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Using the Lugeon test in tunnelling groundwater control - analysis and interpretation

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ABSTRACT: Groundwater control in tunnelling projects is one of the critical elements in tunnel design and construction. This aspect can often drive the entire tunnel concept. The Lugeon or packer test is commonly used to characterise the potential for groundwater inflow into rock tunnels and it is an essential part of geotechnical investigations for tunnel projects. However, the specification, documentation and interpretation of this seemingly simple test has many pitfalls. The paper describes key aspects of Lugeon testing for tunnel projects and provides recommendations for carrying them out. The paper also describes interpretation of these tests and their use in designing groundwater control for tunnel projects.

1 DISCONTINUITIES AND GROUNDWATER FLOW IN A ROCK MASS

1.1 *Types of discontinuities*

Discontinuities (the generic term) can be classified into the categories of bedding, foliation and fractures based on the origin of the discontinuity. Bedding occurs during the sedimentation process while foliation is caused by recrystallisation under heat and pressure, generally normal to the major principal stress at the time of the metamorphism. Fractures are caused by applies stress exceeding the rock strength, either due to tension or shear.

While the processes described above may lead one to suspect that discontinuity spacing is quasi-regular, the conclusions of Priest and Hudson (1976) and Priest (1993) is that the distribution of total discontinuity spacings is modelled by the negative exponential probability density distribution for many situations.

1.2 *Groundwater flow in the rock mass*

Most fractured rocks have very low primary porosity and groundwater is contained within, and moves through, secondary features such as joints and fractures. Krásný and Sharp (2007) provide a comprehensive overview of general subject of groundwater in fractured rocks. Other important general references for fractured rock aquifers include Priest (1993), Cook (2003), Singhal and Gupta (2010), Gustafson (2012) and Sharp (2014).

1.3 *Groundwater flow in an individual discontinuity*

In theory, the transmissivity of a discontinuity is described by the well-known cubic law for the idealised situation of flow in an aperture of smooth parallel walls is:

$$T = \frac{\rho g}{12\mu} \cdot b^3 \qquad (1)$$

where b is the aperture, ρ and μ are the density and dynamic viscosity of water and g is the acceleration due to gravity. Transmissivity has units m^2/s.

Figure 1 shows a series of water-bearing bedding planes daylighting on a slope.

Figure 1. Limestone with bedding planes, Dolomites, Italy.

Each of the beds of limestone are supported on the bed below; there is transmission of vertical force across the bedding planes. However, each of the planes is also transmitting water sub-horizontally. The only way that these two processes can occur simultaneously is if elements of contact and elements of separation occur in the planes (Lombardi 2003). Refer Figure 2.

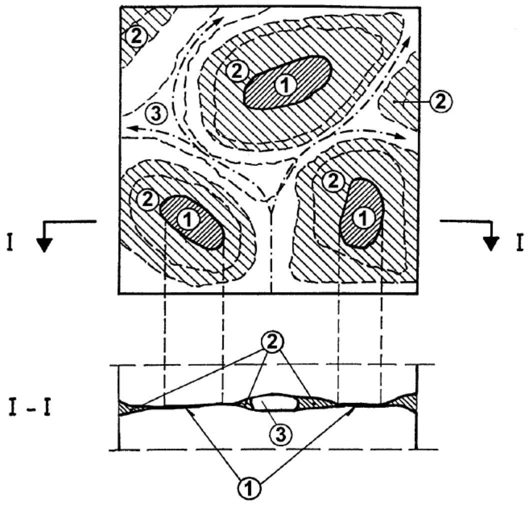

Figure 2. Lombardi conceptual model of a discontinuity (Lombardi 2003). ① full contact areas, ② areas with bound water and ③ areas where water can flow.

2 DATA AND DATA ANALYSIS

2.1 *Preliminaries*

An excellent introduction to data analysis is included in Kitanidis (1997) – Chapter 2. The pre-requisites for data analysis should be obvious:

- The data is drawn from a single population, so that the analysis can provide a useful prediction within that population. For example, if the tunnel passes through completely different materials, it makes little sense to mix data from each material; the analysis will be of low value.
- Similarly, even if within a single geotechnical domain, it makes little sense that the results of different tests are mixed.
- Finally, the data should be a random sample, rather than a "selected" sample. (In some cases this is inevitable; UCS tests cannot be performed on broken or crushed rock core – UCS test are inevitably skewed towards the stronger end of rock strength.

