empirical approach presuming stationary pressure and flow, and assuming steady-state transmission of water from the borehole to the surrounding medium (Hvorslev 1951; Zeigler 1976; Rissler 1977a). Mathematically and physically more rigorous approaches have been developed for the petroleum exploration industry and for the design of waste repositories (summarised, for example, in Gringarten 2008). It is important to note that the permeability values derived from Lugeon tests provide only approximate results. However, in the field of rock engineering works, they are sufficient in many cases.

The Lugeon test can also provide useful information about the hydraulic properties and water absorption capacity of the rock mass under increasing and decreasing pressure

Please send any written comments on this ISRM suggested method to Prof. Resat Ulusay, President of the ISRM Commission on Testing Methods, Hacettepe University, Department of Geological Engineering, 06800 Beytepe, Ankara, Turkey (resat@hacettepe.edu.tr).

✉ Philippe Vaskou
philippe.vaskou@geostock.fr

[1] Geostock, 2 rue des Martinets, CS 70030, 92569 Rueil-Malmaison Cedex, France

[2] BGTech Soil and Rock Engineering Ltda, São Paulo, Brazil

[3] Escola Politécnica, Universidade de São Paulo, São Paulo, Brazil

[4] Sterling Environmental, Latham, NY, USA

[5] Hacettepe University, Ankara, Turkey

and also on the non-linearity of flow. Despite its ambiguity from the viewpoint of quantification of permeability, the Lugeon test yields important information about the variation of the hydraulic properties with depth, at suitable scales of interest for the engineering work.

In addition to the preliminary definition of hydrostratigraphic units for further characterisation, the variation of the hydraulic properties with depth applies to two classical themes in rock engineering: (i) the evaluation of the permeability profile of dam foundations and the subsequent design of the grout curtain, (ii) the estimation and evolution of permeability and water seepage along a tunnel route and the need to pre-grout.

Different aspects of the original Lugeon test have been modified over the years, resulting in the present form (e.g., Houlsby 1976, 1990; Pearson and Money 1977). However, even if the fundamental concepts proposed by Lugeon more than 80 years ago have remained the same, several technological advances have been introduced.

Two of the most important are the use of straddle packers and the introduction of automatic data acquisition systems, accompanied by peripheral devices. Such electronic systems allow accurate recording of flow and effective pressures in real time during the tests, reducing the work in the field and facilitating the data treatment and interpretation of test results.

Also, depending on the accuracy required for the results, borehole imagery (acoustic televiewer and/or optical imaging) may be used to survey the geometrical characteristics of the fractures appearing in the borehole walls, and to assist in detailed statistical analysis of the parameters such as orientation, spacing and apparent aperture. Borehole imagery may also contribute to the planning and selection of the test intervals, if this is to be on a selective basis, rather than continuous.

The Lugeon test is a constant head water injection packer test, applied to civil, mining and subterraneous work in rocks. It should not be confused with other in situ hydraulic tests developed for estimating the hydraulic conductivity in porous media (e.g., the falling-head tests and pumping-out tests used for hydrogeological characterisation). The objectives associated with Lugeon tests differ from those of hydrogeological studies, where the permeability/hydraulic conductivity of large horizontal aquifers is generally the subject of the investigations.

One of the advantages of the Lugeon test is its simplicity. However, despite its apparent simplicity, it is recommended that the test execution and interpretation of results be performed by a trained professional in rock mass testing. Many variations of the test have emerged over the years, leading to distinct procedures to perform the test, sometimes causing difficulties when comparing the results derived from different sites. Drilling companies under consultant's advice sometimes use a "modified Lugeon test" to broaden the scale of the test around the boreholes and allow more sophisticated hydrogeological analyses and interpretations of the test results. Those tests, however, lose the initial simplicity of the method.

The use of the Lugeon test is more appropriate for relatively well-defined geological conditions, where fractured zones can be identified. The area where the tests will be performed is adjusted to the scale of the engineering work and results derived from the tests are valid only for the immediate surroundings of the borehole being tested.

This suggested method is intended to cover only the standard concept of the Lugeon test. The only modifications relate to the use of modern equipment to perform the tests.

2 History

The Lugeon test is related to the name of its inventor, Maurice Lugeon, a French geologist who made his career in Switzerland. Maurice Lugeon proposed his test aiming at the development of a simple tool to characterise and compare pervious zones of dam foundations in different sites. Originally, measurements of zones of higher or lower "absorptions" in dam foundations were identified by means of tests using cement-based slurries during the execution of a grout curtain in dam foundations. However, the comparison of the results ran into numerous difficulties due to the use of slurries of different mixtures and different viscosities. Lugeon identified this problem and required that the use of cement slurry in the boreholes for grouting be preceded by the injection of water in the same holes under comparable conditions, giving the origin to the Lugeon test.

Maurice Lugeon presented his method in a book entitled "Barrage et Géologie", published in Lausanne in 1933, fully dedicated to dam construction. Maurice Lugeon's objective was clearly to differentiate pervious from impervious zones in the rock masses of dam foundations. He believed that the "water injection test" would perfectly characterise the zones of low and high water absorption in dam foundations and could be used to predict the amount of cement needed to execute a grout curtain. In addition, the test could also be performed to analyse the grouting efficiency during the distinct grouting phases. According to Lugeon (1933), for dams lower than 30-m height, absorptions within the foundation should not exceed 3 LU, while for dams higher than 30 m, absorptions within the foundation should not exceed a maximum value of 1 LU. In his book, several cross-sections of dam foundations are presented as well as the use of circles of various sizes to represent water absorption profiles along the boreholes, emphasising the importance of the geological features versus the water absorption measured through the application of his testing method.

When Maurice Lugeon proposed his test, drilling processes were less developed than today. Core barrels were relatively short (1–2 m in general) and only single mechanical packers of small size made of leather or rubber discs were available (inflatable packers started to be used after the Second World War). With such relatively simple equipment, the only feasible way to perform the Lugeon test would be while drilling was progressing, i.e., immediately after retrieving the core on a short, non-uniform test section. The variable length of the core barrel and/or the core run was typically 1–2 m. Pressure gauges, hydrometer and piston pumps at the ground surface were used. Such equipment caused difficulties in maintaining the required stabilisation of the pressures often leading to inaccurate pressure readings during the tests.

With the course of time, several advances were introduced in the original equipment proposed by Lugeon, such as inflatable packers of varied sizes and the use of double (straddle) packer systems. In the latter, a test "window" is provided between the two packers used to isolate the test interval, such that the water can flow out from this zone only. The most recent progress includes improved pump designs that deliver steadier pressure and subsequent flow (e.g., centrifugal pumps) as well as the use of downhole pressure transducers and flow meters, to register pressures and flow during the tests, in parallel with automatic data acquisition systems, able to monitor results in real time, during the test. These advances allowed technical improvements regarding both the acquisition and interpretation of tests, as well as the possibility of performing the tests using the bottom-upwards technique saving time using double (straddle) packers.

3 Objectives

The objective of this suggested method is to provide guidance to contractors, engineers, engineering geologists and other professionals in charge of performing and interpreting Lugeon tests for rock engineering use. The Lugeon test is described here with some adaptations to allow the use of modern and efficient equipment, so that tests can be performed without fundamentally modifying the initial concept proposed by Maurice Lugeon.

Existing standards on the Lugeon test (ASTM D4630-96 2008 and ISO 22282-3 2012) describe terms, definitions, symbols and units used in the test, as well as the test preparation and procedures. The use of systematic rules to carry out the Lugeon test and for interpretation of the results allows a valuable assessment of site conditions and a direct comparison between different sites.

Lugeon tests should never be a substitute for distinct hydrogeological tests which have distinct scopes. Lugeon tests, however, can be used in preliminary definition of hydrostratigraphic units. The relative change of permeability values in LU provides an important tool in hydrostratigraphical characterisation of the lithological units with depth. If accurate hydrogeological characterisation is required, hydrogeological tests adapted to each specific situation should be planned and carried out (e.g., aquifer pumping and recovery tests, falling-head tests, slug tests and others). These can be in addition to the use of Lugeon tests.

The main applications of the Lugeon test as described here are related to the investigation of the water absorption capacity of the rock mass and the estimation of the equivalent isotropic coefficient of permeability/hydraulic conductivity of the rock mass around any given testing borehole.

This will be used to quantify the variable hydraulic behaviour of the rock mass with depth and location to predict the variable amount of grouting to be used in dam foundations and abutments or in other sub-surface excavations in rock. It can also be used to estimate the optimal grouting materials and injection pressures to be used for pre-grouting ahead of tunnels.

4 Description of the Test

4.1 Principle of the Test

The Lugeon test can be defined as a stepwise constant head permeability test performed in an isolated test zone of a borehole. A series of distinct stages of pressures and water injection are used to perform the test at different depths in isolated intervals of the borehole, aiming to characterise the hydraulic properties of the various zones along the borehole and to produce a depth-permeability profile based on the test results.

The first step when performing the test is to record the static groundwater level in the borehole. This level is required to calculate the effective test pressure (P_{eff}) in case a pressure transducer is not used, and to assess any leakage around the packers during the test.

The test consists in measuring the amount of water injected under magnitudes of pressure in an isolated interval of the borehole over a certain period. Inflatable packers are used to isolate the selected test intervals. When the test is made using a single packer, the effective test pressure in the test section (P_{eff}) can be recorded using a pressure transducer located in the centre of the test interval. When a straddle packer is used, the effective pressure in the test section is registered using a pressure transducer placed between the straddle packers. Independent of the way the test is performed, the effective pressure in the centre of the test interval needs to be recorded or calculated if the pressure is recorded at a gauge installed at the well head.

The effective pressure measured in the centre of the test interval depends on the groundwater level and on other factors such as the depth of the test interval, the height of the injection pipe above the ground surface and the head losses associated with flow of fluid through the injection pipes.

The practice of calculating the effective pressure from the readings of gauges placed at the ground surface can lead to much uncertainty in the results. This is mainly due to the lack of accuracy in the estimation of the head losses occurring in the tubes or hoses that conduct the water to the test section. The readings in the gauges could also be inaccurate, due to, for instance, lack of calibration or insufficient gauge sensitivity.

Nowadays, the effective pressure is, in general, recorded directly in the centre of the test interval using a pressure transducer which provides highly accurate and rapid pressure readings. The use of pressure transducers is highly recommended to maximise the accuracy of the test results.

When a pressure transducer is not used inside the test interval, it is necessary to consider the static groundwater level and the elevation of the surface pressure gauge to calculate the effective pressure on the test section.

