ON THE REQUIRED THICKNESS OF GROUT CURTAINS UNDER DAMS

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ABSTRACT

To reduce the water leakage and the uplift pore pressure in the rock foundation, grout curtains are often constructed under dams. However, the design of grout curtains has long been based on empirical knowledge. When designing the grout curtain, focus was mainly given on closing the curtain and limiting the leakage, without considering the thickness of the curtain. However, a too thin grout curtain could lead to high gradients, which with time could result in internal erosion of degraded grout and fracture infilling materials. This could lead to poor performance and durability problems, potentially jeopardizing the dam safety and increasing the cost for remedial measures. In this paper, three design criteria are discussed for determining the required thickness of the grout curtain, including water loss reduction, uplift pore pressure reduction and internal erosion of degraded grout and fracture infilling materials. Analyses on the required thickness are made for a typical concrete gravity dam. The results show that the required thickness is significantly affected by the internal erosion of fracture infilling materials. These results show the need for a more refined design approach for the grout curtains based on the suggested criteria.

***Key words** : grout curtain, thickness, uplift pressure, internal erosion.*

1. INTRODUCTION

Grout curtain under dams plays an important role in the dams' functionality and safety. For a dam constructed on rock, a fractured and permeable rock mass in the foundation is able to provide paths for water to flow through. This may lead to the loss of water from the reservoir. The flow also brings uplift pore water pressure in the rock fractures under the dam, threatening the sliding stability of the dam. To avoid such problems, a grout curtain is usually constructed under the dams (see e.g. Houlsby (1990), ICOLD (1993), CDA (2007) and Weaver & Bruce (2007)). By performing curtain grouting in the rock foundation, most of the large permeable fractures could be sealed with cementitious grout. As a result, the permeability of the rock mass in the grouted zone is reduced as well as the uplift pore water pressure beneath the dam. The latter reduction is particularly beneficial for concrete dams. Besides the above-mentioned reductions on permeability and uplift pressure, durability is also vital for the grout curtain. One of the possible causes for the degradation of the grout curtain is the erosion of fracture infilling materials, if present, as discussed by Spross et al (2016). Therefore, a third factor: preventing internal erosion of any infilling materials in the grouted fractures after the reservoir is filled, should also be accounted for in the long-term performance of a grout curtain.

The thickness, among all the aspects of the geometry of a grout curtain, directly influences the performance of a grout curtain. However, little has been discussed in the literature on the influence from the thickness of the curtain. The thickness of the grout curtain, if not being completely ignored, is usually determined empirically by discussing the number of rows of grout holes, see e.g. Weaver & Bruce (2007) and Houlsby (1990). Chai & Cui (2012) discussed the optimal thickness of the grout curtain based on analytical calculations, but only with respect to the uplift pressure. In recent years, the research on grouting of fractured rock, summarized in the textbook by Stille (2015), has facilitated the theoretical design of the grout curtain (including the thickness) and the design of the grouting work. The theories, especially on the grout spread in rock fractures, also provide control over the grouting process so that the determined thickness can be achieved with higher confidence.

In this paper, three design criteria on the grout curtain thickness will be introduced and discussed: permeability reduction of the rock mass, uplift pore pressure reduction and prevention of internal erosion of infilling materials, if present. Different thresholds will be compared and discussed as the design limit state for the prevention of internal erosion of infilling materials. Analyses will be made on a typical concrete dam on the required thickness of its grout curtain, followed by discussions of the results and of the design process of the thickness of the grout curtain.

2. DETERMINATION OF THE REQUIRED THICKNESS OF GROUT CURTAINS

The grout curtain in the rock foundation under dams is more of a conceptual "curtain" rather than a physical "curtain". Compared to the cut off wall in soil, whose physical shape is a "wall", the actual shape of the grout curtain varies and depends highly on the fracture patterns in the grouted zone. The term *thickness of a grout curtain can be clarified as the spread range of hardened grout that determines the hydraulic gradient in the grout curtain after the reservoir is filled*. Under this preliminary concept, the empirical approach and the analytical approach to determine the required thickness of grout curtains will be introduced respectively in the following sections.