A common practice in geotechnical investigations of the past has been to review the core to locate a few of the largest and apparently wettest fractures in the borehole and then to adjust the packer positions to the least fractured area to avoid packer leakage. A dataset of tests selected in this manner will not be amenable to data analytical methods, for two reasons:

- Obviously, this process of selection is strongly skewed to sample only the high end of the population.
- Less obviously, but still important, different lengths of packer test are in fact different tests, because the length of a packer test is associated with the variability; short packer tests will vary more than long tests – the long test tends to average out the results.

2.2 *Censored data sets*

It is common for data sets to have missing values for various reasons:

- Measurement techniques may fail or may not be accurate at very low values. In the particular case of the packer test, flow meters may not register or be accurate at very low values of flow, or the flow may be indistingushable from leakage.
- Measurement techniques may fail or may not be accurate at very high values. In the particular case of the packer test, it may not be possible to provide sufficient flow down a hose down the borehole.

In both cases described above, the tests have meaning, even if they do not have a defined value. For example, each test with very low flow indicates tight rock, whereas each test with very high flow indicates the opposite. Techniques exist for dealing with censored data which respects the existence and meaning of the tests although the values are unknown.

2.3 *Quantities with and without finite variance*

There are many quantities in nature and engineering in which the values cluster around a mean value. While the individual quantity in question may not necessarily be normally distributed, the Central Limit Theorem says that larger samples (usually larger than 30) of randomly chosen values will be normally distributed. Most undergraduate courses in statistics describe methods for quantities where the Central Limit Theorem holds. If the sample size is not large enough, special techniques are used (Student's "t" distribution is substituted for the normal distribution).

There are some quantities in nature and engineering for which the Central Limit Theorem does not apply. Mathematically, this is where the population variance is not finite.

Taleb (2007) provides an example showing the difference between these cases. An example where the Central Limit Theorem applies is that of human weight. Assume a stadium is full of (say) 100,000 people and the mean weight of the spectators is measured as (say) 75 kg. Pick a person at random and remove them, replacing with the heaviest person in the world and then recalculate the mean. According to Wikipedia, the heaviest person who ever lived was was 635 kg, so the mean weight of the stadium will increase by 5.6 grammes, a negligible amount. However, substituting for the finanicial worth of the spectators, let's assume that the mean turns out to be (say) $750K. Replacing a person at random with one of the multi-billionaires of our time (say $500B), the mean increases by $5M, a very significant increase. The distribution of net worth is well described by a power law, as famously proposed by Pareto. Taleb warns against using techniques, developed where the Central Limit Theorem applies, to situations where it does not apply.

From Adamic and Huberman (2002): "Many man made and naturally occurring phenomena, including city sizes, incomes, word frequencies, and earthquake magnitudes, are distributed accroding to a power-law distribution. A power-law implies that small occurrences are extermely common, whereas large instances are extremely rare."

2.4 *Distributions for discontinuity characteristics*

Table 1 shows distributions proposed for various characteristics associated with discontinuities

Table 1. Distributions proposed for discontinuity characteristics

Characteristic	Distribution	Reference
Transmissivity of individual discontinuities	Pareto distribution	Gustafson and Fransson (2005)
Spacing of discontinuities	Negative exponential distribution	Priest and Hudson (1976)
Number of discontinuities between packers	Negative binomial distribution	Kozubowski et al (2008)
Packer test results	Log-normal distribution	Raymer (2001), Raymer and Maerz (2014)

There are several practical conclusions that arise from Table 1:

- The Pareto distribution is an implementation of the power law. If a packer test is the sum of the transmissivities of a number of discontinuities, the Pareto distribution means that most of the transmissivity is coming from only a very few of them, most likely from one only.
- The Central Limit Theorem does not apply to sums of transmissivities – if it did, the distribution of packer tests would be normally distributed. However, if the sum includes enough samples (in this case discontinuity transmissivities), the analogy of the Central Limit Theorem for the power law suggests the log-normal ditribution.
- Kozubowski et al (2008) study packer tests simulated by combining the Pareto distribution for individual transmissivities with the negative binomial distribution for the number of discontinuities, and show that the log-normal distribution fits the results better when the packer tests are longer, i.e. there are enough fracures in the packer test length for the log-normal distribution.