Classically, when the test window is located below the groundwater table, the calculation of the effective pressure is made (Eq. 1) considering the gauge pressure, corrected for the difference of elevation between the gauge and the groundwater level, decreased by the friction losses occurring in the pipes (see also sketch in Table 3)

$$P_{\mathrm{eff}} = P + H_1 + H_2 - FL. \tag{1}$$

In Eqs. 1 and 2, all units have to be converted into MPa.

In the specific situation where the test window is located above the groundwater table (vadose zone), the calculation of the effective pressure is done using a different formula as follows:

$$P_{\mathrm{eff}} = P + H + L/2 - FL. \tag{2}$$

For vertical boreholes, height (H_1), depth (H_2) and lengths (H and L) are directly measured on the equipment whereas vertical projections of these values must be used for inclined boreholes.

Friction losses (or head losses) depend on the length, diameter and type of pipe or hose, as well as the fittings used in the test assemblage. In such cases, and even if information can be obtained from pipe/tube/hose producers, the friction losses shall be empirically measured at the site with the same tubing used to perform the tests. Table 1 shows a detailed list of equipment needed to perform a Lugeon test.

The use of a straddle packer system to perform the test has increased in many countries in the last 30 years, being nowadays almost a universal practice.

However, it may sometimes be difficult to run straddle packers in unstable zones (fractured/faulted zones or in the case of joints having a low angle to the borehole axis). Inclined boreholes can make the situation even worse. In such cases, it may become necessary to perform a Lugeon test in unstable zones immediately after drilling, then cement the concerned zone to avoid stability issues, and resume drilling.

One of the advantages of the system and method is that multiple tests can be performed sequentially, without interruption after the borehole is drilled and using the same test procedure and apparatus from bottom-upwards. This saves time and allows for a specialised team to perform Lugeon tests, sequentially in multiple boreholes, ensuring a high level of data quality, consistency and continuity in the methodology.

4.2 Test Equipment

The list of equipment given in Table 1 is required to perform the test. This list is suitable for testing with both single and double (straddle) packer systems. While the procedure is similar for the use of one or another type of equipment, the number of devices is different as shown in Table 1.

Automatic data acquisition systems capable of measuring, displaying and recording test data in real time have become commercially available over the last decades. The use of an electronic data acquisition system allows monitoring and recording of the flow rate and pressure values over a specified time interval (for instance, each minute). The information relative to the test performance can be displayed in real time on a liquid–crystal display (LCD) or directly on the screen of a portable computer.

Since this type of equipment can measure both pressure and flow rate in real time, the results can be monitored as the test proceeds. The analysis can be done in real time using the plot of flow rate over the section length (Q/L) versus pressure, which is automatically displayed on the screen during the test. In this relation, Q is the total flow rate (ℓ/min) and L (m) is the length of the test interval.

4.3 Single Packer Test Procedure

Single packer tests, typically, are performed during, not after completion of drilling. A single packer test is performed after each core run as the borehole is advanced progressively deeper to minimise the length of the test interval. This procedure allows a better characterisation of fractures in fresh rock and more accurate conductivity profile along the tested borehole. On the other hand, it involves repeated insertion and removal of drilling rods and packer testing apparatus. Thus, time spent for manoeuvres becomes important in deep boreholes making the single packer procedure less efficient than the double packer method (see Sect. 4.4 below).

Table 1 Detailed list of equipment required to perform Lugeon tests

Location	Type	Quantity		Comments and recommendations
		SP*	DP*	
At surface	Water tank	1	1	Filled with fresh water (min. 1 m^3 per test)
	Valve	2	2	Manual valves (¼ in. and 1 in.) for flow regulation
	Water flowmeter	2	2	Located before the flow regulation valve, measuring ranges: 0–12 ℓ/min, 6–150 ℓ/min, flowmeters
	Injection pump	1	1	Centrifugal pump (0–150 ℓ/min)
	High pressure hoses (min. 2.5 MPa)	4	4	Injection pipes, linking the ground surface equipment to the test zone
	Well head	1	1	Mounted at the top of the test rods linking the injection lines to the test rods
	Pressure-reduction valve	1	1	Gas pressure regulation (nitrogen)
	Nitrogen or compressed air	1	1	In bottles (approx. 20 l, 200 bar for 5 test intervals (DP))
	Enhanced			
	Data acquisition system	1	1	Real-time data-recording system consisting of A/D converter PC and screen (or laptop)
Downhole	Inflatable packer	1	2	Spare packer sleeve recommended
	Slotted pipe or screen (interval access)	1	1	Including interval-extension rods (not necessarily slotted)
	Test rods	–	–	Number and length to be adapted to the test depth
	Packer inflation line	1	2	For individual packer control, two lines are needed when using double packer, or single line with upper packer pass-through
	Enhanced			
	Downhole valve	1	1	Highly recommended for low permeability zones
	Pressure transducers	2	3	For locations of pressure transducers, see Figs. 2 and 3
	Data cable	1	1	
	Optional			
	Pressure gauge	–	1	Used to detect any leak around the lower packer from the test interval downward, if no real-time pressure transducer is located below the lower packer

(*) *SP* single packer; *DP* double packer

The basic equipment needed to perform the Lugeon test using a single packer is shown schematically in Fig. 1. The test is, in general, performed in boreholes with static water level below the ground surface and above the test section (in the saturated zone).

The test interval often varies from 1.5 to 3.0 m. Sometimes, 5-m intervals are used but are not recommended, because of the reasons discussed in the next paragraph. The test interval is limited in the lower portion by the bottom of the borehole and in the upper portion by the packer. The packer is, in general, 1–1.5 m in length and should never be less than 1 m long.

Shorter test intervals are preferred to longer intervals to ensure accuracy in the representativeness of the Lugeon value. The effects of the water-conducting rock fractures in the test interval (in general fractions of a millimetre scale) that provide narrow pathways for the water flow into the rock mass become less evident if the length (L) of the test interval considered in the formulae is too great. Narrow fractured zones are also a key issue, because of their potentially high conductivity, unless they are clay filled and act as hydraulic barriers.

During the test, water is injected under a series of pressure steps and the resulting pressure is recorded when the flow has reached a steady or quasi-steady state condition. Before starting the test, it is necessary to calculate the maximum pressure ($P_{\max}$) and to programme the pressures to be applied in each stage during the test.

Two pressure transducers are required: one placed above the packer to detect potential water leakage around the packer, and one in the centre of the test chamber to record the test pressure. In most projects, the host rock is not a uniform porous medium, but a fractured rock mass. The test section is crossed by fractures having distinct geometrical characteristics leading to different hydraulic conductivities and even different pressures. A transducer located at the centre of the test section will accurately measure an averaged pressure that will be the basis for the DP increments of 0.3, 0.5, 0.7 and 1.0 MPa excess pressure. Both pressure transducers are linked to the data acquisition system at the surface.

The test procedure for the single packer test is given below:

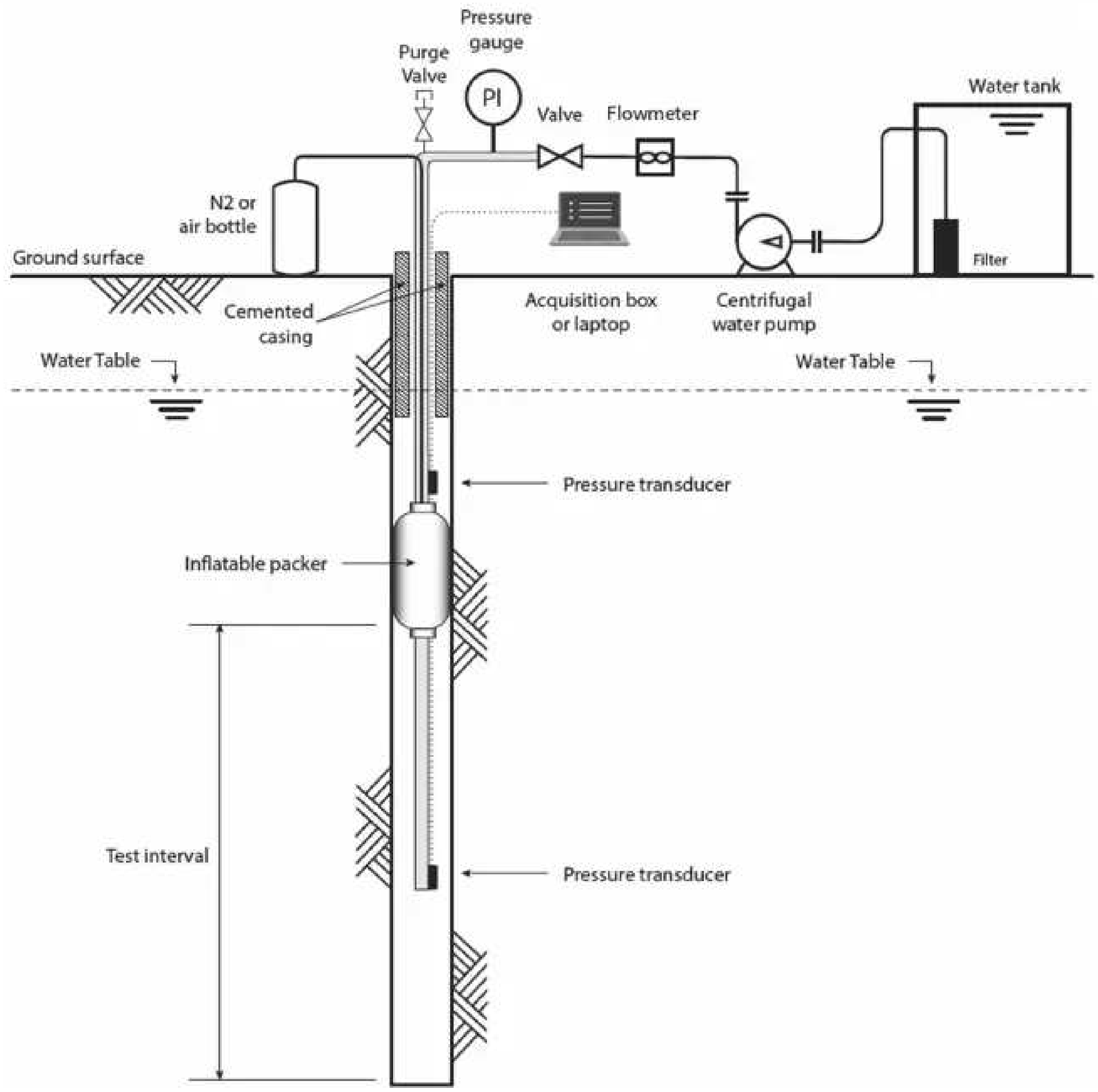


Fig. 1 Typical assemblage of equipment to perform a single packer Lugeon test using an automatic data acquisition system

(a) Cleaning of the borehole. Circulation of the drilling water should be continued (in general, for 10–15 min) until the water appears clear and free of debris.

