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Optimization of Hydraulic Barriers in Dams: A Comparative Analysis of Grout Curtains and Cut-off Walls

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ABSTRACT: This study presents a comparative evaluation for optimizing the depth of two types of hydraulic barriers in dams: grout curtains and cut-off walls. Through a parametric analysis using steady-state seepage models (SEEP/W), calibrated with over 300 Lugeon tests, the performance of both solutions was evaluated under multiple scenarios of depth, permeable stratum thickness, and foundation hydraulic conductivity.

The results reveal two fundamentally different optimization mechanisms. For cut-off walls, optimization is a threshold problem: their effectiveness is marginal with partial penetrations but becomes nearly absolute (>95% flow reduction and phreatic level collapse) when keyed into the low-permeability stratum. In contrast, grout curtains show a gradual performance, allowing for a cost-benefit-based optimization where efficiency increases progressively with depth.

It is concluded that depth optimization depends on the barrier type. For cut-off walls, the optimal depth is that which ensures embedment into the low-permeability stratum. For grout curtains, where performance is gradual, optimization is based on a cost-benefit analysis. Although prescriptive rules (e.g., 2/3H) can serve as a starting point in early stages with limited data, this study demonstrates that performance-based numerical modeling is essential for an efficient final selection and design, allowing for a strategic assessment of construction risk versus operational performance.

KEYWORDS: Hydraulic barrier, grout curtain, cut-off wall, Lugeon test, hydraulic conductivity, seepage control, dam foundation.

1 INTRODUCTION

The safety and viability of a dam rely heavily on controlling seepage through the foundation soil and abutments. Uncontrolled flow can cause internal erosion, raise the phreatic level reducing stability, generate critical gradients, and lead to significant water loss. To prevent this, subsurface systems such as grout curtains and cut-off walls are employed.

A grout curtain is a subsurface barrier that reduces the permeability of the foundation soil beneath dams and other hydraulic structures. It is constructed by means of one or more lines of boreholes parallel to the structure's axis, through which grouts are injected to seal fractures and pores, forming a continuous hydraulic barrier. This solution is especially useful in fractured or highly permeable rock masses (Houlsby, 1990; Lombardi, 2003).

A cut-off wall is a continuous structure excavated into the subsurface to form a homogeneous, low-permeability element, commonly used in soils and highly fractured rock. It typically employs cement-bentonite mixes, which ensure uniform hydraulic conductivity values. Although its cost per linear meter is higher than that of a grout curtain at great depths, it offers greater uniformity and construction control in heterogeneous soils.

2 PERMEABILITY CHARACTERISTICS OF GROUT CURTAINS

2.1 *Permeability reduction: variability and determining factors*

The permeability reduction achieved by grout curtains is not uniform along the works and is conditioned by multiple factors. Among the most relevant are the initial hydraulic conductivity of the rock mass, the lithology and its degree of fracturing, the type of grout injected and its penetrability, as well as the construction methodology and execution control. Their use is more frequent in rock masses, whereas in soils their application is usually more limited.

2.2 *Permeability reduction reported in literature and standards*

Various authors, as well as technical guides and standards, have proposed indicative values for the achievable permeability reduction as a function of the initial condition of the rock mass:

Table 1. Indicative values for reduction or final hydraulic conductivity according to different authors and standards.

Source (year)	Initial k_r	Reduction / Final Permeability
Houlsby (1990)	> 100 LU	1–3 OM
	≈ 10 LU	1–2 OM
	≤ 3 LU	Marginal effect
Power (2007)	1×10^{-6} m/s	1 OM
USACE (2017)	50–100 LU	≤ 10 LU
	≈ 10 LU	≈ 1 LU
Friedrich (2018)	< 5 LU	Marginal effect
Weaver (2007)	-	1–3 LU
ICOLD (2017)	-	1–5 LU

Notes:
k_r: initial rock mass hydraulic conductivity
OM: order of magnitude
1 LU (Lugeon Unit) ≈ 1.3×10^{-7} m/s

2.3 *Background from real projects*

The results are based on a previous study (Huaiquil & Vergara 2024) that analyzed 155 pairs of Lugeon or packer tests (310 measurements) in tailings dam walls, comparing super-primary (SP, pre-injection) boreholes with verification (V, post-injection) boreholes. In all cases, a cement-bentonite grout with Portland cement (Blaine fineness 4,000–4,500 cm²/g) and three injection lines were used.