2.1 Empirical approach

The concept "thickness" in the classical dam foundation grouting textbooks (Weaver & Bruce (2007) and Houlsby (1990)) is vague. Both textbooks do not use the term thickness, but introduced the same concept by discussing the number of rows of grout holes in the curtain.

Weaver & Bruce (2007) and Houlsby (1990) shared some opinions on the number of rows for a grout curtain. A single-row curtain, which indicates a small thickness, may require high grouting execution quality with ideal geological conditions. Therefore, it is believed to be "risky" to have single-row curtains. In addition, the single-row curtain can be "vulnerable" due to its small thickness. Small thickness of the grout curtain results in steep hydraulic gradient in it, which potentially threatens any weak materials such as fracture infilling materials that can be easily eroded. As a result, Weaver & Bruce (2007) and Houlsby (1990) advised to use the multiple-row curtain to achieve a larger thickness of the curtain.

However, no detailed guideline was provided showing the required thickness of the grout curtain. Houlsby (1990) advised that the rows should not be too far apart in order to make the grout penetrations from different rows to meet. He also gave suggestions on the commonly-used spacing of two adjacent rows of grout holes. It was usually around 1.5 m or 1 m, but was also subject to changes according to the working conditions. Houlsby's advice is valuable yet empirical. Although the empirical approach has succeeded in many projects and is able to guarantee good quality on the grout curtain under most of the conditions, engineers have limited control because no theoretical background is supporting the design. In addition, the efficiency of the empirical approach is questionable since it might result in conservative design and excessive grouting work.

2.2 Analytical approach

The empirical approach has long been implemented for dam foundation grouting projects, mainly because of the large epistemic uncertainties involved in the rock formation and the grouting processes.

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ABSTRACT:

Figure 1 : Persistent fractures beneath the dam and the conceptual thickness of the grout curtain.

In recent decades, extensive research has been performed in Sweden on rock grouting. The interpretation of hydraulic tests, grout mix properties, grout penetration length, stop criteria of grouting, grouting pressure in relation to jacking, internal erosion concerns and the use of the observational method have been covered in the recent research work (most of the theories are summarized in the textbook by Stille (2015)). These theories have been able to facilitate the development of an analytical design approach for grout curtain under dams.

In principle, the required thickness of the grout curtain will be pointless without the knowledge of the grout penetration length, as designers cannot know if the determined thickness will be achieved or not. Having this premise, the thickness of the grout curtain can be determined based on the theories concerning grout penetration length presented by Stille (2015).

However, due to the nature of rock grouting, it is impossible to fully reduce all uncertainties. The main aim is to reduce the epistemic uncertainties when designing the grout curtain. To simplify the design without sacrificing its validity, a conservative assumption is made based on what is believed to be a dangerous condition: horizontal and persistent fractures throughout the rock mass beneath the dam. The spread of grout in such fractures is assumed to be represented by a 2D-disc. Under these assumptions, the thickness of the grout curtain can be presented as the thickness of the overlapping area in the sketched illustration shown in Figure 1.

The performance of the grout curtain is closely related to its thickness, both for its short term and long term. The design criteria for the thickness include: permeability reduction of the rock mass, uplift pore pressure reduction and prevention of internal erosion of any infilling materials. These criteria will be introduced in detail in the following paragraphs.

2.2.1 *Permeability reduction of the rock mass*

Flow control is the most direct effect that a grout curtain is able to contribute to. Houlsby (1990) has given recommendations on the required hydraulic conductivity in the grouted zone. This recommendation can still be seen as a guideline on the standard of grout curtain in terms of reducing the permeability of the rock mass. The permeability of the rock mass in the grouted zone is mainly determined by the sealing efficiency of the grout mix as well as on the hydraulic properties of the ungrouted rock mass. Although it does not directly affect the determination of the thickness, this criterion for the design provides the fundamental to the other two criteria.