(b) The initial water level in the borehole is measured for a period of at least 5 min.

(c) Selection of the test interval (if continuous zones are not to be measured) is often based on the observation of cores or use of borehole imaging techniques. The test interval is bounded by the bottom of the borehole and the single packer on the upper portion as shown in Fig. 1.

(d) Before assembling the equipment, it is necessary to define the maximum pressure to be used in the respective interval of testing and to programme the pressure increments which will depend on the maximum pressure.

(e) The packer is introduced and set into the borehole; one pressure transducer is located below the single packer to measure the effective pressure in the test section, and another pressure transducer is located immediately above the single packer to monitor water head variations during the test and detect potential water leakage around the packer.

If above the water table, water must be injected until a constant rate of water loss is achieved indicating that the surrounding of the test section is saturated.

(f) The packer is inflated using a gas bottle (often nitrogen) or by means of a gas compressor on the surface, with the objective to isolate the test section. The use of water to inflate packers is not recommended for practical reasons, and in particular, to the difficulty of allowing packer deflation in deep boreholes with high water column.

(g) It is recommended to inflate the packer following the manufacturer technical specifications to avoid any leakage. The pressure depends on the diameter of the borehole and frequently reaches 2 MPa. The packer inflation pressure must be sufficient to overcome the hydrostatic pressure of the water column in the borehole, and to account for the selected test pressure(s).

(h) After the packer is inflated, the static water level in the borehole is measured for a period of at least 5 min.

(i) Water is injected through the pipe into the isolated section of the borehole (Fig. 1). The trapped air in the line is purged through a valve located at the highest point of the injection line and a flowmeter is used to record the amount of flow into the test section during the test (Fig. 1).

(j) When applying the first stage of pressure, the efficiency of the packer can be evaluated by monitoring the water level in the borehole. Generally, the water level in the borehole rises if the packer is not tightly sealed.

(k) For each pressure stage, the flow rate per length Q/L is registered, where Q is the total flow rate (ℓ/min) and L (m) is the length of the test interval. The pressure and the flow rate could be recorded in intervals of seconds or minutes depending on the planned test programme (five to ten stages) and the software used in the data acquisition system.

(l) Each pressure stage is continued for 10 min after the pressure is stabilised. Recording of total flow is recommended to be taken at least every minute during the 10 min used for each pressure step. Use of automated instrumentation simplifies the process and allows a higher frequency of data recording.

(m) Five to ten steps of increasing pressure are used, followed by the steps of pressure decrease.

4.4 Straddle Packer Test Procedure

Figure 2 presents a typical assemblage of equipment for performing the Lugeon test using a straddle packer. This is a system composed of a machined metal or PVC pipe connecting two (or more) packers and instrumented with electronic devices. The pipe (or the hose) connecting the packers extends to the ground surface.

A slotted section (window) is provided between the two packers in the test section, for exit and entrance of water. This centrally located window allows the water to flow through the test interval to the surrounding rock mass. A nitrogen (or air) source and an inflation system are used for inflating the packers (see remark in single test procedure, sect. f).

Three pressure transducers are installed in the system: one above the test interval, one within, and another below the lower packer to monitor the pressure changes during the test. Leakages can be monitored by means of pressure readings during the test. The transducer installed in the test section (window) is used to register the pressure during the test. Increases in pressure measured by the transducers above the upper packer and below the lower packer indicate leakage along the outside of the packers or through the rock joints or matrix, when these are permeable enough to 'short-circuit' the flow around the packers.

Quinn et al. (2012) define three generic types of leakage that may occur during a test between packers (see Fig. 3):

(i) Between the packers and the borehole wall (case A).

(ii) Through the existing fracture network in the surroundings of the test window (case B).

(iii) Around the packers if the rock mass is pervious (case C).

Sources of leakage can be monitored in the straddle packer system by the pressure transducers located above the upper packer and below the lower packer.

When it is not possible to control the leakage, one solution is to increase the length of the packers. Due to the flexibility of the straddle packer system, this could be done through the assemblage of packers using an extended length. Another solution could be to move the equipment to a new position in the borehole where the sealing could be improved. In this case, a new test section should be programmed.

The test procedure using a straddle packer system is similar to the one using a single packer, except for the number of packers and the instrumentation required:

(a) Cleaning of the borehole: the cleaning should continue until the water of circulation appears clear and free of drilling debris.

(b) The initial water level in the borehole is measured for a period of at least 5 min.

(c) The second step is to select the test section into the borehole based on core observations and/or borehole imaging.

(d) Before assembling the equipment, it is necessary to define the maximum pressure to be used in the respective interval of testing and to programme the pressure stages which will depend on the maximum pressure as described in Sect. 4.5 and Table 2.

(e) The three pressure transducers are installed before the system is set into the borehole: one in the centre of the test window to register the effective pressure during the test, one above the upper packer to measure water head

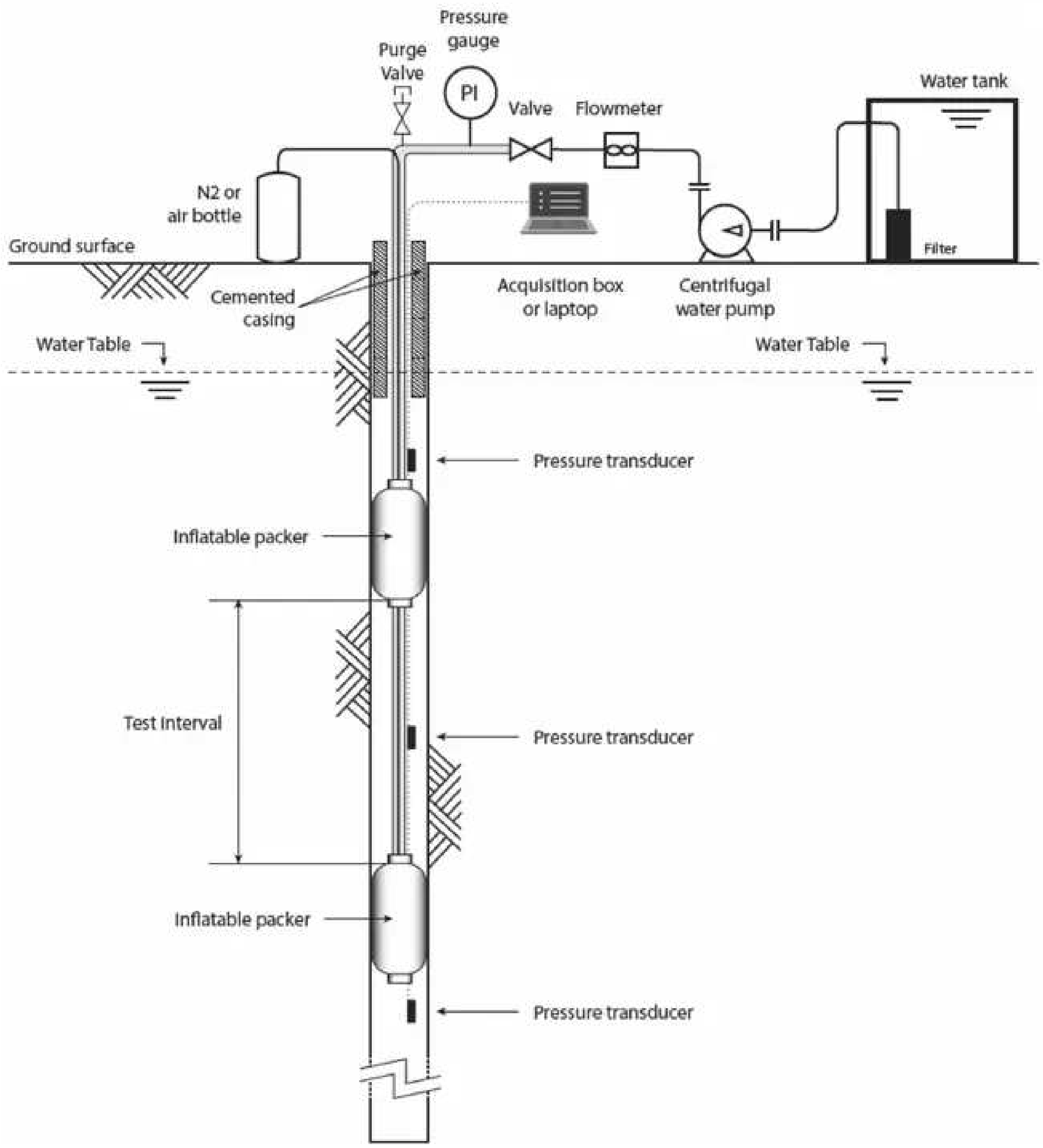


Fig. 2 Typical assemblage of equipment to perform the Lugeon test using the straddle packer and an automatic data acquisition system

variations and to detect potential leakage between the packer and the borehole walls; and one below the lower packer to monitor potential pressure changes and leakages during the test. All the pressure transducers are linked to the data acquisition system set on the surface.

(f) The straddle packer is introduced into the borehole (Fig. 2). The window is adjusted to the test section.

(g) After the straddle packer is set and the packers are inflated, the water level in the borehole is measured for a period of at least 5 min.

(h) The test is started using consecutive increasing and decreasing pressure steps according to the pre-determined pressure programme.

(i) When applying the first stage of pressure, the efficiency of the packer seal should be evaluated by observing the water level in the borehole. Generally, the water level rises when the packer is not tightly sealed.