3 THE PACKER (OR LUGEON) TEST

3.1 *History and general usage*

Lugeon (1932) is credited with the test for water absorption in a borehole. His paper of 1932 includes a diagram of test results for the planning of curtain grouting for the Sarrans dam. Figure 3 shows the diagram in full and a magnified snip of the legend. Note that the tests are all of the same length and not "selected"; rather they are sequentially located.

Translating the legend in Figure 1 loosely, the units of the test are "absorption of water per metre of borehole in litres per minute for an overpressure of 10 kg/cm^2." Modern sources substitute the overpressure as 1 MPa = 10 bar, which is approximately equal to 10 kg/cm^2.

Modern standards for running the test include ASTM D4630-96, ISO 22282-3:2012(E), and the ISRM suggested method by Vaskou et al. (2019). Papers describing the theory and practice of the test include Houlsby (1976 and 1990), Pearson and Money (1977), and Quiñones-Rozo (2010). Vaskou et al. (2019) describe the history of the test in detail and make the important point that, while other hydrogeological tests are designed for ground with a primary porosity, the packer test is more specifically used for fractured rock masses.

The ISO standard defines the test unit to be "Lugeon". Vaskou et al propose "LU". (The ASTM standard does not refer to the Lugeon unit at all.) For this paper, the nomenclature of "Lugeon" will be used, or in abbreviation, "Lu".

If the 1 MPa pressure is converted to 100 m of water head, the possibility exists of a direct conversion to m/s, with 1 Lugeon = 10^{-3} m^3 / (60 s x 100 m x 1 m) = 1.667 x 10^{-7} m/s. This paper argues against adopting this conversion for two reasons:

- There are many methods for converting Lugeon test results to hydraulic conductivity with results in units of m/s but with factors different to the value above. There is a significant possibility of confusion.
- As will be argued further, it makes little sense in converting individual packer tests to a hydraulic conductivity as if the local fractured rock mass was an isotropic Darcy media.

