KTH ROYAL INSTITUTE OF TECHNOLOGY

SVENSKT VATTENKRAFTCENTRUM

Design of grout curtains

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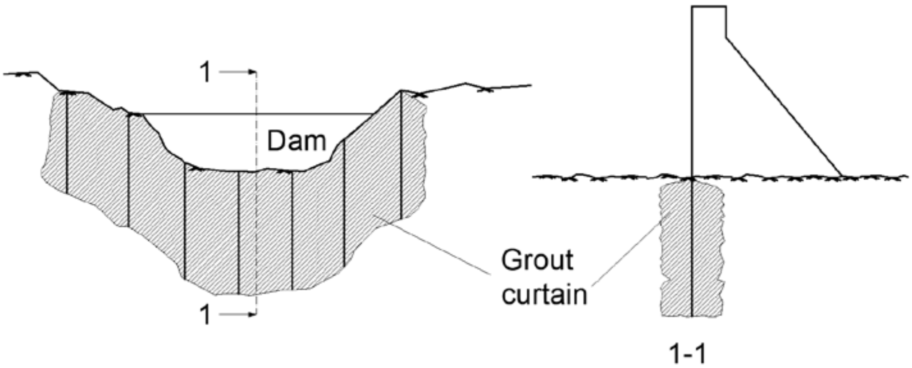
Background

Grout curtains are constructed under dams to:

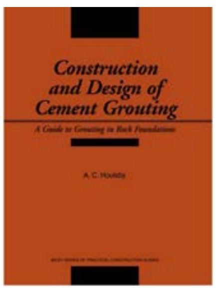
- ➢ Reduce the hydraulic conductivity of the rock foundation
- ➢ Reduce the water leakage through the rock mass
- ➢ Reduce the uplift pressure

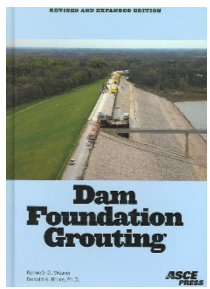


Background

Empirical design

- Grouting has long been an empirical technique
- Design of grout curtains based on “rules of thumb” and experience





Limitations

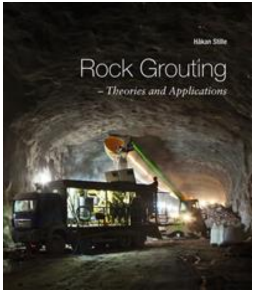
- Quality of the grout curtain relies on experience of the designer, lack of experience could lead to inadequate or over-conservative design.
- Internal erosion of the fracture infilling material is not directly taken into consideration.
- “Refusal” as stop criterion can lead to long grouting time.
- Hydraulic jacking can occur if grouting pressure is not properly chosen.

Houlsby AC (1990) *Construction and design of cement grouting*, ISBN 0-471-51629-5, John Wiley & Sons, Inc., USA.
Weaver K, Bruce D (2007) *Dam foundation grouting, revised and expanded*, ASCE press, USA.