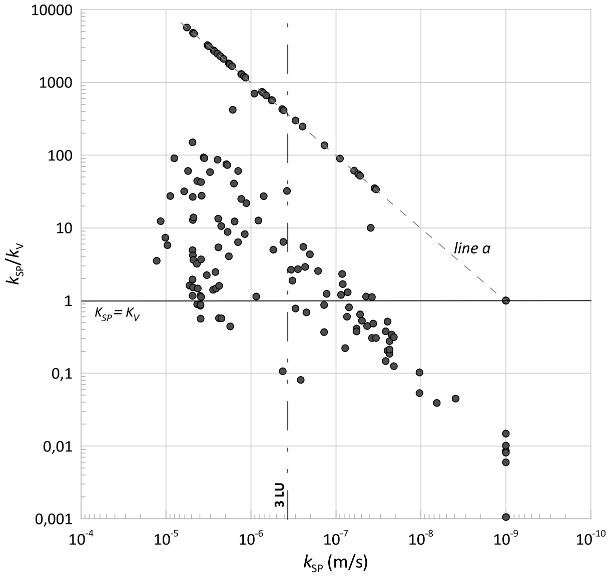


Figure 1. Relationship between hydraulic conductivity in SP holes (k_{SP}), representing the original rock permeability, and the k_{SP}/k_V ratio, where k_V denotes the post-injection conductivity from V holes. *Line a* indicates tests classified as “no admission” in V holes.

The data in Figure 1 show that the efficiency of permeability reduction increases with the initial hydraulic conductivity of the rock mass. This effect is significant in rocks with hydraulic conductivities greater than 50 LU, while it is limited in rocks with conductivities of 3 LU or lower.

2.4 *Recommended reductions for design*

Based on the background and field experience, typical hydraulic conductivity reductions (k_r/k_{in}) are proposed for grout curtains with cement-bentonite grouts and cement with Blaine fineness of 4,000–4,500 cm²/g, as summarized in Table 2.

Table 2. Recommended hydraulic conductivity reduction for grout curtain design.

Rock hydraulic conductivity k_r (LU)	Hydraulic Conductivity Reduction k_r/k_{in}
> 100	50
50 – 100	30
10 – 50	20
5 – 10	10
3 – 5	5
1 – 3	3
< 1	1

Notes:
k_r: initial rock hydraulic conductivity
k_{in}: hydraulic conductivity of the injected rock

Table 2 adopts a hydraulic conductivity reduction factor of 50 for rock masses with initial conductivities greater than 100 LU, consistent with the trend observed in Figure 1 and the limited field-based evidence available for highly fractured or karstic rock masses. Reported case histories indicate initial hydraulic conductivity values on the order of 100 to 500 LU prior to grouting (Bruce & Millmore, 1983; Dhawan et al., 2019) and suggest that reductions of one to two orders of magnitude may be achievable under favorable groutability conditions (Houlsby, 1990). However, based on engineering practice, achieving residual permeabilities below approximately 10 LU should not be assumed as systematic, as grout injection may preferentially fill larger voids and dominant fractures, limiting penetration into finer fissures and microfractures.

3 PERMEABILITY CHARACTERISTICS OF CUT-OFF WALLS

Unlike grout curtains, the hydraulic conductivity of a cement-bentonite cut-off wall is essentially homogeneous and depends on the mix design and construction control, not on the original hydraulic conductivity. The literature reports:

- Evans (1993): typical values between 1×10^{-7} and 1×10^{-9} m/s, achievable with strict control of the water/cement ratio and bentonite content.
- Jefferis (1997): replacement of more than 60% of cement with ground granulated blast-furnace slag (GGBS), achieving < 1×10^{-9} m/s.
- Opdyke & Evans (2005): replacement of 70–80% with slag, obtaining 2×10^{-10} m/s due to a denser microstructure and lower pore connectivity.

Collectively, the studies agree that hydraulic conductivity on the order of 1×10^{-9} m/s or lower can be achieved (ICOLD, 2017).