Stille (2015) recommended an expression relating the residual hydraulic conductivity Kg in the grouted zone with the laboratory-measured critical aperture bcrit of the grout mix. The critical aperture bcrit of the grout mix is the boundary aperture of the fracture above which the grout mix can fully penetrate.

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where k_1 is the ratio between mean and maximum section transmissivity of all hydraulic tests in the project, the value usually varies between 0.2 and 0.6. k_1 indicates the overall tightness of the rock, as tight rock may lead to small k_1 and a more permeable rock mass may indicate a higher value. k_2 is the ratio between maximum section transmissivity and maximum fracture transmissivity, usually varying between 1.1 and 2.0. The choice of k_2 is based on the fact that the section transmissivity is mainly dominated by the maximum single fracture transmissivity within that section (Hernqvist et al (2014)). k_3 is the ratio between maximum physical aperture and maximum hydraulic aperture, usually varying between 1.5 and 2.0. k_4 is the ratio between measured critical aperture (b^{crit}) and maximum ungrouted physical aperture, usually varying between 0.8 and 1.2. L is the length of the borehole section. μ is the viscosity of water ($1.3 \cdot 10^{-3}$ Pa·s) and ρ is the density of water (1000 kg/m^3).

The calculated Kg should not exceed the pre-defined requirement from for example Houlsby (1990). In this design criterion, the only changeable variable is bcrit. Therefore, the grout mix could be chosen to fulfil a b_{crit} resulting in an acceptable Kg.

2.2.2 *Uplift pore pressure reduction*

The uplift pore water pressure is one of the main factors that influence the sliding stability of a concrete dam.

The grout curtain under dams reduces this pressure and usually functions together with the drainage holes to reduce the uplift pore water pressure. In this paper, only the contribution from the grout curtain will be discussed.

The thickness of the grout curtain plays a vital role on the uplift pore pressure reduction. In this paper, an analytical expression relating the uplift pore pressure to the thickness of the grout curtain has been derived. As shown in Figure 2, the water head in the reservoir is Hw (m), the dam width is W (m), the grout curtain is located at the heel of the dam with a thickness of T (m). The uplift pore pressure downstream of the grout curtain Hdown (m) as well as the hydraulic gradient in the grout curtain ig (m/m) are to be found in relation to T.

Under the assumptions of constant Darcy flow (equation 2, 3 and 5) within and downstream of the grouted zone in a continuum medium, the expression of Hdown can be derived by combining equation 1 to 5.

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2.2 *Analytical approach*

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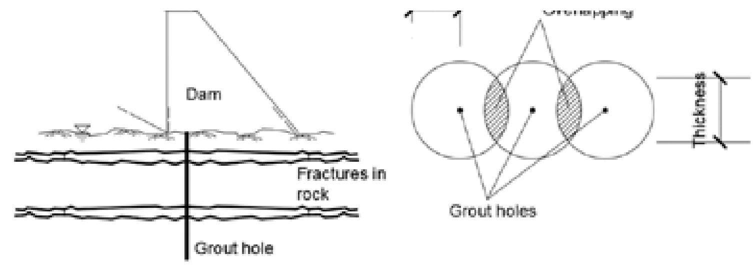

Figure 1. Persistent fractures beneath the dam and the conceptual thickness of the grout curtain.

where A is the cross-section area for water flow, Qdown is the flow in the rock mass downstream of the grout curtain, Kdown is the hydraulic conductivity of the rock mass downstream of the grout curtain, bmh is the maximum hydraulic aperture measured from the hydraulic tests. Through geometrical calculations, the total uplift force Fup (kN/m) can be expressed as

summarized in the textbook by Stille (2015)). These theories have been able to facilitate the development of an analytical design approach for grout curtain under dams.

In order to ensure the stability of the dam, the thickness of the grout curtain should at least make sure that the Fup does not exceed the value used in the design of the dam body. Further optimization on the thickness of the grout curtain can be performed in order to have a minimum Fup so that the dam could have a larger safety margin. This optimization to find the minimum Fup could be performed using a trial-and-error method given that the deviation of Fup maybe tedious to calculate analytically.