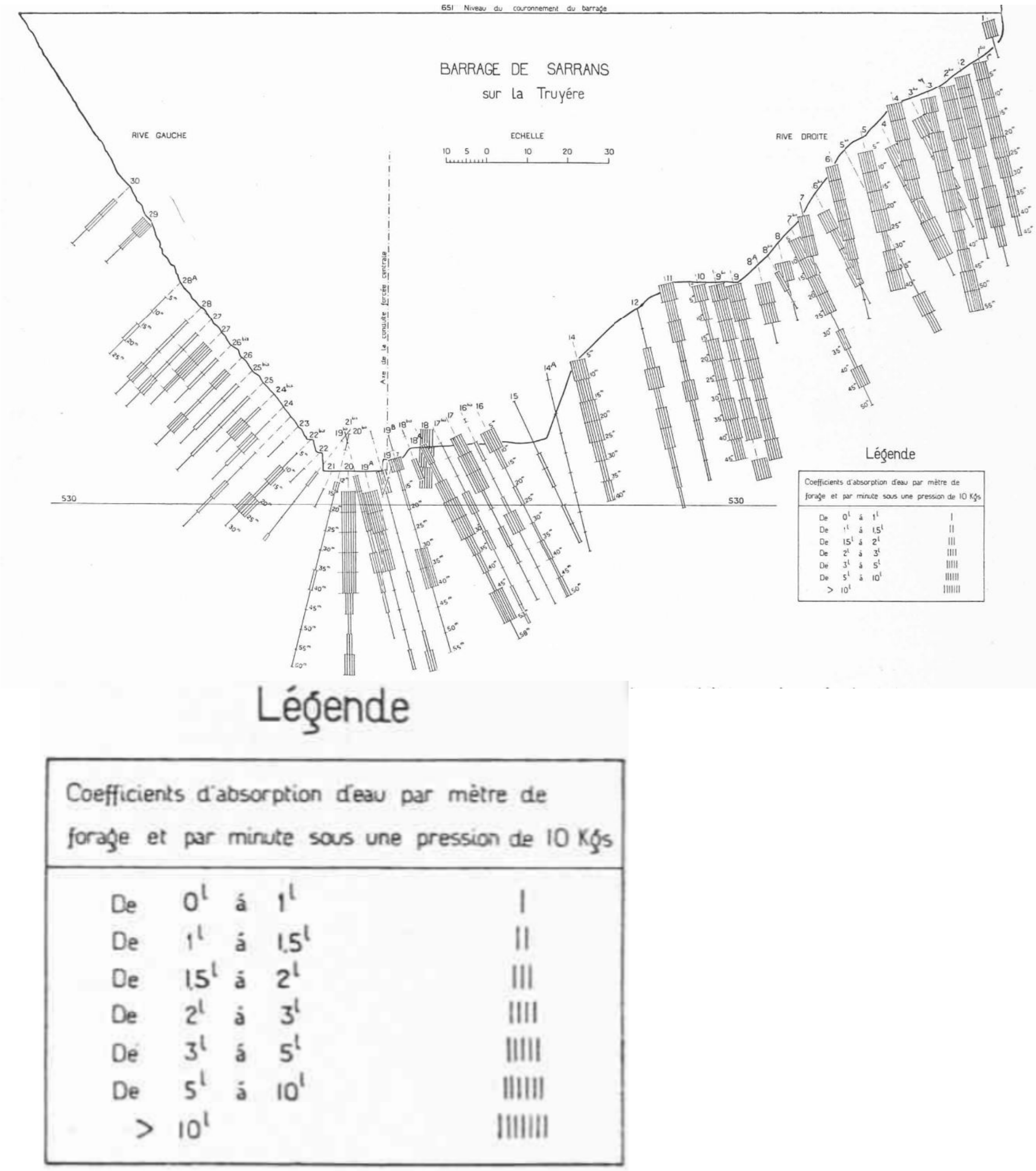

Figure 3. Diagram in Lugeon (1932), with detail enlarged.

The Lugeon test has remained in use because it is closely aligned to practical uses. Speaking generally for both tunnels and dam foundations, values around 1 Lugeon represent tight rock, which in most cases will not require treatment in that local area. Values above 10 Lugeon almost certainly will require treatment. The Lugeon test is also relatively cheap to conduct in conjunction with cored boreholes.

The Lugeon test is usually carried out in five stages, starting and ending with a lower pressure, and then progressing up and down again in pressure. In perfect theoretical conditions, there should be a linear relationship between the flows measured at the pressures. Houlsby (1976) describes the interpretation of the results when the linear relationship is not seen.

3.2 *Quantitation limits*

While water absorption in a borehole can vary over many orders of magnitude, there are practical limitations on the accuracy of the test over a subset of this range.

As described above, at the lower end of the test range, small flows cannot be measured accurately and may be indistinguishable from leakage in the system. At the upper end of the test range, there are practical limitations on the delivery of large flows of water to the test. Raymer (2001) calls these limits the Lower and Upper Quantitation Limits (LQL) and (UQL). Understanding that these limits exist is key to understanding the packer test.

Raymer suggests typical values for these, with recommended values:

- LQL = 0.1 Lugeon
- UQL = 50 Lugeon

As will be seen below, the analysis method proposed by Raymer (2001) is not sensitive to these values; the user may vary these values and return similar results. Note that in Figure 3, Lugeon implicitly adopts an LQL and UQL.

3.3 *Direct conversion to hydraulic conductivity?*

Many authors, including the international standards, suggest various formulae or methods for directly converting a packer test result to a hydraulic conductivity. A commonly quoted formula is from Moye (1967) which assumes cylindrical flow in an isotropic Darcy material and derives the following for the equivalent hydraulic conductivity K:

$$K = \frac{Q}{2\pi \cdot L \cdot \Delta h} \cdot \left[1 + \ln\left(\frac{L}{2 \cdot r_w}\right)\right] \quad (2)$$

with flow Q in a borehole radius r_w, length between packers L and overpressure (expressed as a head) of Δh.

Gustafson (2012) provides an alternative formula:

$$K = \frac{Q}{2\pi \cdot L \cdot \Delta h} \cdot \ln\left(\frac{L}{r_w}\right) \quad (3)$$

As discussed below, the correct viewpoint is to consider individual packer tests as part of a statistical population with an effective hydraulic conductivity resulting from analysis of all of the tests.