4 DEPTH CRITERIA ACCORDING TO LITERATURE

4.1 *Grout Curtain - Background*

Since the first grouting programs in dams in the 20th century, the depth of the curtain has often been defined by rules proportional to the dam's height or hydraulic head. These rules, summarized in Table 3, have served as a reference in numerous projects, although over time they have been subject to revision and adjustment in various guides and technical publications.

Table 3. Historical criteria based on hydraulic head to define the depth of grout curtains.

Source (year)	Formula / Criterion
USBR (1977)	D = (1/3 H) + C
BIS–IS10087 (1982)	D = (2/3) H + 8
ICOLD (1983)	D ≈ (1/3 to 2/3) H
BIS–IS11293 (1985)	H/3 ≤ D ≤ H
RIDAS (2011)	H <30 m → D ≤20 m; H ≥30 m → D ≤ (2/3) H
Tosun (2018)	D = 0.307 H + Cc ; D = 17.01 $H^{0,44}$

Notes:
H: dam height or hydraulic head (m)
D: curtain depth (m)
C: empirical constant, between 7.5 to 22.5 (m)
Cc: corrected coefficient = 17.01 (m)

While these rules are simple to apply, they have been widely questioned for their prescriptive nature and for not sufficiently considering the specific geology of the site. Ewert (2018) rejects the practice of equating depth to hydraulic head, proposing instead a hydrogeological approach that distinguishes between two scenarios:

- Connected curtain: reaches and is keyed into a low-permeability layer; Weaver & Bruce (2007) suggest rock with ≤ 3–5 LU as a target. It is the preferred option when technically and economically feasible.
- Hanging curtain: used when such a layer cannot be reached, seeking to lengthen the flow path and reduce gradients.

In both cases, detailed hydrogeological studies and progressive Lugeon tests are recommended to verify an acceptable residual hydraulic conductivity (< 3–5 LU). The use of numerical modeling, such as finite element analysis, allows for the evaluation of the effect of depth on flow rates, uplift pressures, and gradients, identifying the point from which greater embedment ceases to provide significant benefits and optimizing the cost-benefit ratio (Powers et al., 2007; Fell et al., 2014).

4.2 *Cut-off Wall - Background*

The depth of cut-off walls in earth-fill dams has been primarily defined by their penetration into a very low-permeability sealing stratum or, alternatively, to a depth that reduces gradients and uplift pressures to acceptable levels. In the first documented projects (USBR, 1974; USACE, 1986), it was common practice to cut through the permeable materials and key the wall 1–1.5 m into the low-permeability stratum to ensure a hydraulic seal. When such a stratum was not available at a reasonable depth, partially penetrating walls were executed, with the final depth determined by experience and comparisons with previous works.

Over time, this empirical approach was replaced by performance-based criteria. Standards such as EM 1110-2-1901 (USACE, 1993) and Design Standards No. 13 (USBR, 2014) state that the depth should be defined by hydraulic objectives, connecting the wall to the sealing stratum whenever possible or, if not, justifying the depth through seepage analyses that verify residual flow, gradients, and uplift pressures are within safety limits. In recent decades, guides and authors such as Fell et al. (2014) have promoted the use of numerical modeling and flow nets to compare alternatives and determine the point at which greater depths no longer significantly improve seepage control, thus prioritizing the analysis of actual hydraulic performance over prescriptive rules.

5 DEPTH EVALUATION THROUGH SEEPAGE ANALYSIS

5.1 *Analysis Criteria*

The objective of this study was to evaluate the influence of the barrier's depth—whether a grout curtain or a cut-off wall—in relation to a constant hydraulic head, and to determine its capacity to reduce seepage downstream of the dam. In all cases, the barrier's position was kept fixed, located at the upstream toe of the dam, and the analysis was performed for a defined set of hydraulic and geotechnical conditions using numerical modeling with SEEP/W v.2024 under steady-state conditions.

Three hydraulic barrier configurations were considered, applied systematically to all parameter combinations:

- A three-line grout curtain, modeled with an equivalent thickness of 6 m.
- A one-line grout curtain, modeled with an equivalent thickness of 2 m.
- A cut-off wall, modeled with a thickness of 1 m.