2.2.3 *Prevention of internal erosion of infilling materials*

By observing the drilled core samples or the water flushed out during drilling of the holes, the presence of natural infilling material in the fractures could be identified. Usually, flushing of the holes is performed after the drilling is finished to clean the holes, trying to remove any infilling materials in the fractures between the holes. Although very limited knowledge can be obtained about the exact infilling conditions in the fractures after the flushing, three scenarios can be generalized: (a) unfilled fractures, (b) fully-filled fractures and (c) partly-filled fractures, as shown in Figure 3. The regimes that water flows in these scenarios are different. In fully-filled fractures, water may flow between the soil particles or might even not be able to flow if the infilling material is impervious. Darcy flow can describe the flow in the scenario with fully filled fractures. In partly-filled fractures, however, water flow can be analogized to pipe flow with a regime of laminar flow, as in unfilled fractures.

The internal erosion could be controlled by limiting the hydraulic gradient under a critical value. With a larger thickness of the grout curtain, the hydraulic gradient will be lower. Based on equation 2, the expression relating the hydraulic gradient in the grouted zone ig (m/m) and the thickness of the grout curtain T (m) can be written according to equation 8. Proper thresholds for erosion of infilling materials should be chosen to find the critical hydraulic gradient in the grouted zone i_{crit} (m/m).

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can fully penetrate.

Figure 3 : Fracture infilling scenarios: (a) unfilled, (b) fully-filled and (c) partly-filled.

as tight rock may lead to small k_1 and a more permeable rock mass may indicate a higher . k_2 is the ratio between maximum section transmissivity and maximum fracture nissivity, usually varying between 1.1 and 2.0. The choice of k_2 is based on the fact that the

For the fully-filled scenario, although the grout curtain is able to effectively reduce the uplift pressure when the reservoir is filled, the hydraulic gradient within the grouted zone becomes high as a result of the permeability reduction. Higher hydraulic gradient could result in higher water flow velocity in the ungrouted fractures. Except for the fine fractures that the grout could not penetrate, the fractures fully-filled with fine soils, could not be grouted, either. These fine soil infillings are jeopardized by the high Darcy velocity. Over time, they could be gradually eroded by the water flow and the small pipes or channels will be gradually created and expanded resulting in higher flow. Consequently, large openings will be formed and the permeability of the grouted zone will eventually increase, indicating that the grout curtain is degraded.

The existence of infilling material can be observed from drilled cores or flushing water. However, it is difficult to obtain undisturbed core samples for quantitative analysis of infilling materials due to the water flushing during the drilling process. Due to the limited knowledge about the infillings in the fractures, the following premises and simplifications need to be clarified: 1) Sand infilling with hydraulic conductivity higher than 0.1 cm/s can be penetrated by the grout (Littlejohn (1982)), meaning that if the fracture is fully or partly filled with coarse sand it will still be grouted. The grout will stop the flow from eroding the sand particles. 2) The ordinary hydraulic gradient within the grout curtain in normal dams could hardly erode cohesive soils such as clay or silt, given the strong cohesion between particles and their low hydraulic conductivity, resulting in low Darcy velocity. Having 1) and 2), infilling materials such as fine sand becomes the main focus when designing to avoid internal erosion of the infilling materials, whose conductivity can be as high as 0.1 cm/s.

Existing research on internal erosion in embankment dams may be used as an initial reference for the fully-filled fractures. Among the four major mechanisms of internal erosion in the embankment dams: Concentrated leaks, Backward erosion, Contact erosion, and Suffusion – none of these mechanisms is completely similar to the erosion process of infilling materials within rock fractures. The major difference between the analyses of erosion in embankment dams and in fractures lie in the scale and the knowledge of the infilling materials. Designers have thorough knowledge on the formation of the embankment dam infillings, since it is a part of the man-made structure. On the contrary, the fracture infillings in the rock mass is naturally formed, and the designers usually have limited knowledge about the exact composition of the infilling materials.