(j) For each pressure stage, the flow rate per length, Q/L is registered. The pressure and the flow rate per length (Q/L) should be recorded in intervals of seconds or

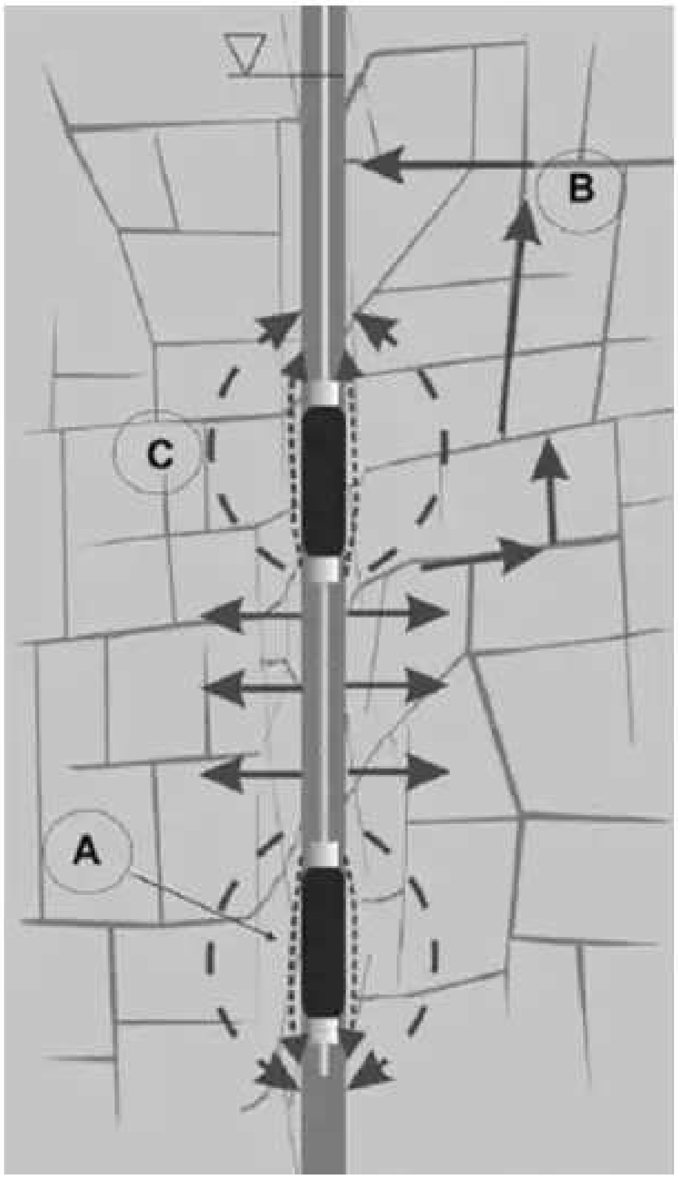


Fig. 3 Straddle packer showing three types of potential leakage within the borehole which can be monitored by pressure transducers located above the upper packer and below the lower packer. A: small dashed lines around packers; B: continuous arrows along fractures and C: large dashed lines around packers (after Quinn et al. 2012)

minutes, depending on the test programme (5 or 10 stages) and the software used in the data acquisition system.

(k) Each pressure step is continued for 10 min after pressure stabilisation. Recording of data is made automatically using the same time interval for each step.

(l) Five to ten steps of increasing pressure are used, followed by the steps of pressure decrease.

4.5 Pressure Stages

The pressure stages applied in the Lugeon test depend on technical, practical and empirical factors, including the density of the rock mass, the depth of the test interval and the regional practice as well. The estimation of the maximum effective pressure is one of the first steps required when performing the Lugeon test. After the equipment is inserted into the borehole and the static water level is recorded, it is necessary to calculate the pressures to be used in the test (Table 2). In general, these pressures are recorded in MPa.

The maximum effective pressure can be based on several parameters: the average unit weight for the rock mass (around 2700 kg/m^3 or less in case of sedimentary rocks), the depth of the test interval, the water level above the test interval and the pressure losses in the drill rods. The use of electronic devices and pressure transducers recommended allowing the effective pressures to be automatically measured and recorded when the equipment is assembled. The pressure stages in the increasing and decreasing cycles are programmed depending on the maximum effective pressure.

In many countries, the common practice is to use nine effective pressure stages (ten pressure stages, including the initial stabilisation phase of zero pressure) with four increasing steps, one maximum pressure step and four decreasing steps. However, depending on the accuracy and the objective of the test, a higher number of increasing and decreasing pressure stages can be used. The use of five effective pressure stages (six stages including the initial stabilisation phase of zero pressure) is considered as a minimum and a three-step procedure shall be avoided. Some suggestions and examples for the effective pressure to be applied in Lugeon tests are shown in Table 2, based on the general practice. Five pressure stages is the minimum acceptable number of steps.

In dam engineering, the criterion to define the maximum test pressure (P_{max}) in the test is generally based on the depth of the test interval (0.023 MPa to 0.025 MPa per metre of depth) or ¾ of the overburden pressure, with use of the density of the overburden (Oliveira et al. 1975; Banks 1972). These two ways are valid (results are rather similar when using a density of 2.7) whereas the first one is generally used for boreholes and dam engineering practice at shallow depth (less than 200 m), and the second one in tunnels, caverns and at much greater depth in underground research laboratories (URL).

In such cases, the maximum pressure should be calculated considering the minimum principal rock stress at the site to avoid hydraulic fracturing. It is important to note that this is not the pressure to be applied at the ground surface, but the effective pressure recorded by the pressure transducer at the test interval, which should not exceed 1.0 MPa greater than the static hydraulic head of water. Nowadays and especially in dam engineering, due to the increasing height of dams and the subsequent deepening of the investigations, the influence of stresses at the site should also be considered.

5 Calculations

A single Lugeon value (Lugeon unit or LU, expressed in ℓ/min/m at 1.0 MPa of effective test pressure) is calculated for each pressure stage using the following equation:

Table 2 Suggestions for pressure stages based on general practice

Pressure stages			Comments (pressures are in MPa)
Number	Phase	Stages	
10	Increasing phase	P_0	$P_0 = 0$ (initial conditions)*
		Initial conditions	for checking the pressure of the water column and stabilisation after packer inflation (zero flow)
		$P_1 = P_{min}$	P_{min} = minimum effective pressure
		P_2	P_{max} = maximum effective pressure
		P_3	(generally $P_{min} = 0.10–0.4\ P_{max}$)
		P_4	The maximum pressure P_{max} shall be adapted to the site and work conditions, limited to 1.0 MPa of excess pressure
	P_{max}	$P_5 = P_{max}$	
	Decreasing phase	P_6	*Example 1 (ten stages)*
		P_7	Increasing phase: 0 (static level)/0.2/0.4/0.6/0.8 MPa of excess pressure $P_{max} = 1$ MPa (excess pressure)
		P_8	Decreasing phase: 0.8/0.6/0.4/0.2 MPa of excess pressure
		P_9	*Example 2 (ten stages)*
6	Increasing phase	P_0	Increasing phase: 0 (static level)/0.2/0.4/0.6/0.8 MPa of excess pressure
		Initial conditions	$P_{max} = 1$ MPa (excess pressure)
		$P_1 = P_{min}$	Decreasing phase: 0.7/0.5/0.3/0.1 MPa of excess pressure
		P_2	
	P_{max}	$P_{max} = P_3$	*Example 3 (six stages)*
	Decreasing phase	P_4	Increasing phase: 0 (static level)/0.4/0.7 of excess pressure $P_{max} = 1$ MPa (excess pressure)
		P_5	Decreasing phase: 0.7/0.4 MPa of excess pressure

(*) The initial zero pressure corresponds to the existing hydrostatic pressure at the centre of the test interval. The test pressures (the effective pressures) are pressures in excess to the hydrostatic pressure, which are limited to 1 MPa of excess pressure

$$\mathrm{LU} = \frac{Q}{L}, \quad \text{in } \ell/\text{min/m, at 1 MPa effective pressure.} \tag{3}$$

The analysis of the test results is made considering the relationship between the flow rate per length in the test section (Q/L) and the corresponding effective pressure (P_{eff}). Both parameters are automatically recorded by the electronic data acquisition system.

The Lugeon unit, in litre per minute and per metre, is considered at 1 MPa for comparison purpose, but in practice, many Lugeon tests are run under lower pressure and even sometimes at higher pressure (e.g., in the case of high dams).

The practice to express the result in Lugeon units is to correct the result to the equivalent at 1 MPa using a correction factor as expressed in the following equation:

$$\text{if } P_{eff} \neq 1\ \text{MPa, LU} = \frac{Q}{L} \times \frac{1\ \text{MPa}}{P_{eff}} \text{ in } \ell/\text{min/m.} \tag{4}$$

Therefore, the water absorption is expressed in Lugeon units, corrected to 1 MPa, although it has been tested under other pressures.

It has to be noted that the correction factor (1 MPa/P_{eff}) considers a linear relationship between the flow rate (Q) and the pressure (P) which may be a valid assumption at quite low-pressure ranges, but may be invalid at higher pressures (due to variation in the aperture of the fractures induced by hydrojacking, resulting in changes in the flow regime). To validate this assumption or have a better evaluation of the flow behaviour during the test, the test results (Table 4) should be graphed as shown in Table 5.

6 Reporting of Results

Results should be presented for each borehole using tables with identification of the client, details on the assemblage of equipment, test results in terms of Lugeon and permeability/hydraulic conductivity, histograms and diagrams as shown in Tables 3, 4 and 5. Photographs of the test apparatus and instrumentation are useful to document conditions and for reference if questions arise during analysis of test results.

The following three tables present examples of Lugeon tests performed using a single packer and a pressure gauge located at the ground surface. Thus, the data sheets refer to the most complicated case and several parameters must be measured to calculate the effective pressure. Simplified data sheets can be adopted when the effective pressure is automatically measured using digital pressure gauges set in the test windows.