The simulations included a constant hydraulic head (H = 50 m), variations in the permeable stratum thickness (S = 30 m, 50 m, and 100 m), and in its hydraulic conductivity (1×10^{-5} m/s and 1×10^{-6} m/s). The barrier depth (D) was evaluated in several scenarios: a base case without a barrier and cases as a function of H, such as: 1/5H, 1/3H, 2/3H, H, and up to 2H for the 100 m stratum). For the grout curtains, the design hydraulic conductivity was defined according to Table 2; for the cut-off wall, a hydraulic conductivity of 1×10^{-9} m/s was adopted.

Figure 2 shows the conceptual model and the input parameters used, including the geometry of the dam–foundation system, the boundary conditions, the location of the downstream drain, and the layout of the barriers for each evaluated depth.

The analysis focused on two main indicators: (1) the reduction of seepage flow rate compared to the base case, measured at the dam crest axis; and (2) the position of the phreatic level within the dam body, as a reference for the control of pore water pressures.

The following section presents the results obtained for each indicator.

- For (1), heatmaps are included showing the flow reduction values for the three permeable stratum configurations (30 m, 50 m, and 100 m) and the two evaluated hydraulic conductivities (1×10^{-5} m/s and 1×10^{-6} m/s).
- For (2), figures are presented showing the phreatic levels within the dam for permeable stratum 50 m thick, for the three construction solutions (3-line grout curtain, 1-line grout curtain, and cut-off wall) with a hydraulic conductivity of 1×10^{-5} m/s.

5.2 *Effects on Downstream Flow*

This subsection presents heatmaps showing the percentage and numerical (L/s) reduction of the seepage flow rate compared to the base case (depth 0 m), evaluated at the crest axis. Combinations for three permeable stratum thicknesses (30 m, 50 m, and 100 m) and two hydraulic conductivities (1×10^{-5} m/s and 1×10^{-6} m/s) are included, considering the three mentioned construction solutions. These charts allow for the identification of how depth and barrier type influence the control of downstream flow.