The threshold that the authors implemented in this paper for fully filled fractures was based on the graphical presentation of data from tests done for the critical Darcy velocity of contact erosion from ICOLD Bulletin 164 (2017). A critical Darcy velocity of 10 mm/s was chosen as most of the test results were above 10 mm/s, meaning 10 mm/s is on the conservative side.

According to Darcy's law, the critical Darcy velocity vcrit (0.01 m/s) in relation to the critical hydraulic gradient icrit (m/m) can be expressed as

Figure 2. Uplift pore pressure under the dam with filled reservoir and a complete grout curtain.

where k is the hydraulic conductivity of the fracture infilling, which is approximately 0.1 cm/s for fine sand, which is the main focus of the analysis.

For the partly-filled condition, the erosion process has certain similarities with the sediment erosion of rivers or channels. Axelsson (2009) implemented the Hjulström diagram (Hjulström (1935)) as an indicator to find the critical mean velocity v_{crit} (m/s) and then the i_{crit} in the maximum unsealed fractures with an aperture of bcrit (closed channel flow was assumed). However, it is

doubted that Axelsson correctly used the Hjulström diagram. This affected his recommendation on the critical mean velocity and led to too conservative values. From the original Hjulström diagram, one can observe that high velocity is required to erode the cohesive soils (around 20 cm/s for silt and around 50 cm/s for clay). The high critical velocities correspond to high critical gradients that are beyond the gradient in ordinary dam grout curtains. For cohesionless soils, Shields diagram (Shields (1936)) could be used instead.

3. ANALYSES ON THE THICKNESS OF THE GROUT CURTAIN UNDER A TYPICAL CONCRETE GRAVITY DAM

Analyses was performed on a fictitious concrete gravity dam. The thickness of the grout curtain under this dam was analyzed with respect to the three design criteria introduced in Chapter 2.

3.1 Basic information

The basic information about the dam is presented in Table 1 and Figure 4.

Table 1 : Information about the fictitious dam.

Geometry of the dam	
Base width of the dam (W)	20 m
Depth of the reservoir (Hw)	20 m
Properties of the rock foundation	
Maximum hydraulic aperture (bmh)	240 μm
Fracture infilling materials	Mainly silt and fine sand
Other properties	
Critical aperture of the grout (bcrit)	90 μm
Section length for hydraulic tests (L)	3 m

The pre-defined design criteria for the thickness of the grout curtain are presented in Table 2. Most of the fractures are unfilled, but some of the fractures are expected to be filled with silt and fine sand. The fine sand is subject to the threat of being eroded. The fully-filled scenario is to be considered in this analysis for the filled fractures. The critical hydraulic gradient icrit was calculated by implementing equation 9 with the critical Darcy velocity vcrit (0.01 m/s) and hydraulic conductivity of the fracture infilling k (0.1 cm/s). In equation 1, k1 was chosen as 0.47, k2, k3 and k4 were assumed as 1.25, 2 and 1 respectively.

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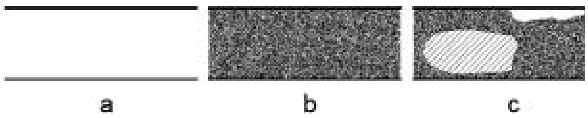

Figure 3. Fracture infilling scenarios: (a) unfill

Figure 4 : Outline of the fictitious dam.

Table 2 : Design criteria for thickness of grout curtain.

Design criteria	Threshold value
Residual hydraulic conductivity (K_g)	1.67·10-7 m/s (1 Lu)
Total uplift force (F_{up})	Lowest possible
Critical hydraulic gradient (i_{crit})	10 m/m

3.2 Analysis results

The results from the analyses are shown in Figure 5, where the thickness of the grout curtain must fulfill all the criteria listed in Table 2.

The first criterion, residual hydraulic conductivity, was evaluated according to equation 1. A residual hydraulic conductivity was calculated to be $1.07 \cdot 10^{-9}$ m/s or nearly 0 Lu. It is lower than the criterion, thus the grout material can fulfill the requirements, given the assumed geological conditions in Table 1, and the design of the thickness of the grout curtain can proceed.