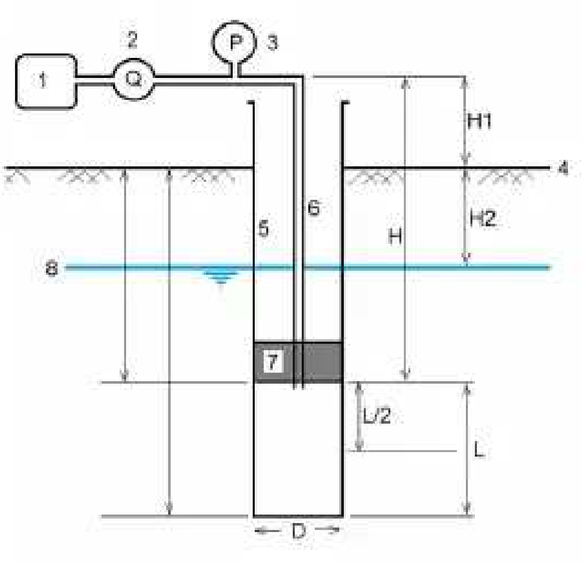
Table 3 Identification of the test

LOGO	**PROJECT NAME** **Constant Pressure Step Injection Test (Lugeon Test)**	**Borehole No**
TEST CONDUCTED BY:	**DATE:**	**TEST No:**

TECHNICAL DATA & CHARACTERISTICS

Test Interval From:	m/drilled	Length of test interval:	m
To:	m/drilled	Borehole inclination:	° / Vertical
Ref. Point Elevation:	m/ground level	Borehole diameter:	mm
Initial Hydrostatic Level:	m/Ref. Point	Ground Surface Elevation:	m / Sea Level
Final Hydrostatic Level:	m/Ref. Point	Injection Pipe	
Pressure Gauge Level:	m/Ref. Point	Diameter:	mm
Packer Type:		Length:	m
Packer Length:	m	Pump Type:	
Packer Pressure:	MPa		

EQUIPMENT LAYOUT

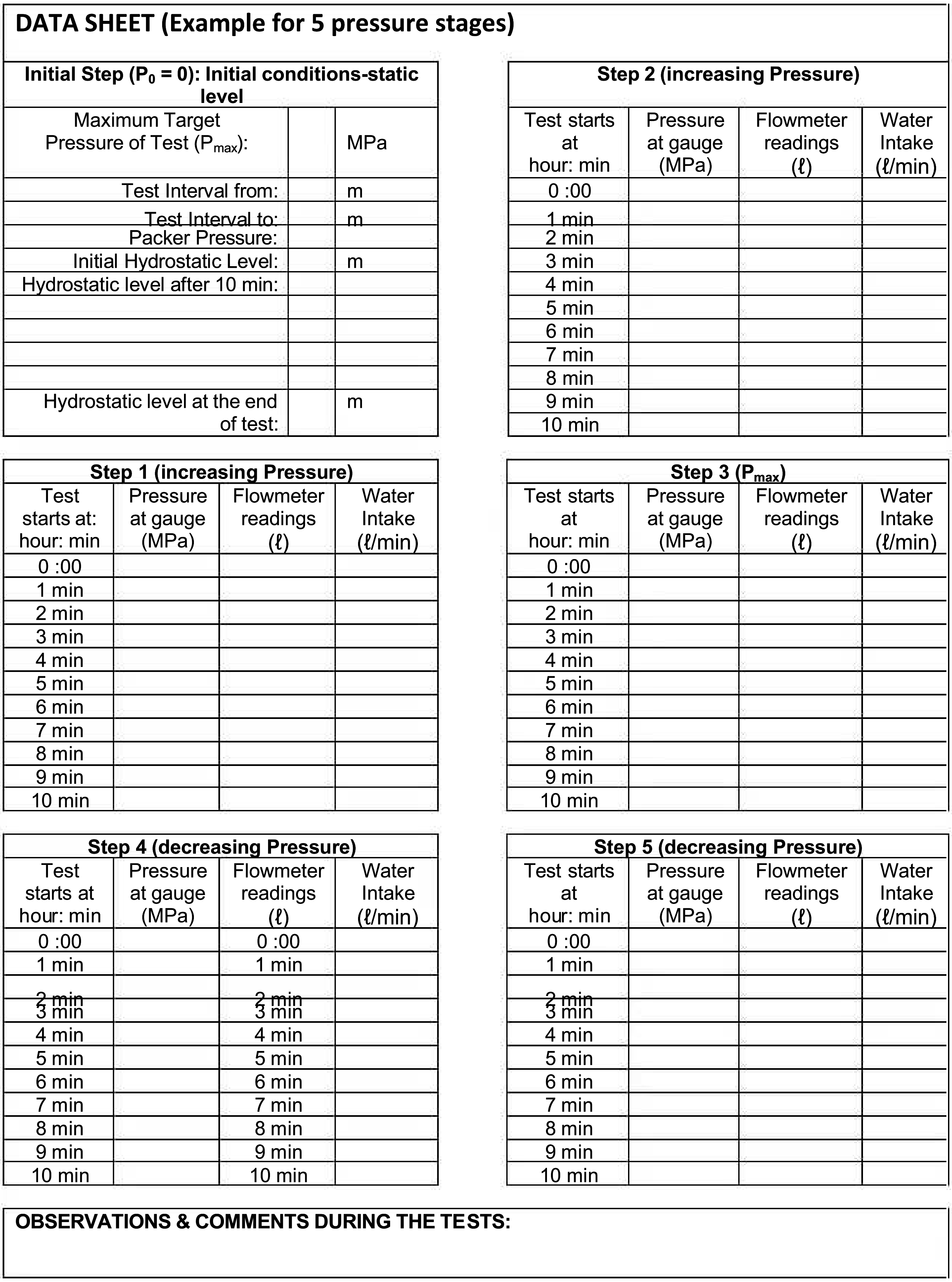


1: Pump
2: Flowmeter
3: Surface pressure gauge
4: Ground surface
5: Drillhole
6: Water injection pipe
7: Inflatable packer
8: Groundwater level

Q: Water flowrate (ℓ/min)
L: Length of test intervals (m)
D: Diameter of test intervals (m)
P_{eff}: Effective pressure $P_{eff} = P + H1 + H2 - FL$ (all units in MPa)
P: Pressure at gauge (MPa)
H: Length between surface pressure gauge and bottom of (upper) packer (m)
H_1: Height of pressure gauge above ground level (m)
H_2: Depth of groundwater level in borehole (m)
FL: Friction losses (in MPa)

LU = Q / L at P_{eff} = 1 MPa

Table 4 Data sheet showing the field test results



DATA SHEET (Example for 5 pressure stages)

Initial Step ($P_0 = 0$): Initial conditions-static level

Maximum Target Pressure of Test (P_{max}):		MPa
Test Interval from:		m
Test Interval to:		m
Packer Pressure:		
Initial Hydrostatic Level:		m
Hydrostatic level after 10 min:		
Hydrostatic level at the end of test:		m

Step 2 (increasing Pressure)

Test starts at hour: min	Pressure at gauge (MPa)	Flowmeter readings (ℓ)	Water Intake (ℓ/min)
0 :00			
1 min			
2 min			
3 min			
4 min			
5 min			
6 min			
7 min			
8 min			
9 min			
10 min			

Step 1 (increasing Pressure)

Test starts at: hour: min	Pressure at gauge (MPa)	Flowmeter readings (ℓ)	Water Intake (ℓ/min)
0 :00			
1 min			
2 min			
3 min			
4 min			
5 min			
6 min			
7 min			
8 min			
9 min			
10 min			

Step 3 (P_{max})

Test starts at hour: min	Pressure at gauge (MPa)	Flowmeter readings (ℓ)	Water Intake (ℓ/min)
0 :00			
1 min			
2 min			
3 min			
4 min			
5 min			
6 min			
7 min			
8 min			
9 min			
10 min			

Step 4 (decreasing Pressure)

Test starts at hour: min	Pressure at gauge (MPa)	Flowmeter readings (ℓ)	Water Intake (ℓ/min)
0 :00		0 :00	
1 min		1 min	
2 min 3 min		2 min 3 min	
4 min		4 min	
5 min		5 min	
6 min		6 min	
7 min		7 min	
8 min		8 min	
9 min		9 min	
10 min		10 min	

Step 5 (decreasing Pressure)

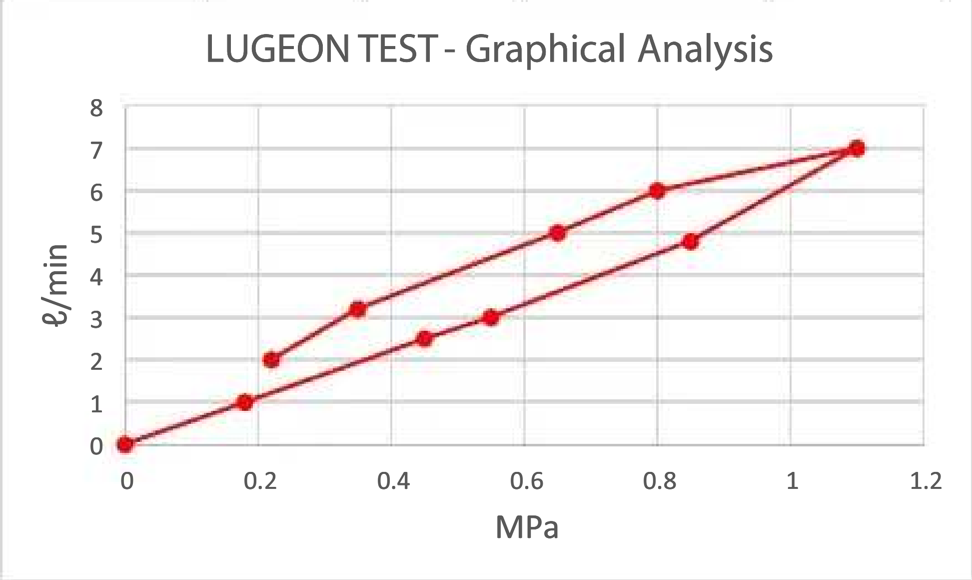
Test starts at hour: min	Pressure at gauge (MPa)	Flowmeter readings (ℓ)	Water Intake (ℓ/min)
0 :00			
1 min			
2 min 3 min			
4 min			
5 min			
6 min			
7 min			
8 min			
9 min			
10 min			

OBSERVATIONS & COMMENTS DURING THE TESTS:

Table 5 Interpretation of test results

LUGEON – Graphical Analysis

P (MPa)	H_1 (MPa)	H_2 (MPa)	FL (MPa)	P_{eff} (MPa)	Q (ℓ/min)	LU (ℓ/min/m)



7 Interpretation of Lugeon Test Results

7.1 Characteristics of the Relationship Between Flow Rate Per Length Versus Pressure

Interpretation of Lugeon test results is made through the analysis of the relationship between the flow rate (Q) and pressure (P) corresponding to each stage of the test and considering the flow regime, according to the diagrams presented in Table 6. Such diagrams are generic. However, they can be used whatever the purpose of the testing is (e.g., assessment of the hydraulic conductivity, need for grouting, analysis of the grouting efficiency).