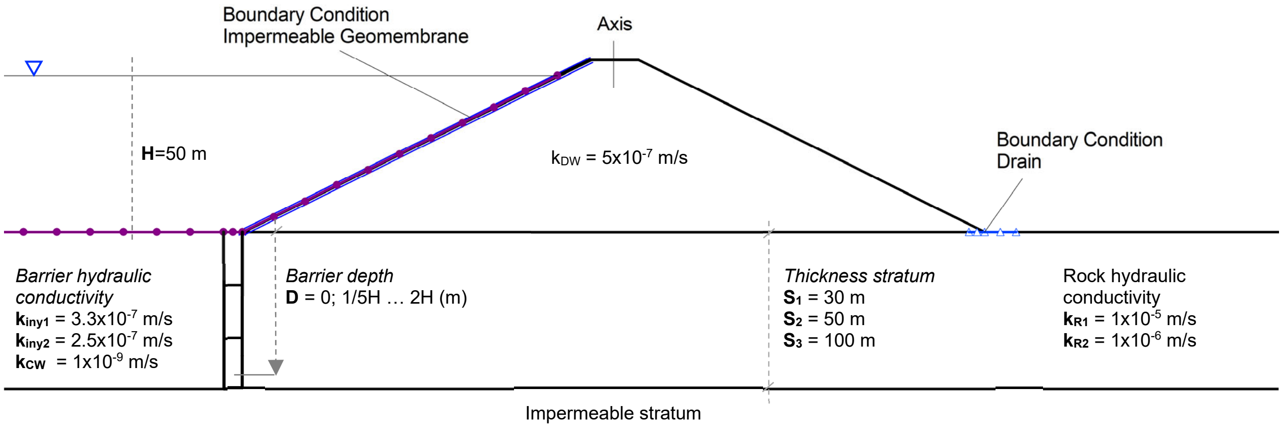
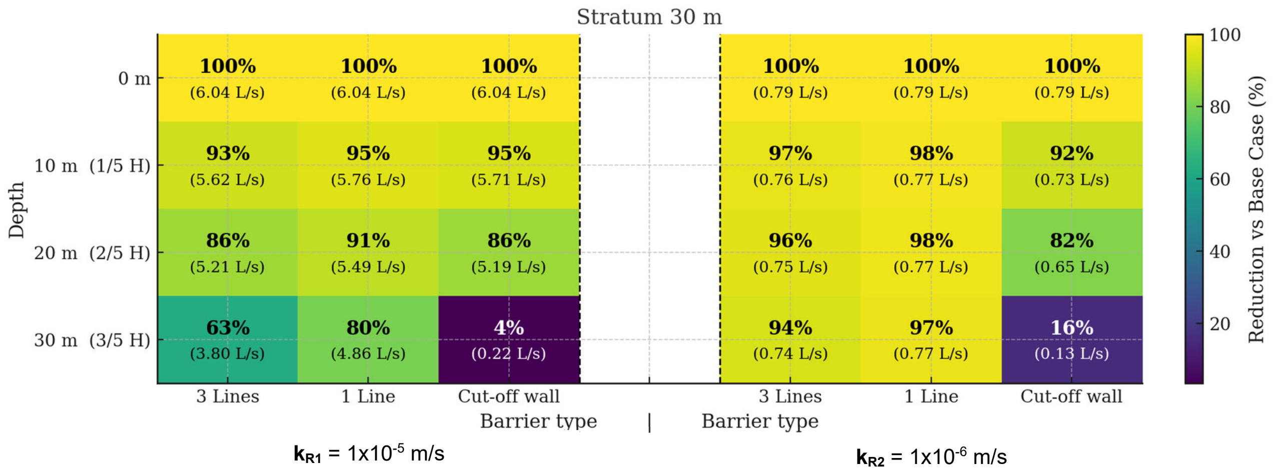
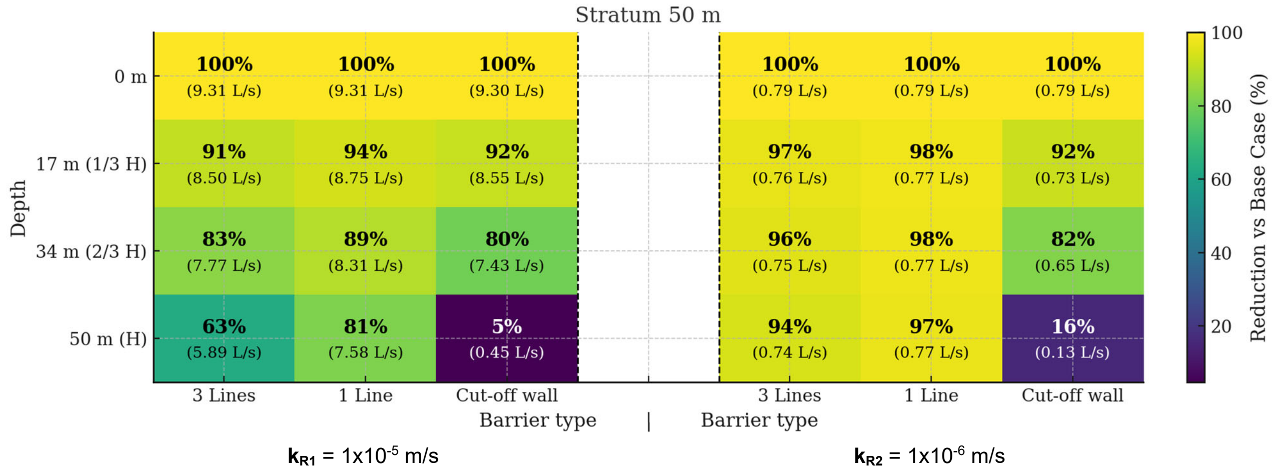


Figure 2. Geometry, boundary conditions, and layout of the hydraulic barrier (1 and 3-line grout curtains, and cut-off wall) considered in the conceptual seepage model.