In Figure 5, the uplift pressure can be significantly reduced by having a grout curtain; although after the maximum reduction at small thickness the uplift pressure starts to increase with increasing thickness. The maximum reduction can be achieved with a thickness of 0.5 m, which can be seen as the optimal thickness of the grout curtain if only considering the uplift pressure reduction.

At this point, the third criterion needs to be involved and evaluated by comparing the hydraulic gradient in the grouted zone and the critical hydraulic gradient with respect to the internal erosion of any potential fracture infilling materials. As in Figure 5, the intersection between the curve ig vs T and the boundary line icrit indicates the minimum allowed thickness of the grout curtain to control the internal erosion in the filled fractures. A thickness of around 4 m is required under this criterion.

After considering and comparing all three criteria, a thickness of 4 m was chosen for the grout curtain in order to give an ideal reduction of the uplift force and to control the internal erosion of fracture infilling materials.

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Figure 5 : Total uplift force (Fup) in relation to the thickness of grout curtain (T), Hydraulic gradient (ig) in relation to the thickness of grout curtain (T), and the critical hydraulic gradient (icrit).

4. DISCUSSION

4.1 Permeability reduction of the rock mass

The permeability of the rock mass can be significantly reduced by grouting. In the calculation results, nearly zero residual conductivity was calculated for the grouted rock mass. However, "perfect" grouting will never be performed and the calculation result may be very ideal. In addition, significant uncertainties exist in the coefficients in equation 1. These uncertainties can be reduced by performing more thorough geological and hydro-geological investigations. It is also recommended that sensitivity analyses are performed to analyze the possible range of hydraulic conductivity after grouting.

4.2 Uplift pore pressure reduction

From Figure 5 one can observe that the reduction of the total uplift force from the grout curtain was significant, especially for a grout curtain with small thickness. Due to the boundary conditions with reservoir water head at the dam heel and zero water head at the dam toe, the reduced uplift force increased again after the optimal thickness. Although not as optimal as the maximum reduction, a slightly larger thickness of the grout curtain is able to effectively reduce the uplift force. In theory, if a finer grout was used with a lower bcrit, the curve is expected to move left with an optimal reduction at a thickness close to zero, as the fine grout is able to provide a higher sealing efficiency.

Although some dam design guidelines do not allow designers to account for the reduction of uplift pressure brought by the grout curtain, such as the Swedish guidelines for dam safety RIDAS (Swedenergy (2012)), a significant reduction is still beneficial to obtain a larger safety margin against sliding.

4.3 Prevention of internal erosion of infilling materials

It can be observed from the results and further anticipated that if the "erodible" infilling material e.g. fine sand exists, they will likely govern the thickness of the grout curtain. The thin grout curtain that gives optimal reduction of uplift pressure create high hydraulic gradients in the curtain which is not acceptable with respect to the prevention of internal erosion. This effect also coincides with the empirical approaches of using several rows for the grout curtain.

According to existing literature, the internal erosion of infilling materials in rock fractures has not been thoroughly studied. Because of this, the threshold for erosion of fully filled fractures was in this paper assumed to coincide with the threshold for contact erosion in embankment dams. More studies should be made on the applicability of these thresholds. The criteria used in the analyses in this paper is open for future changes if better thresholds are introduced. A model that is able to describe the mechanism of erosion of infilling materials in rock fractures is desired for a better understanding of this process. Thus, more research on this topic is needed.

5. CONCLUDING REMARKS

In this paper, a theory-based approach to determine the required thickness of the grout curtain under dams has been proposed. This approach consists of three design criteria for the determination of the grout curtain thickness: permeability reduction of the rock mass, uplift pore pressure reduction and prevention of internal erosion of infilling materials. The thickness of the grout curtain should be able to fulfil the requirements from all three criteria. This pre-determined thickness can then act as a guideline on the required grouting time and stop criteria in each grout hole. Example analyses have been performed on a fictitious concrete gravity dam, showing the detailed process to determine the thickness of the grout curtain given the pre-investigation results.

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