Table 6 shows some typical diagrams derived from the test results:

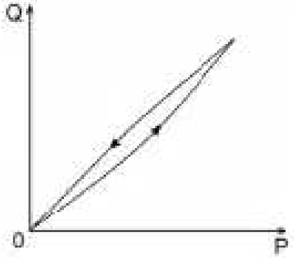
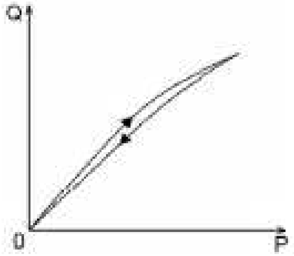
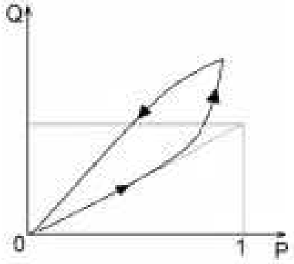
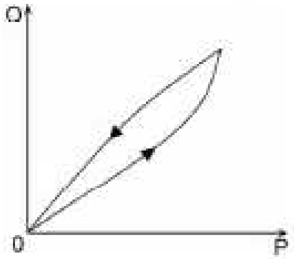
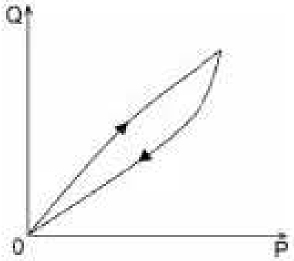
(a) *Laminar flow*: this flow is assumed to occur when the relationship between the specific flow versus pressure "Q/P" is approaching a straight line. In this case, the representative Lugeon value and the associated permeability coefficient, K (see "Appendix") can be estimated using the average of the five values.

(b) *Turbulent or transitory flow:* occurs when the graph of specific flow versus pressure is non-linear. If the rock is sound in the test section, this could be the result of head losses occurring during the flow processes. The representative Lugeon value for the maximum pressure (P_{max}) could be of smaller magnitude than those derived from the intermediate pressures and represents the value for the turbulent flow regime. This value of Lugeon is recommended for grouting absorption evaluation. To estimate the permeability coefficient, the use of the geometric average of the lower range of pressures (minimum or intermediate pressures) is the most appropriate.

(c) *Deformation (dilation)*: when the Lugeon values calculated from the increasing pressure stages are smaller than those calculated from the decreasing stages and the two minimum values corresponding to the first and the last pressures are approximately equal, temporary deformation of the rock mass maybe taking place. If ideal elastic behaviour occurs, the Lugeon values of increasing and decreasing pressure stages are equal. To evaluate grouting absorption, the representative Lugeon value obtained at the maximum pressure stage is recommended. The permeability coefficient, K, can be estimated from the lowest pressure stage or, in case of the linearity of flow versus pressure, from the geometric average of increasing pressure stages.

(d) *Wash-out of joint-filling materials or permanent deformation*: a progressive increase in the Lugeon values without a return to values recorded prior to the use of

Table 6 Interpretation of Lugeon test results based on the relationship between the flow rate Q (in ℓ/min) versus pressure P (in MPa) Modified after Houlsby (1976)

Flow regime and hydraulic behaviour	Relationship between flow rate Q (in ℓ/min) and pressure P (in MPa)	Description of the graph	Interpretation
Laminar flow		The graph is near linear. Water absorption is nearly equal in the increasing and decreasing stages of pressure; Lugeon values remain approximately equal at all stages	Lugeon value and permeability coefficient can be estimated using the average test results
Transitory or turbulent flow		Flow decreases when the pressure increases. The minimum Lugeon value is recorded at the maximum pressure stage	Lugeon value at the highest pressure is in the transitory or turbulent flow regime; estimation of the permeability coefficient should use the lowest or intermediate pressure stages
Deformation/dilation of joints		Initially, linear flow is observed before normal stress acting on existing joints is exceeded. The maximum flow will be reached with the maximum pressure. In the stages of decreasing pressures, the flow is higher or equal to that of the increasing pressure stages. The highest Lugeon value is observed with the highest pressures, due to the joint opening	Lugeon value at the lowest pressure stages or from the average of increasing pressure stages, if the slope of the graph is linear, should be used for permeability estimations. For the evaluation of groutability, the highest pressure stages should be used
Wash-out or erosion of joint-filling materials or permanent deformation		Increasing flow with non-linear increasing pressure; higher flow at decreasing pressure stages compared to the corresponding increasing stages. Lugeon values increase as the test proceeds. Joint infilling is progressively washed-out by the water under pressure	The highest Lugeon value occurs at the highest pressure. The minimum pressure stage (first stage) can be used for permeability estimations. The highest pressure stages should be used for groutability evaluations, based on the assumption of joint filling washing-out, replaced by cement slurry
Void or joint filling		Flow decreases as the test proceeds. Either non-persistent discontinuities are progressively being filled or other phenomena such as swelling occur	The highest Lugeon value occurs at the maximum pressure. The first pressure stage can be used to estimate permeability and the highest pressure stage is used for the evaluation of groutability

maximum pressure suggests a permanent *wash-out* of the joint-filling material or a permanent deformation of the rock, caused by excessive pressures during the test. For grouting estimations, the highest Lugeon value derived from the last injection/pressure stage can be used. To estimate the permeability coefficient K, the first pressure stage is recommended.

(e) *Void or joint filling*: a progressive decrease in the Lugeon value could suggest that some materials filling voids or joints may have been gradually loosened and transported during the test, filling some joints close to the zone of the test, or that the joints distant from the test interval are of limited extent. The highest Lugeon value is recommended for grouting absorption estimation. For permeability estimations, the first pressure stage would provide the most appropriate and representative values.

As a rule of thumb, estimations for the permeability coefficient should use the results obtained from the lowest pressure stages. For grouting predictions, the results from the highest stages of pressure are the most appropriate.

Some of the most commonly used techniques to estimate the equivalent isotropic hydraulic conductivity coefficient (K) based on Lugeon test results are shown in the "Appendix".

7.2 Factors Influencing the Execution of the Test and Interpretation of the Results

Planning of the Lugeon test should be based on geological surveys at the scale of the engineering work. The test intervals should be designed taking into consideration the information surveyed from the borehole logging or imagery, so that the interpretation of the test results can be made according to the characteristics of the joints appearing in each test interval.

The range of pressures to be applied should be planned according to the engineering structure to be built. Hydroelectric projects and tunnels are the most common type of engineering structures where the Lugeon test is performed. In these types of works, the depths of investigations are in general smaller than 100–200 m.

The selection of the maximum effective pressure may need to be directly related to the rock mass unit weight and to the depth of the structure.

If high accuracy is needed in the test results, smaller test intervals are recommended when trying to isolate a transmissive geological feature/joint in the test section to estimate the hydraulic conductivity of the isolated feature. This allows a better estimation of the permeability coefficient as shown by Cruz et al. (1982) and Cruz and Quadros (1983).

Geometrical parameters of the joints, such as orientation, spacing, aperture, roughness of the joint walls and length, have great influence on the test results. Nowadays, with the sophisticated imaging instrumentation able to survey the parameters of the joints inside boreholes, some of these parameters, such as orientation and spacing, can be statistically estimated with acceptable precision by means of dedicated software.

Aperture and roughness are the main governing parameters for flow in rock joints. These two parameters affect the head losses and consequently the flow regime used to interpret the graphs shown in Table 5. Many authors have demonstrated the influence of aperture and roughness based on laboratory experiments (Lomize 1951; Louis 1967; Rissler 1977b; Barton and Quadros 1997; Esaki et al. 1999). The first two authors listed above have used artificial non-mating fractures in glass and concrete. Parameters of influence in flow in rock joints and rock masses are also thoroughly described in Wittke (2014).

Interpretation of Lugeon test results using an isotropic permeability coefficient K, based on Darcy's law can be challenging, because the calculations are based on the length of the test interval which in general varies from 1.5 to 3 m, while the joints generally have sub-millimetric apertures. It is important to note that smaller intervals, allow more accurate results. When the rock matrix is almost impervious (e.g., granite, gneiss), it can lead to unrealistic permeability results unless the joints can be properly isolated in the test section (Sect. 4.4). Also, the calculation of the permeability coefficient is based on many simplified assumptions; one being that the flow obeys the Darcy's law, which presupposes a linearity between flow and pressure, which may not hold true.

Non-linearity has been proved by many researchers and the linearity assumed in the Darcy law is only valid in the lowest range of pressures (Sharp and Maini 1972; Maini et al. 1972; Zeigler 1976; Cruz and Quadros 1983; Raven and Gale 1985; Elsworth and Doe 1986).

The method proposed by Snow (1968) could be used to estimate the isotropic coefficient of permeability considering the statistics of the conductive and non-conductive joints in the test section. However, this method has been more applied in research projects than in the current practice of dam engineering. Much research in this area has been conducted in the underground research laboratories due to the need for high accuracy in the execution and interpretation of the test results.

Evaluation of groutability is one of the reasons to perform Lugeon tests. Therefore, it is worth noting that permeability and groutability are not always related. Groutability depends on the number and aperture of the rock joints and to a lesser extent on joint connectivity (far field grouting). Connectivity could be relatively less important due to the limited travel of the grout in most cases, except in zones of very high permeability. Head losses are high when the cement grout travels into the rock joints, contributing also to reduce the extension of the grouting, which is one of the reasons for using high pressures when pre-grouting is applied ahead of tunnels.

Barton et al. (1985) and Barton (2004, 2006) proposed a useful diagram based on Lugeon test results, using a modification of the Snow (1968) proposal. The purpose was to predict the necessary fineness of the grout (industrial grade, micro or ultrafine cements) based on the results of the Lugeon tests. This method, involving back-calculated hydraulic apertures converted to physical apertures using the joint roughness coefficient (JRC), is rather easy to apply in the field. The approximations used in this case assume that the physical apertures are larger than the conducting apertures due to roughness of fractures and rock contacts.

One of the main limitations of the Lugeon test is linked to the fact that the test results are valid only for a limited volume of the rock mass around the borehole. According to Bliss and Rushton (1984), the effect of a test performed in an interval of 3-m length is restricted to an approximate radius of 10 m around the borehole, which suggests that the permeability estimated from the Lugeon test is valid for a cylinder of rock limited by the length of the test interval and the radius given above.

Based on laboratory experiments reported by Quadros and Cruz (1995), the analysis of the effective hydraulic head versus the distance from the borehole walls also showed that the water pressures are quickly dissipated at small distances from the borehole walls. The experience has shown that this distance depends on the amount of flow, the flow regime and the Reynolds number (Rissler 1977a, b; Quadros and Cruz 1995). Only about 50% of the injection pressure may remain at 1.0 m of radius.