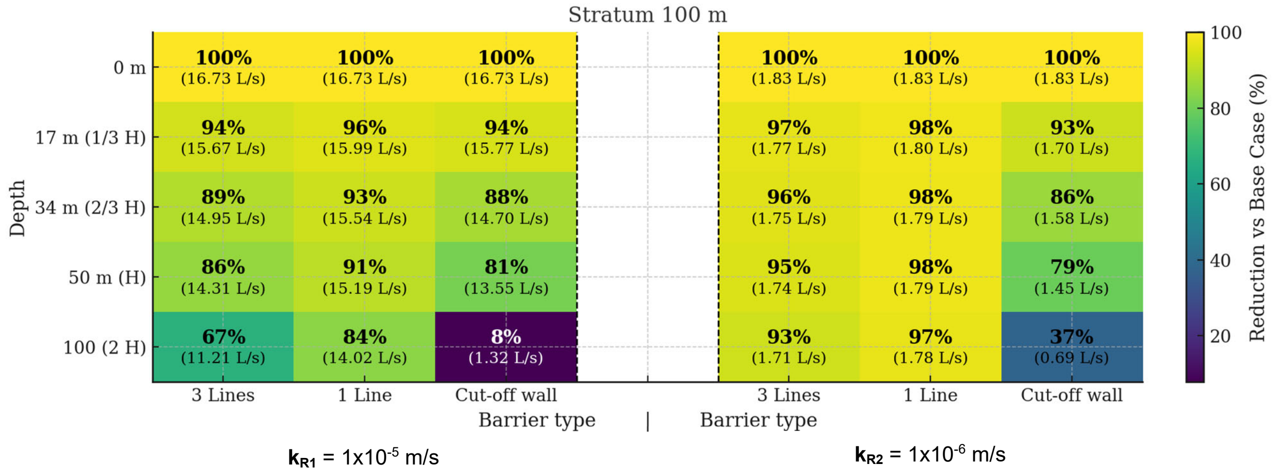
Depth	3 Lines	1 Line	Cut-off wall	3 Lines	1 Line	Cut-off wall
0 m	**100%** (6.04 L/s)	**100%** (6.04 L/s)	**100%** (6.04 L/s)	**100%** (0.79 L/s)	**100%** (0.79 L/s)	**100%** (0.79 L/s)
10 m (1/5 H)	**93%** (5.62 L/s)	**95%** (5.76 L/s)	**95%** (5.71 L/s)	**97%** (0.76 L/s)	**98%** (0.77 L/s)	**92%** (0.73 L/s)
20 m (2/5 H)	**86%** (5.21 L/s)	**91%** (5.49 L/s)	**86%** (5.19 L/s)	**96%** (0.75 L/s)	**98%** (0.77 L/s)	**82%** (0.65 L/s)
30 m (3/5 H)	**63%** (3.80 L/s)	**80%** (4.86 L/s)	**4%** (0.22 L/s)	**94%** (0.74 L/s)	**97%** (0.77 L/s)	**16%** (0.13 L/s)

Figure 3. Heatmap of flow reduction measured at the dam crest axis as a function of hydraulic barrier depth, for a S_1=30 m thick permeable stratum.



Depth	3 Lines	1 Line	Cut-off wall	3 Lines	1 Line	Cut-off wall
0 m	**100%** (9.31 L/s)	**100%** (9.31 L/s)	**100%** (9.30 L/s)	**100%** (0.79 L/s)	**100%** (0.79 L/s)	**100%** (0.79 L/s)
17 m (1/3 H)	**91%** (8.50 L/s)	**94%** (8.75 L/s)	**92%** (8.55 L/s)	**97%** (0.76 L/s)	**98%** (0.77 L/s)	**92%** (0.73 L/s)
34 m (2/3 H)	**83%** (7.77 L/s)	**89%** (8.31 L/s)	**80%** (7.43 L/s)	**96%** (0.75 L/s)	**98%** (0.77 L/s)	**82%** (0.65 L/s)
50 m (H)	**63%** (5.89 L/s)	**81%** (7.58 L/s)	**5%** (0.45 L/s)	**94%** (0.74 L/s)	**97%** (0.77 L/s)	**16%** (0.13 L/s)

Figure 4. Heatmap of flow reduction measured at the dam crest axis as a function of hydraulic barrier depth, for a S_2=50 m thick permeable stratum.



Depth	3 Lines	1 Line	Cut-off wall	3 Lines	1 Line	Cut-off wall
0 m	**100%** (16.73 L/s)	**100%** (16.73 L/s)	**100%** (16.73 L/s)	**100%** (1.83 L/s)	**100%** (1.83 L/s)	**100%** (1.83 L/s)
17 m (1/3 H)	**94%** (15.67 L/s)	**96%** (15.99 L/s)	**94%** (15.77 L/s)	**97%** (1.77 L/s)	**98%** (1.80 L/s)	**93%** (1.70 L/s)
34 m (2/3 H)	**89%** (14.95 L/s)	**93%** (15.54 L/s)	**88%** (14.70 L/s)	**96%** (1.75 L/s)	**98%** (1.79 L/s)	**86%** (1.58 L/s)
50 m (H)	**86%** (14.31 L/s)	**91%** (15.19 L/s)	**81%** (13.55 L/s)	**95%** (1.74 L/s)	**98%** (1.79 L/s)	**79%** (1.45 L/s)
100 (2 H)	**67%** (11.21 L/s)	**84%** (14.02 L/s)	**8%** (1.32 L/s)	**93%** (1.71 L/s)	**97%** (1.78 L/s)	**37%** (0.69 L/s)

Figure 5. Heatmap of flow reduction measured at the dam crest axis as a function of hydraulic barrier depth, for a S_3=100 m thick permeable stratum.