Background

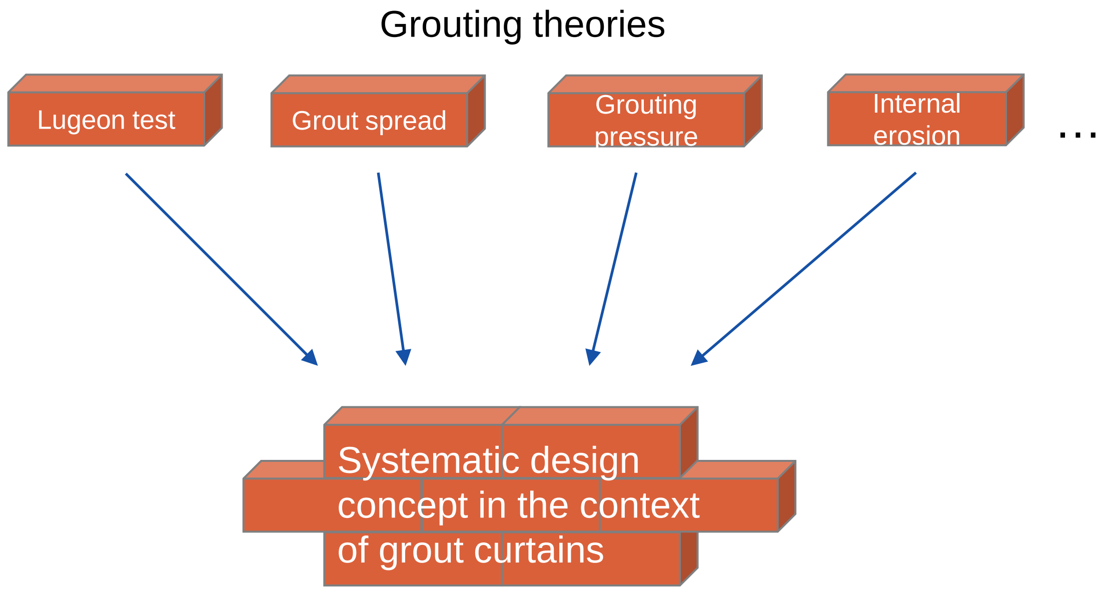
Theory-based design

- Extensive research on grouting has been preformed in recent decades
- More theory-based design method under the framework of observational method will become possible



Stille H (2015) *Rock Grouting- Theories and Applications*, BeFo, Stockholm, Sweden.

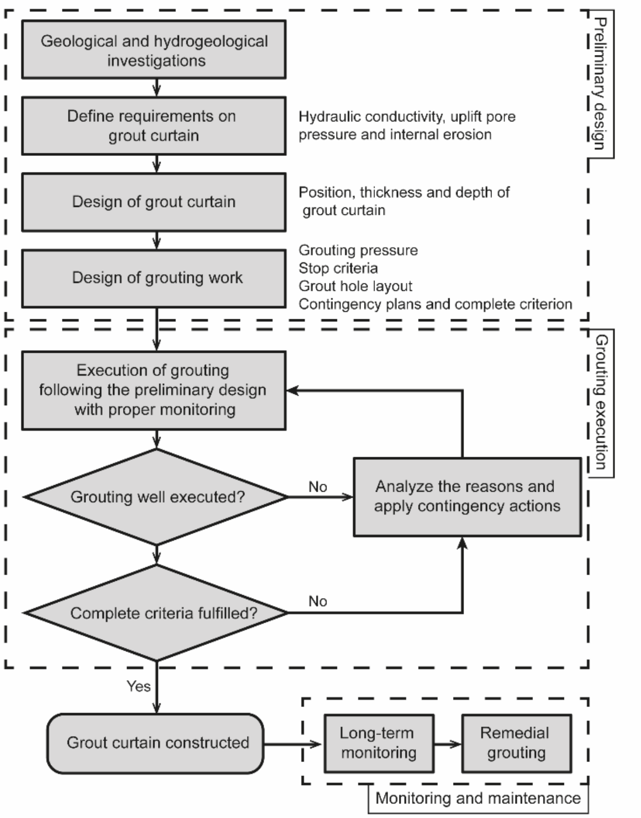
New design concept for grout curtains



New design concept for grout curtains

Design flowchart

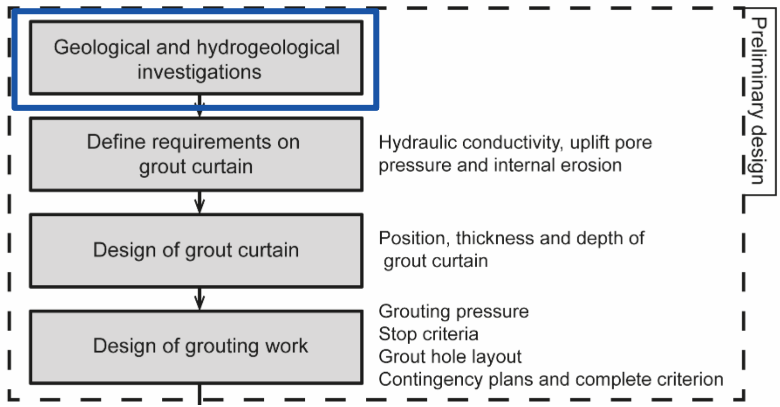
- Preliminary design
- Grouting execution
- Monitoring and maintenance