Guerra et al. (1968), Arhippainen (1970), Lancaster-Jones (1975) and Cruz et al. (1982) have discussed the existence of turbulent or transitory flow when performing the constant head tests and the differences in the relationship between flow versus pressure when the flow is laminar or turbulent. These authors also agree that the geometrical parameters of the joints have an important influence on the flow during the tests.

Due to the relatively small volume of the rock mass reached by Lugeon tests, extrapolations of results when desirable must be carefully made and based on a sound knowledge of the structural geology. Analytical solutions that rely on the assumption that a large portion of the rock mass is involved in the test should not be used. Therefore, the recommended practice is for an accurate planning of the borehole locations and selection of the intervals of testing, such that the results are representative of the geology at the site and of the hydraulic behaviour of the rock mass at the scale of the engineering work as well.

8 Notes and Recommendations

The following notes and recommendations are essentially practical and mostly deal with field activities and procedures:

1. It is highly recommended to perform Lugeon tests using automated data logging and recording equipment which eases the site activities, reduces the working time and provides more accurate results. If such equipment is not available, the effective pressure shall be calculated using the geometry of the assemblage, the depth of the ground water level and the head losses measured empirically at site with the same tubing used to conduct the water to the test intervals (diameter and length).
2. The use of straddle packers is recommended since it is an efficient way to save time and perform numerous tests sequentially after the borehole is totally drilled. Straddle packers shall be used in conjunction with pressure transducers to detect water leakages (even below the lower packer).
3. When weak zones or highly fractured rocks are encountered during the drilling, which can produce collapse of the hole, performing the Lugeon test as soon as possible is recommended, if required cement the concerned zone for stability, and resume the drilling after the test.
4. Most of the Lugeon tests are performed in vertical holes. In case of inclined boreholes, e.g., 30° vertical, the use of straddle packers after complete drilling of the borehole shall be restricted to good geological conditions to ensure a total stability of the hole and to prevent loss of testing equipment.
5. Packer(s) shall be properly set to avoid fractured zones and prevent water leakage. If it is not possible to have both packers sealed in unfractured rock when a straddle packer is used, the length of the test interval shall be changed (lengthened or shortened), so the two packers are sealed in compact rock sections.
6. Prior to performing a Lugeon test, the number of fractures appearing in the test interval needs to be checked based on the use of borehole imagery (acoustic and/or optical televiewers) or the observation of cores. This can help one choose the proper test intervals and provides more accurate analysis during the interpretation of the test results. Considering that the test sections are much larger than the apertures of the individual fractures, the hydraulic conductivities will be underestimated. Therefore, the shorter the length of the test interval, the greater accuracy will be obtained when performing a Lugeon test.

7. The pressure stages applied in the Lugeon test depend on technical, practical and empirical factors. The maximum effective test pressure should be calculated after the assemblage of the equipment, before performing the Lugeon test. The maximum effective pressure can be defined considering an average specific weight of about 2700 kg/m^3 for the rock mass, or less depending on the local geological conditions.
8. Selection of the gauge pressure (and hence that of test section measured by a transducer) depends on the effective hydraulic head on the test section and the overburden stress/pressure (plus friction losses). Determination of the effective hydraulic head on the test section may depend on several factors including measured overnight water levels during drilling, depth of casing and records from nearby piezometers, and may not be reflected as a simple measure of the water column in the drill string.
9. A proper evaluation of Lugeon test results requires the values to be correlated with the geological structure. The test interval should be designed based on the information from the borehole log or borehole imagery, so that results can be related to the characteristics of the joints appearing in the test interval. The test and the range of pressures to be used should be planned according to the engineering structure to be built, such as a dam or a tunnel.
10. Interpretation of Lugeon test results through the estimation of an isotropic permeability coefficient K, based on Darcy's law, considers the linearity of flow versus pressure and a laminar flow regimen, which could be observed only in the lower stages of pressures. This coefficient should also be representative of the flow through rock joints having, in general, submillimetric apertures and not of the flow through the whole test interval having, in general, some 1.5–3 m length.
11. The method proposed by Snow (1968) could be used to estimate the isotropic coefficient of permeability considering the spacing and conductive aperture statistics in the test section. A graph considering the relationship between spacing (S) and the hydraulic aperture (e) based on the cubic network model from Snow is proposed by Barton (2006), which is useful for taking to the field due to the correlations proposed by the author (Fig. 4, in "Appendix").
12. Roeper et al. (1992) discussed the applicability of the Lugeon test to hydrogeological investigations. They also recommended that the representative Lugeon values are those estimated at low pressures, since the groundwater flow occurs under natural hydraulic gradient.

Acknowledgements The authors wish to thank all reviewers for their constructive comments on the manuscript versions with special thanks to Resat Ulusay (Hacettepe University) and Christophe Vibert (Stucky, Switzerland). They also extend their gratitude to Nick Barton (Barton & Associates) for his support and valuable contribution regarding the 3D flow in rock masses.

Compliance with Ethical Standards

Conflict of interest The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no financial support for this work that could have influenced its outcome.

Appendix

Estimation of the equivalent isotropic coefficient of permeability (hydraulic conductivity K) and estimation of the transmissivity (T).

General Considerations

Available equations and techniques to estimate the permeability/hydraulic conductivity coefficient (K) based on Lugeon test results, in general, are based on Darcy's law and consideration of a laminar flow regimen. The use of the diagrams shown in Table 6 allows evaluation of the flow regime from the test results. The recommended practice is the use of the lowest stage of pressures when the objective is the evaluation of the rock mass permeability. The higher stages of pressure are used when the objective is to estimate grouting absorption. Diagrams obtained from the test are used to select the best linear relationships and the average values are to be used in the formulae.

Due to the specific difficulties related to the application of the flow laws valid for rock fractures (Louis 1967; Rissler 1978; Quadros 1982), the equivalent isotropic hydraulic conductivity coefficient K is used in the current practice to interpret results of Lugeon test. If the characteristics and number of the discontinuities in the test section are known, some of the main features contributing to the flow might be deduced.

Estimation of the Equivalent Isotropic Permeability or Hydraulic Conductivity Coefficient (*K*) and Estimation of the Transmissivity (*T*) Based on the Lugeon Test Results

(a) Method proposed by Franciss (1970)

The method proposed by Franciss is based on Babouchkine (1965) for the analysis of flow in wells where the test

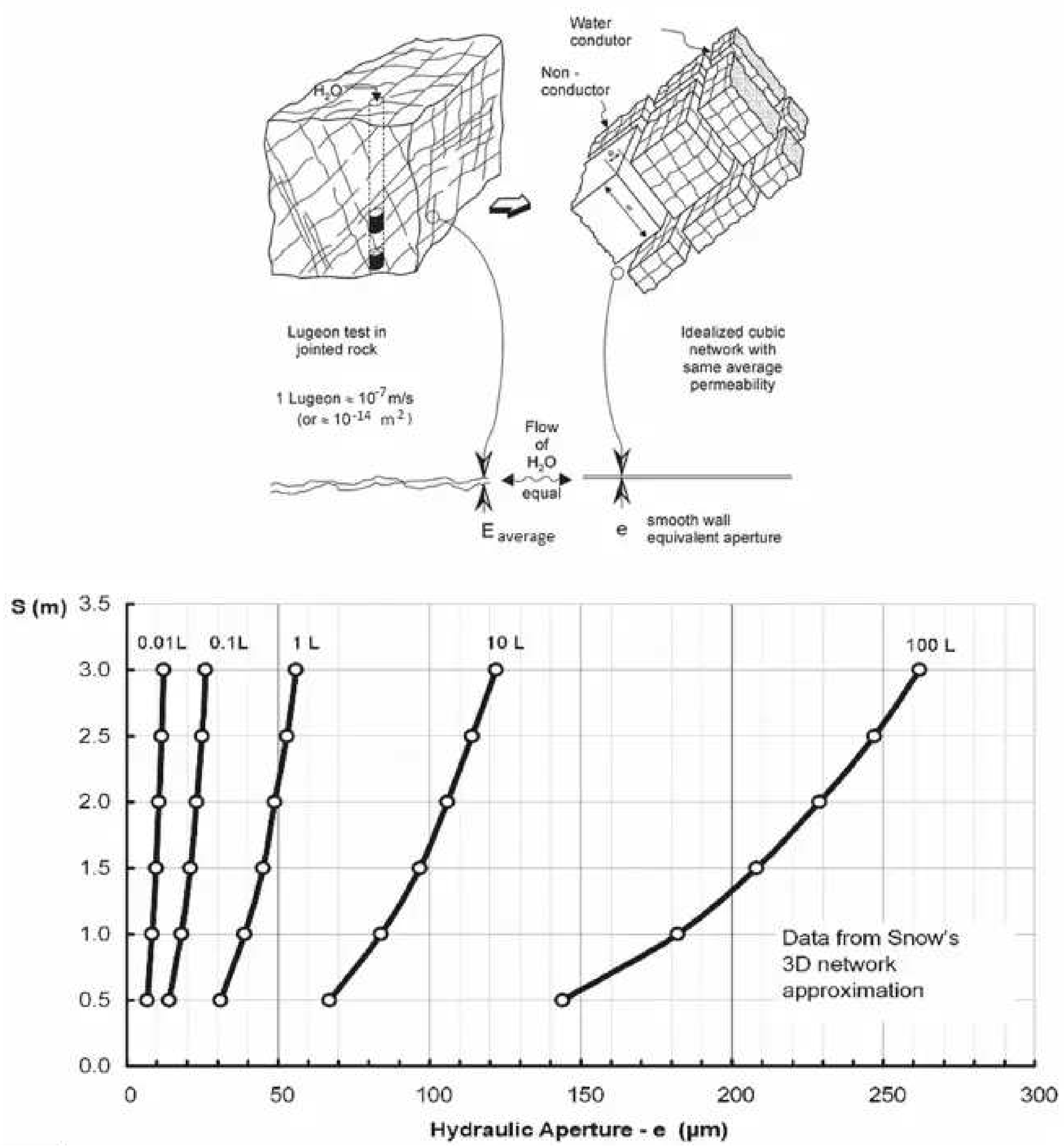


Fig. 4 Representation of a jointed rock mass as a cubic network of conducting joints following Snow (1968) and Barton et al. (1985) and graph for the estimation of the Lugeon value from hydraulic aperture (*e*) and spacing of fractures (*S*) from Barton (2004)

section is at a certain distance from the water table (which is the general practice). According to the author, the equivalent hydraulic conductivity coefficient can be estimated using the following equation valid for laminar flow (refer Table 6):

$$K = \frac{Q}{2\pi HL} \ln\left[\frac{0.66L}{D/2}\right]. \tag{5}$$

(b) Use of Thiem's equation to estimate the transmissivity *T* (Thiem 1906)

The transmissivity T can be related to the permeability/hydraulic conductivity (K) in the test interval through the expression $K = \frac{T}{L}$ and the use of a radial flow model, where L is assumed to have the following two meanings:

(i) L is equal to the length of the test section. In this case, a general porous media approach is used to interpret the test results. This hypothesis considers that the rock matrix is pervious.