5.3 *Effects on Phreatic Level*

The following figures illustrate the different resulting phreatic level profiles inside the dam wall, for 50 m thick strata with a hydraulic conductivity of $1{\times}10^{-5}$ m/s. The three hydraulic barrier configurations are compared: three-line grout curtain, one-line grout curtain, and cut-off wall. These visualizations allow for the evaluation of the effect of the barrier's depth on the control of pore water pressures in the dam.

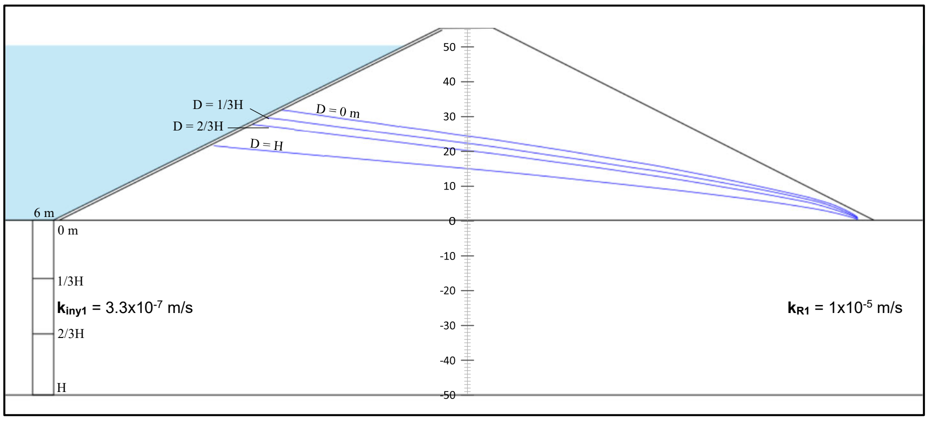


Figure 6. 3-line grout curtain: Piezometric profile within the dam wall – $S_2 = 50$ m stratum.

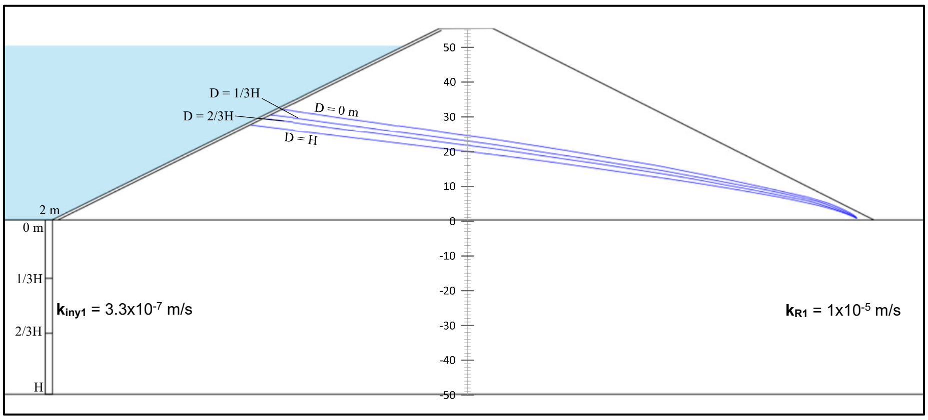


Figure 7. 1-line grout curtain Piezometric profile within the dam wall – $S_2 = 50$ m stratum.