New design concept for grout curtains

Preliminary design

- Investigate the fracture patterns and rock properties by geological investigations
- Investigate the permeability of the rock mass and fracture aperture by Lugeon tests (water loss measurements)



New design concept for grout curtains

Preliminary design

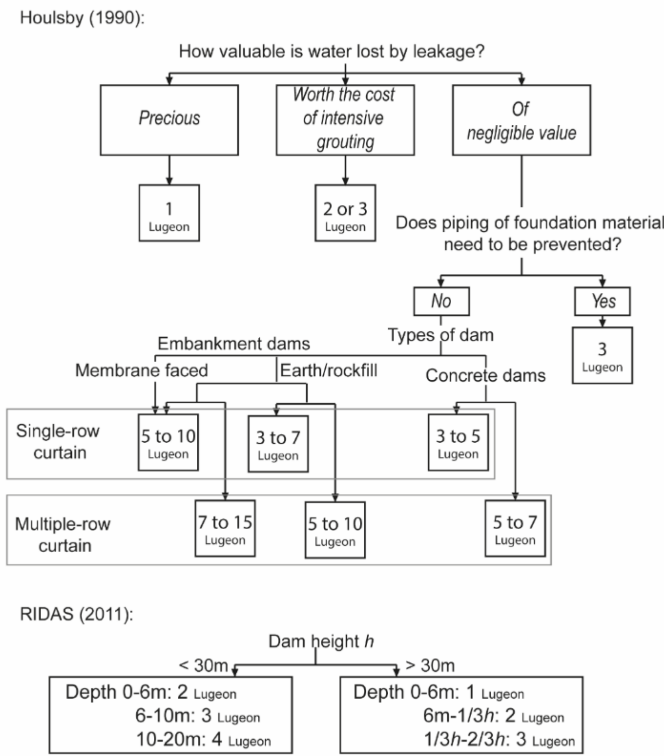
Requirements on grout curtain:

- Hydraulic conductivity of the rock mass

$$K_g < K_{acc}$$

- Reduce the uplift pressure.
- Internal erosion of fracture infilling materials

$$i_g < i_{crit}$$



Houlsby AC (1990) *Construction and design of cement grouting*, ISBN 0-471-51629-5, John Wiley & Sons, Inc., USA.
Swedenergy. (2011) *Kraftföretagens riktlinjer för dammsäkerhet (RIDAS) Avsnitt 7.2 Fyllningsdammar Tillämpningsvägledning*. Swedenergy AB, Stockholm, Sweden.

New design concept for grout curtains

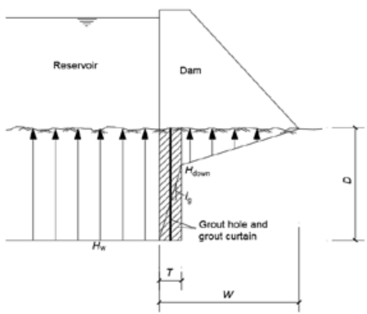
Preliminary design

Design of grout curtain:

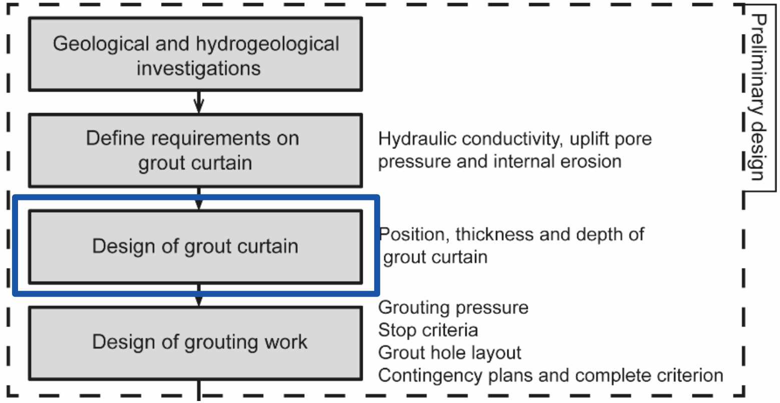
- Position

  Close to the heel of the concrete dam

- Thickness



- Depth (in relation to the Lugeon test results)



Design the grout curtain as a structural component of the dam foundation, instead of a foundation treatment under the dam.

