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Grout curtain efficiency through permeability tests

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ABSTRACT: In the design of grouting curtain projects, various factors must be considered, including depth definition, number of lines, projection axis, pressure-volume methodology, grout type, and well inclination. However, one of the most relevant parameters is to define what is the permeability reduction due to injection. This parameter, through infiltration analysis, allows estimating variables such as the water table level, flow rates, hydraulic gradients, subpressures, among others, which influence structure design. This study assesses injection efficiency based on the background of several construction projects carried out on tailings dam walls. The determination of injection efficiency is closely linked to the development of Lugeon tests conducted before and after the injection curtain. The results of over 300 Lugeon tests are analyzed for this purpose.

KEYWORDS: Grout curtain, Lugeon test, permeability, cement-bentonite, conventional method

1 INTRODUCTION.

Ensuring the stability and environmental control of dam walls or tailings dam walls largely depends on the foundation soil conditions. In this context, grout injection into the rock emerges as a vital technique to control subsurface infiltrations and, in some cases, to consolidate and reduce the potential for internal erosion.

To verify the effectiveness of injection, the development of permeability tests using Lugeon tests, demonstrating measurements before and after injection, provides the best opportunity to visualize and evaluate these outcomes (Warner 2004).

The Lugeon test or Packer Test (Lugeon 1933) relies on measuring the water flow absorbed by the rock through its cracks and pores over a specific length and period of time. The Lugeon Unit (LU) is defined as the amount of water absorbed over one meter of borehole length, within one minute, at an effective pressure of 10 kg/cm².

During the course of an engineering project, the methodology for conducting the test involves carrying out 5 to 9 stages of hydraulic loading, each lasting 10 minutes. This practice allows for the examination of phenomena such as dilation, laminar flow, turbulent flow, clogging, among others, to adjust and calibrate test results. However, during the grout curtain construction phase, the testing methodology is often simplified to fewer loading stages, sometimes even just one.

The relationship between Lugeon Unit and hydraulic conductivity is commonly expressed as 1 LU = $1.3 \cdot 10^{-5}$ cm/s (Shibata 1981).

2 EFFECTIVENESS OF GROUT CURTAIN THROUGH PERMEABILITY TESTING

2.1 *Literature Review*

Various bibliographic sources provide estimates of the effect of cement grout injections on rock permeability reduction:

Power (2007) drawing on previous studies, suggests that with efficient techniques, injection curtains can reduce the initial hydraulic conductivity of $1 \cdot 10^{-4}$ cm/s by an order of magnitude.

U.S. Army (2017) indicates that in clean fractured rocks with 50 – 100 LU, permeabilities of 10 LU or less can be achieved. Rocks with permeabilities around 10 LU may reach 1 LU.

Houlsby (1990) notes that in easily injectable rocks, such as those with 100 LU or more, reductions of one to three orders of magnitude may be possible. In marginally injectable rocks, around 10 LU, reductions of one to two orders of magnitude could be feasible.

Regarding the permeability of the rock where injection has a marginal effect, Power (2007) defines it as $1 \cdot 10^{-5}$ cm/s. Friedrich (2018) states that rocks with permeabilities less than 5 LU are practically uninjectable.

On the other hand, it is common for the target permeability value required for dam projects to be in the range of 1 to 3 LU, as indicated by Houlsby (1990); see Figure 1.

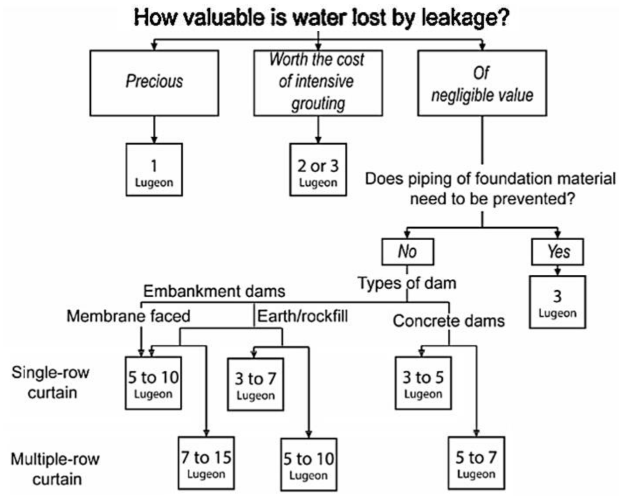

Figure 1. Allowable seepage based on economics (Houlsby 1990)

2.2 *Injection Efficiency Based on Real Project*

To estimate the reduction in rock hydraulic conductivity, four projects for tailings dam walls conducted between 2016 and 2021 were reviewed. Lugeon test results from superprimary wells (SP) and verification wells (V) were compared section by section. SP wells represent the initial injection development wells, which include permeability tests, and their results can be considered indicative of the original rock permeability. V wells are conducted post-construction of the designed curtain to assess its efficiency and the need for further reinforcement with additional wells.