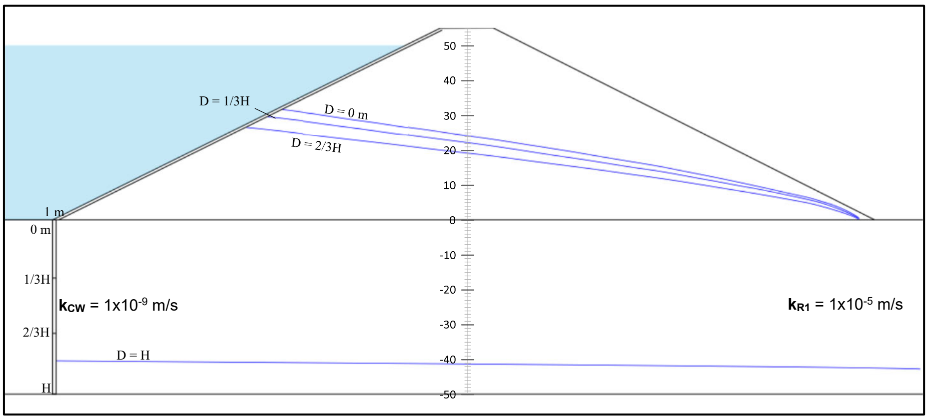


Figure 8. Cut-off wall: Piezometric profile within the dam wall – $S_2 = 50$ m stratum.

5.4 *Analysis of Results*

The comparative analysis of the hydraulic barriers reveals two fundamentally different seepage control mechanisms. The performance of the cut-off wall is binary, critically dependent on its embedment. With partial penetrations, its effectiveness is marginal, achieving flow reductions of less than 20% and a modest phreatic level drawdown (a reduction of ~4.5 m for a depth of 2/3 H). However, upon reaching the low-permeability stratum, its efficiency becomes nearly absolute, reducing seepage flow rate by more than 95% and causing the phreatic level to collapse below the dam's foundation (to -42 m).

In contrast, grout curtains exhibit a gradual and progressive performance with depth. Although they do not achieve the watertightness of an embedded cut-off wall, they achieve significant flow reductions (up to 37% for the 3-line curtain at maximum depth) and a phreatic level drawdown of 8.8 m in the same scenario. A consistent superiority of the 3-line configuration over the 1-line is observed. This behavior positions grout curtains as a flexible mitigation solution, whose benefit is directly proportional to the depth achieved; however, unlike a cut-off wall, reaching a low-permeability stratum does not result in an abrupt or particularly significant increase in performance.

The correlation between flow attenuation and piezometric drawdown is direct and confirms that the design objective—whether reducing a volume of water or dissipating pore water pressures—determines the suitability of each solution.

6 CONCLUSIONS

- The optimization of a cut-off wall's depth is a threshold problem, not a gradual one. The study shows that the optimal depth is that which guarantees embedment into the low-permeability stratum. Shallower depths result in suboptimal performance that does not justify the investment, making the feasibility of this solution dependent on the ability to reach this sealing elevation.

- The optimization of a grout curtain is based on a cost-benefit analysis. Unlike the cut-off wall, its progressive performance allows for optimizing the depth as a balance between the investment and the desired level of seepage control. This makes it the preferred solution for optimization in geological scenarios where reaching a sealing stratum is not feasible.

- Numerical modeling is the essential tool for depth optimization. The study validates that a performance-based design approach, fed by field data, allows overcoming the limitations of prescriptive formulas. This method is indispensable for quantifying the relationship between depth and efficiency, enabling a real optimization that minimizes technical risk and project cost.

- The integration of field data into numerical analysis is key to reducing uncertainty. The methodology combining Lugeon tests with parametric modeling is confirmed as a robust practice that allows for design calibration, hypothesis validation, and informed decision-making, overcoming the limitations of purely empirical approaches.

- The choice of barrier defines the project's risk management strategy. A cut-off wall implies a higher geotechnical construction risk (the need to ensure the seal), but a lower long-term operational risk. Conversely, a grout curtain offers lower construction risk but requires a monitoring plan and possible future maintenance. This life-cycle risk assessment is important for design decision-making.

- Optimization of design solutions. The scope of this study, focused on rock, allows for outlining criteria for the optimization of design solutions. Of practical interest is the analysis of combined solutions (e.g., cut-off walls or cut-off trenches supplemented with localized injections) and the economic sensitivity evaluation that integrates construction cost with the hydraulic efficiency obtained. Additionally, it is recommended to evaluate the barrier-drain system jointly and to analyze the behavior of the solutions under transient regimes (e.g., first filling), for a comprehensive optimization of the seepage control system.

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