New design concept for grout curtains

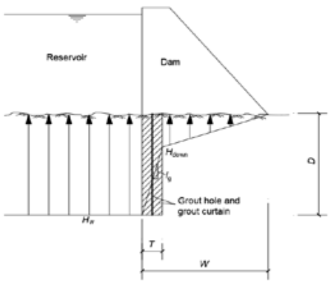
Preliminary design

Design of grout curtain:

- Position

  Close to the heel of the concrete dam

- **Thickness (a multi-factor determination)**



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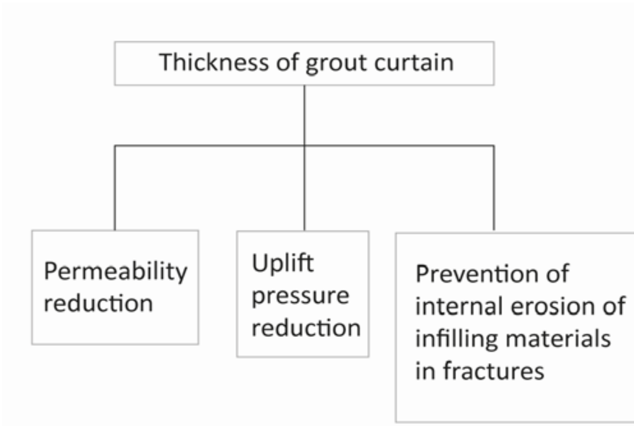
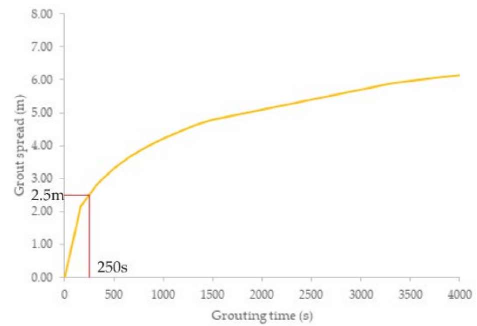


New design concept for grout curtains

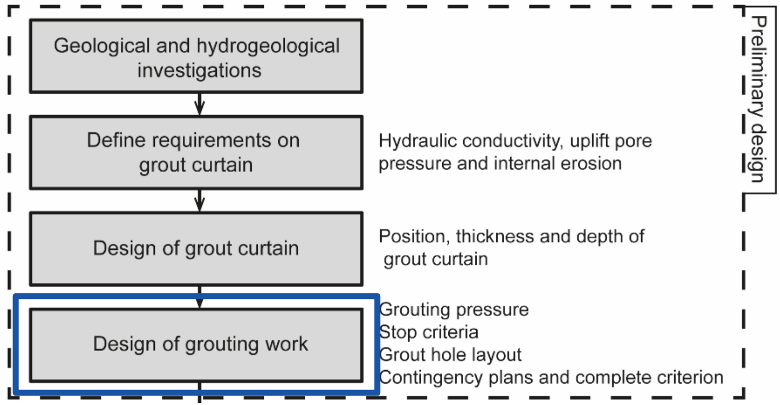
Preliminary design

- Grout spread *vs* Time (stop criteria)



- Additional stop criteria - Volume

$$V_{tot} = \pi I^2 \cdot b = \pi \left(I_D \cdot I_{\max} \right)^2 \cdot b = \pi I_D{}^2 \left[\frac{\Delta P_g}{2\tau_0} \right]^2 \cdot b^3$$