A total of 155 pairs of permeability test results (310 Lugeon tests) were evaluated. The average distance between the comparison sections of SP and V wells ranged from 2 to 3 m.

The same curtain design was considered in all projects. The design characteristics and definitions used to estimate the injection efficiency are as follows:

- Three injection lines spaced 1.5 m apart.

- As a baseline verification condition, in each line, wells are spaced 3 m apart. Some of these sections were later improved by the inclusion of intercalated or quaternary (C) wells, however, this improvement is not accounted for in the V results.

- The conventional method pressure-volume was employed, where the pressure level is a function of depth. The typical mathematical expression used was:

$$p = 2 + ((25 - Q) \cdot H)/40 \quad (1)$$

  Where p is the injection pressure in kg/cm^2, Q is the flow rate in l/min which was no more than 25 l/min or less than 5 l/min and H is the distance in meters from the center of the injection section to the nearest free surface. The volume of grout was dependent on the pressure behavior, which considered waiting times or the transition to the more viscous grout.

- Cement-bentonite grouts was used as the injections. Cement with Blaine fineness between 4,000 to 4,500 cm^2/g was utilized.

- Four types of grouts were employed, ranging from initial grout with 31 to 33 seconds of flow to final grout with 90 to 95 seconds.

- Lugeon tests in SP wells were conducted at one load level for 15 minutes. V wells were tested at three load levels, each for 10 minutes. The maximum pressure applied in V wells was lower than that in SP wells.

- For tests declared as "no admission", a hydraulic conductivity of $1 \cdot 10^{-7}$ cm/s was assigned. It is noteworthy that the minimum reported hydraulic conductivity from Lugeon tests was $1.3 \cdot 10^{-7}$ cm/s.

- The maximum reported hydraulic conductivity in Lugeon tests was $1.3 \cdot 10^{-3}$ cm/s; no tests were reported where flow rate could not be recorded due to high admission volume. Therefore, this analysis is conducted from 100 LU to lower permeability.

- The lithology varied, including andesites, volcanic breccias, and rhyolites with varying degrees of fracturing and weathering.

Figure 2 depicts the comparison results between the hydraulic conductivity of SP wells (k_{SP}), which are indicative of the original rock permeability, and the ratio k_{SP}/k_V, illustrating the magnitude of permeability reduction due to injection, based on the Lugeon test result of the V well. For clarity, a k_{SP}/k_V value of 10 represents one order of magnitude reduction, while k_{SP}/k_V equal to 100 indicates a reduction of two orders of magnitude. Table 1 presents the results categorized by the original rock permeability or k_{SP}.

Table 1. Injection efficiency evaluated in several projects in tailings dam walls

Range k_{SP} (LU)	Lugeon pair test (No)	Average k_{SP} (LU)	Average k_V (LU)	Average k_{SP}/k_V
50 – 100	9	64	1,9	33
10 – 50	57	24	1,1	22
5 – 10	19	7	0,05	141
3 – 5	11	3	0,3	10
1 – 3	7	1,7	0,6	3
0,1 – 1	40	0,34	0,31	1
< 0,1	12	0,01	0,21	0,05