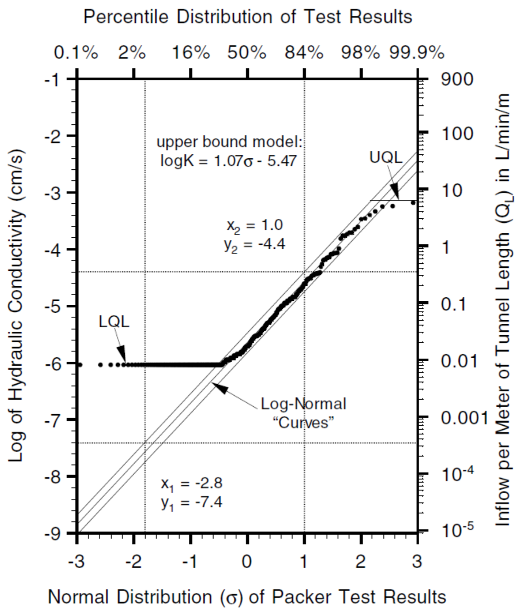

Figure 4. Raymer plot for a set of packer results (from Raymer 2001)

3.4 *Raymer analysis*

Raymer (2001) describes a graphical technique for fitting censored data to the log-normal distribution. The procedure is to consider all tests, including those where the result is expressed as either “no flow” or “flow too small to measure” (which are assigned the value of the LQL).

Figure 4 shows the Raymer plot of a typical set of packer tests (from Raymer 2001). It can be seen from Figure 4 that the result is insensitive to the choice of LQL and UQL. The fitted line is to a log-normal distribution, with an intercept and slope. Due to the use of the base 10 log, the parameters estimated for the log-normal distribution need to be adjusted as follows:

$$\mu = ln(10) \cdot intercept \quad (4)$$

$$\sigma = ln(10) \cdot slope \quad (5)$$

Note that the parameters (μ, σ) are not the mean and standard deviations, but are the parameters of the log-normal distribution:

$$p_x(x) = \frac{1}{\sqrt{2\pi} \cdot \sigma \cdot x} \cdot \exp\left[-\frac{(\ln(x) - \mu)^2}{2 \cdot \sigma^2}\right] \quad (6)$$

4 PRESENTATION AND USAGE OF DATA

4.1 *Presentation of the data*

From the parameters μ and σ, the following can be calculated:

- arithmetic mean: $\exp\left(\mu + \frac{\sigma^2}{2}\right)$
- median (= geometric mean): $\exp(\mu)$
- mode: $\exp(\mu - \sigma^2)$
- variance: $[exp(\sigma^2) - 1] \cdot \exp(2\mu + \sigma^2)$

What does not make any sense, but is frequently seen, is to calculate the mean and standard deviation using the arithmetic. The conventional calculation of the mean and variance of log-normal data, even when the data is not censored, is known to be highly unstable, because the data sets are dominated arithmetically by the highest values.

When the data is censored, there is no excuse to attempt to calculate the mean and standard deviation using the conventional formulae – the results must be meaningless.

4.2 *Use of the analysis*

Estimation of the effective hydraulic conductivity of the rock mass: Parsons and Raymer (2024) provide a comprehensive discussion of this topic, based on the parameters (μ, σ) derived from a Raymer analysis.

Estimation of apertures: If the number of fractures is recorded with the packer test results, it is possible using Fransson’s method (Fransson 2002) to estimate the parameters of the Pareto distribution, and therefore to estimate the ditribution of the aperture values.

Probing and grouting: Asche and Smith (2013) provide a method for calculating the probability that probe triggers are exceeded during probing and pre-excavation grouting for tunnels.

5 CONCUSIONS AND RECOMMENDATIONS

The following recommendations are provided:

1. Packer tests should be randomly selected, or what is effectively similar, to conduct tests head-to-tail sequentially up the borehole,
2. Packer tests should all be the same length,
3. The proposed constant length is 5 m so that the packer test represents the sum of enough transmissivities that the log-normal distribution is a reasonable fit.
4. The fracture count between the packers is routinely recorded with the packer test result
5. The Packer test result is retained in Lugeon values rather than attempting to ascribe a fictitious hydraulic conductivity value to individual test results
6. The tests are analysed by the Raymer (2001) or similar method which correctly accounts for censored data
7. The results are reported as the parameters μ and σ with further calculations based on those values. Arithmetic methods should never be used on the raw data.

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