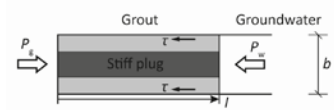
Unique expression of 2D radial spread (with relative grout spread I_D and relative grouting time t_D)

$$I_D = \sqrt{\theta^2 + 4\theta} - \theta \qquad \theta = \frac{t_D}{2(3 + t_D + 0.23 \ln t_D)}$$

where

$$I_D = \frac{I}{I_{max}} \qquad I_{max} = \left(\frac{\Delta P_g}{2\tau_0} \right) b$$

$$t_D = \frac{t}{t_0} \qquad t_0 = \frac{6 \Delta P_g \mu_g}{\tau_0^2}$$



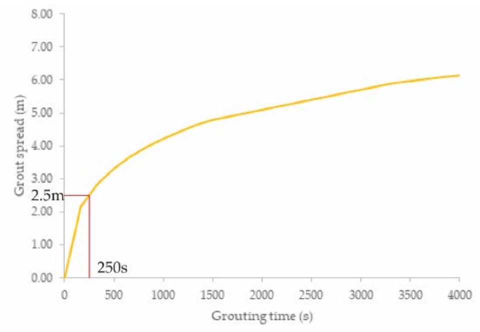
After Gustafson (2012)

Stille H (2015) *Rock Grouting- Theories and Applications*, BeFo, Stockholm, Sweden.
Gustafson, G. (2012). *Hydrogeology for Rock Engineers*, BeFo, Stockholm, Sweden.

New design concept for grout curtains

Preliminary design

- Grout spread *vs* Time (stop criteria)



- Additional stop criteria - Volume

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Stop criteria should be designed considering a “boundary fracture aperture”, which is defined as the fracture aperture above which a fully sealed fracture can be expected (larger than b_{crit}).

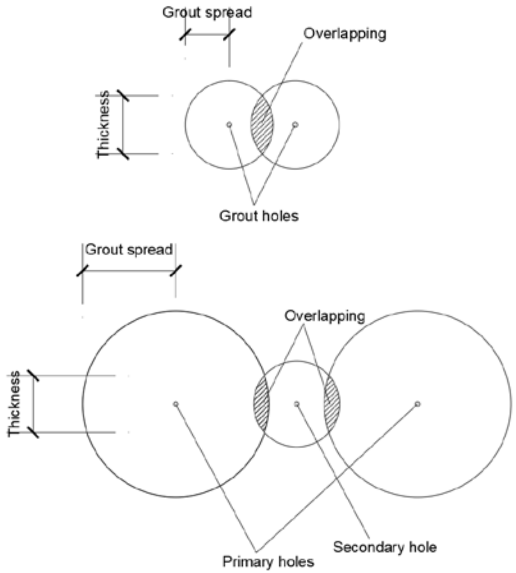
It is not necessary to seal very small fractures. The grouting time will become much longer to obtain the same grout spread, which is not efficient.

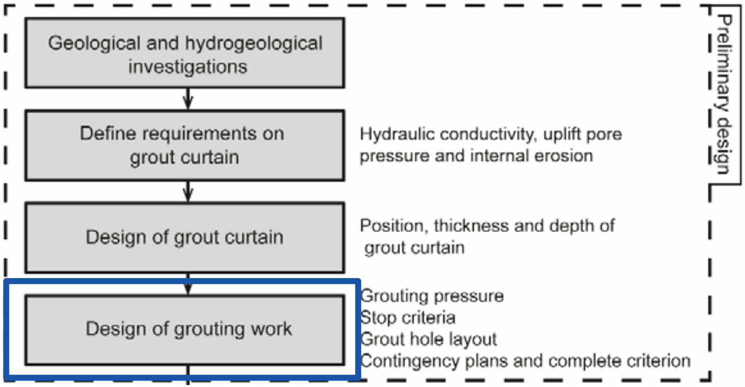
Stille H (2015) *Rock Grouting- Theories and Applications*, BeFo, Stockholm, Sweden.