(ii) $L = e$, where e is the equivalent aperture of the joint (or joints) appearing in the test interval. In this case, a radial flow model is used to evaluate the transmissivity around the test section and the rock matrix is assumed to be impervious.

According to Thiem (1906),

$$T = \frac{Q \ln \left[\frac{R}{r}\right]}{2\pi P}. \quad (6)$$

In Thiem's equation (Eq. 6), the radius of influence R is affected by many factors, and among them:

- The hydraulic conductivity of the test section which is deeply dependent on the hydraulic conductivities of the rock joints;
- the interconnectivity of the joints;
- the hydraulic boundaries;
- the pressures applied during the test.

As this parameter occurs within a natural logarithmic function, one can use an approximation. For example, for a borehole in HQ diameter (95.3 mm, $r = 0.0477$ m) considering R values of 1, 5, 10 and 100 m, the value of Ln (R/r) would be, respectively, 3.04 m, 4.61 m, 5.3 m and 7.65 m. Hence, the value of R attributed to Eq. 5 will have only a small effect on the estimated value for the transmissivity, T, using Eq. 6 and the Lugeon test results.

(c) Practical rule proposed by Nonveiller (1989)

A simple relationship between 1 LU and K is proposed by Nonveiller (1989), for a test interval of 5-m length, where r is the radius of the borehole

$$K = 1.5 \times 10^{-5}\,\text{LU (in cm/s)}, \quad \text{when } r = 4.6\,\text{cm},$$

$$K = 1.3 \times 10^{-5}\,\text{LU (in cm/s)}, \quad \text{when } r = 7.6\,\text{cm}.$$

As this relation considers only the length of the test interval, its use should be restricted for rough estimates.

(d) Representation of a jointed rock mass as a cubic network of conducting joints, following Snow (1968) and Barton et al. (1985) (Fig. 4).

Note that the e versus S curves for specific Lugeon values are derived from the given equation which assumes that flow is possible through two of the three sets, or through lesser fractions of all three assumed sets as the gradient rotates around the cube. The next step is to convert e to E (mechanical/physical aperture) using the joint roughness coefficient JRC, then test that $E > 4\ d_{95}$ of the cement particles and choose grout type and injection pressure accordingly.

The hydraulic aperture can be estimated using the following formula:

$$e \approx \left(L \times 6 \times S \times 10^{-8}\right)^{1/3} \quad (7)$$

In this equation, the hydraulic aperture (e) and the mean fracture spacing (S) are in mm. Each of the above apply to a given structural domain, to the whole borehole, or to a specific rock type (Barton 2004).

References

Arhippainen E (1970) Some notes on the design of grouted curtains on the basis of water-pressure tests. In: Proceedings in international congress on large dams, Montreal, pp 137–145

ASTM D4630-96 (2008) Standard test method for determining transmissivity and storage coefficient of low-permeability rocks by in situ measurements using the constant head injection test

Babouchkine V in Bogomolov G (1965) Hydrogéologie et notions de Géologie d´Ingénieur. Editions de la Paix, Moscou

Banks DC (1972) In situ measurements of permeability in basalt. In: Proceedings in international symposium on percolation through fissured rock, Stuttgart, 1972. IAEG/ISRM, Deutsche Gesellschaft, T1-A, pp 1–6

Barton N (2004) The theory behind high pressure grouting. Tunn Tunn Int, Sept: 28–30, Oct: 33–35

Barton N (2006) Integrating Q-logging with seismic refraction, permeability, pre-grouting, tunnel, cavern support needs and numerical modelling performance. Keynote lecture, Hong Kong, Institute of Engineers, Geotechnical Division Annual Meeting, May 2006

Barton N, Quadros EF (1997) Joint aperture and roughness in the prediction of flow and groutability of rock masses. Int J Rock Mech Min Sci Geomech Abstr 34:252–267

Barton N, Bandis S, Bakhtar K (1985) Strength, deformation and conductivity coupling of rock joints. Int J Rock Mech Min Sci Geomech 22(3):121–140

Bliss C, Rushton KR (1984) The reliability of packer tests for estimating the hydraulic conductivity of aquifers. Q J Eng Geol Hydrogeol 17:81–91

Cruz PT, Quadros EF (1983) Analysis of water losses in basaltic rock joints. In: Proceedings on 5th international congress on rock mechanics, melbourne, B, pp 119–123

Cruz PT, Quadros EF, Correa FD, Marrano A (1982) Evaluation of opening and hydraulic conductivity of rock discontinuities. In: 23rd symposium on rock mechanics (USRMS), Berkeley, pp 25–27

Elsworth D, Doe TW (1986) Application of non-linear flow laws in determining rock fissure geometry from simple borehole pumping tests. Int J Rock Mech Min Sci 23(3):233–244

Esaki T, Du S, Mitani Y, Ikusada K, Jing L (1999) Development of a shear-flow test apparatus and determination of coupled properties for a single rock joint. Int J Rock Mech Min Sci 36:641–650

Francis FO (1970) Contribution à l'étude du mouvement de l'eau à travers les milieux fissurés. Thèse de Doctorat: Faculté des Sciences de l'Université de Grenoble

Gringarten AC (2008) From straight lines to deconvolution: the evolution of the state of the art in well test analysis. In: 2006 spe annual technical conference and exhibition, publisher: Society of Petroleum Engineers, pp 41–62. ISSN: 1094-6470

Guerra JR, Weyermann W, Mota OS (1968) Le caractère de la percolation d'une roche d'après les observations préalables faites pour le projet d'écran d'étanchéité. In: Proceedings in 9th international congress on large dams, Istanbul, vol 1, pp 109–122

Houlsby AC (1976) Routine interpretation of the Lugeon water-test. Q J Eng Geol 9:303–313

Houlsby AC (1990) Construction and design of cement grouting: a guide to grouting in rock foundations. Wiley, Hoboken

Hvorslev MJ (1951) Time lag and soil permeability in ground-water observations. U.S. Army Corps of Engineers, Waterways Experiment Station, Bulletin No. 36

ISO 22282-3:2012(E) (2012) Geotechnical investigation and testing—geohydraulic testing—part 3: water pressure tests in rock

Lancaster-Jones PFF (1975) The interpretation of the Lugeon water-test. Q J Eng Geol 8:151–154

Lomize G (1951) Fluid flow in fissured formations (in Russian). Gosenergoizdat, Moscow, in Louis, 1967

Louis C (1967) Étude des écoulements d'eau dans les roches fissurées et de leur influence sur la stabilité des massifs rocheux. Bulletin de la Direction des Études et Recherches, Paris 3:5–132 **(Thèse Doct. Université Karlsruhe)**

Lugeon M (1933) Barrages et Géologie. Dunot, Paris

Maini Y N T, Noorishad J, Sharp J (1972) Theoretical and field consideration on the determination of in situ hydraulic parameters in fractured rock. In: Proceedings in ISRM international symposium on percolation through fissured rock, Stuttgart

Nonveiller E (1989) Grouting—theory and practice. Elsevier, Amsterdam

Oliveira AMS, Silva RF, Ferreira JJ (1975) Water pressure tests (in Portuguese). Brazilian Association of Engineering Geology (ABGE), São Paulo, Bulletin No. 2

Pearson R, Money MS (1977) Improvements in the Lugeon or packer permeability test. Q J Eng Geol 10(3):221–239

Quadros EF (1982) Study of the flow characteristics in rock fractures. Polytechnical School of São Paulo University, Department of Civil Engineering **(in Portuguese)**

Quadros EF, Cruz PT (1995) Water pressure tests and flow in single rock fractures. In: Proceedings in 35th U.S. symposium, Reno, Nevada. Balkema, Rotterdam, vol II, pp 901–906

Quinn SA, Liss D, Johnson D, van Wonderen JJ, Power T (2012) Recharge estimation methodologies employed by the Environment Agency of England and Wales for the purposes of regional groundwater resource modelling. In: Shepley MG, Whiteman MI, Hulme PJ, Grout MW (eds) Groundwater resources modelling: a case study from the UK, vol 364. Geological Society, London, pp 65–83 **(special publications)**

Raven KG, Gale JE (1985) Water flow in a natural fracture as a function of stress and sample size. Int J Rock Mech Min Sci Geomech 22:251–261

Rissler P (1977a) Determination of the permeability of jointed rock. Institute for Foundation Engineering, Soil Mechanics, Rock Mechanics and Water Ways Construction, RWTH Aachen, vol 5

Rissler P (1977b) Empfehlung Nr. 9 des Arbeitskreises 19 – Versuchstechnik Fels - der Deutschen Gesellschaft für Erd- und Grundbau e.V. Wasserdruckversuch in Fels, Bautechnik 194(4):112–117

Rissler P (1978) Determination of water permeability of jointed rock. Aachen, RWTH University, Institute for Foundation Engineering, Soil Mechanics, Rock Mechanics and Waterways, p 149

Roeper TR, Soukup WG, O'Neill RL (1992) The applicability of the Lugeon method of packer test analysis to hydrogeologic investigations. In: Focus conference on eastern regional ground water issues. National Ground Water Association Dublin, pp 661–671

Sharp JC, Maini YNT (1972) Fundamental considerations on the hydraulic characteristics of joints in rock. In: Proceedings in international symposium on percolation through fissured rock, Stuttgart, IAEG/ISRM, Deutsche Gesellschaft, T1F, pp 1–15

Snow DT (1968) Rock fracture, spacings, openings and porosities. J Soil Mech Found Div Am Soc Civ Eng 5736:73–91

Thiem G (1906) Hydrologische method. Gebhardt, Leipzig

Wittke W (2014) Rock mechanics based on an anisotropic jointed rock model. Ernst & Sohn GmbH & Co. KG, Berlin

Zeigler TW (1976) Determination of rock mass permeability. Technical report S-76-2. US Army Engineer Waterways Experiment Station. Vicksburg, MS