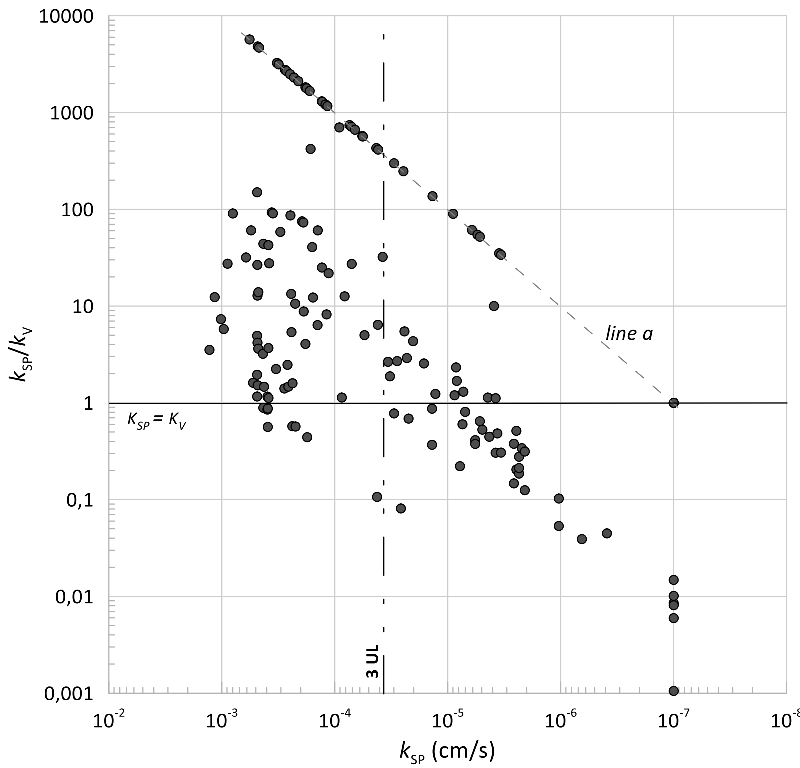

Figure 2. Hydraulic conductivity measured in SP wells (k_{SP}), representative of original rock permeability, vs the k_{SP}/k_V ratio, which considers the result of hydraulic conductivity of the V wells (k_V), representative of the injection permeability. *line a* corresponds to those tests reported as "no admission" in V wells.

In Figure 2, although a dispersion of results is observed, it is evident that the efficiency of an injection curtain is a function of the original permeability of the rock. In fact, only if this variable is analyzed, the higher the original permeability of the rock, the higher the level of permeability reduction, which can reach up to two orders of magnitude. On the other hand, when the hydraulic conductivity is close to 1 LU, the results indicate that the efficiency of a curtain is very low.

It's noteworthy that when the original permeability is low, a significant portion of results falls below $k_{SP}/k_V = 1$. In this range, many tests in SP wells were described as having "no admission". The possibility of hydraulic fracturing occurring or the injection process worsening the original rock permeability is minimal, given the low to negligible subsequent grout admission, and the fact that k_V conductivity remained low. A reasonable explanation could be attributed to the margin of error in the test. Indeed, when the water admission is minimal in SP and V wells, any change in variables can greatly alter the result. These variables may include changes in execution procedure (altering pressure criteria and hydraulic load quantities), operator changes, tests conducted at slightly different inclinations or locations, among others.

Finally, based on these results and calibrated with recommendations from bibliographic sources, for a standard injection design with cement-bentonite grouting curtain, the injection efficiency results proposed in Table 2 are recommended. These results, or injection efficiency, could be improved with the inclusion of C wells or the use of higher penetrability grout (micro-cement, resins, etc.), or if the rock exhibits ideal injection characteristics (clean fractures). However, reducing permeability to a design value below 1 LU is a costly process and requires a significant number of permeability tests with rigorous control for demonstration.

Table 2. Proposed permeability reduction for grout injections. k_r represents the permeability of the original rock and k_{in} represents the permeability of the injected rock.

Rock Permeability k_r (LU)	Permeability Reduction k_r/k_{in}
50 – 100	30
10 – 50	20
5 – 10	10
3 – 5	5
1 – 3	3
0,1 – 1	1
< 0,1	1

3 CONCLUSIONS

Given the considerable variability in Lugeon test results, it is not advisable to assess the efficiency of a grouting curtain with just one or a few tests. A representative sample of multiple in-depth tests across the curtain is required.

There is a clear direct relationship between the original rock permeability and the expected grouting outcome. The higher the permeability, the greater the expected efficiency.

Cement grouting, in general, are inefficient in reducing permeability in rocks of 3 LU or less. Therefore, the effect on reducing water levels or flows should be marginal.

Aiming for permeabilities below 1 LU not only requires ideal lithological conditions or costly solutions, such as quaternary wells or higher penetrability grout, but also demands rigorous control in conducting Lugeon tests, as these results are highly sensitive in low permeabilities.

The results demonstrate that achieving 3 LU is feasible even in rocks with an initial permeability of 100 LU.

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