New design concept for grout curtains

Preliminary design

Relate the thickness of grout curtain to the grout spread and hole spacing:





New design concept for grout curtains

Grouting execution

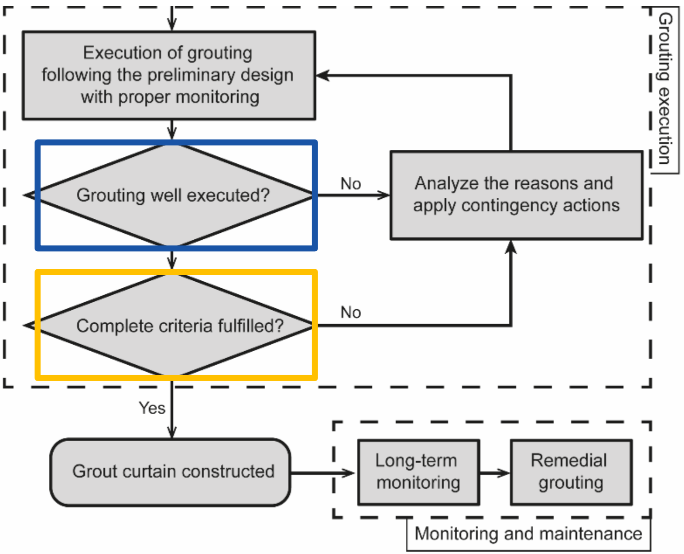
Following the observational method

- The data on grout volume (or flow) *vs* time should be collected and analyzed during grouting.
- Hydraulic jacking should be monitored with extensometers at surface or by analyzing the grout volume (or flow) data.

Residual hydraulic conductivity

- should be checked in control holes by Lugeon tests:

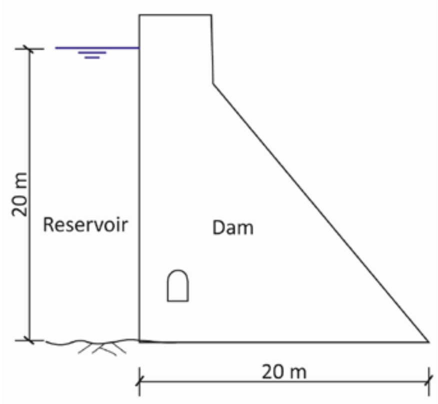
$$K_g < K_{acc}$$



Design example

Fictitious concrete dam

- Concrete gravity dam. Dam height (*H*) is 20m and width (*W*) is 20m.
- The water head (H_w) is assumed to be 20 m above the ground when the reservoir is filled.
- The exploratory holes and the grout holes are vertical and the sections for water testing and grouting are assumed to be 4 m in length. Sections are distributed as follows: 0-4m, 4-8m, 8-12m, 12-16m, 16-20m, 20-24m and 24-28m.
- Grout material INJ30.
- Expected residual conductivity: <1 Lugeon

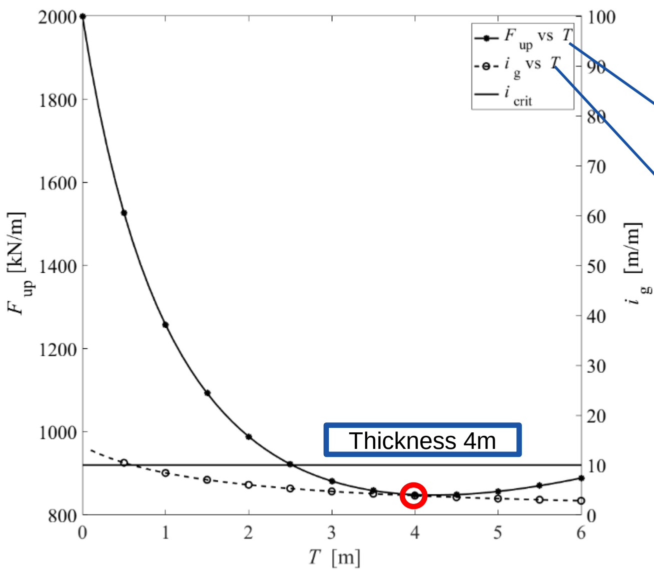


Design example

Thickness of grout curtain

b^{crit}	k_1	k_2	k_3	k_4	K_g	Lu	Result
90µm	0.47	1.25	2	0.45	9.37E-08 m/s	0.6	OK!

$$K_g = \frac{k_1 k_2}{k_3^3 k_4^3} \frac{1}{L} \frac{\rho g}{12\mu} b_{crit}^3$$



$$H_{down} = \frac{b_{crit}^3 (W - T)}{b_{crit}^3 (W - T) + k_3^3 k_4^3 b_{mh}^3 T} H_w$$

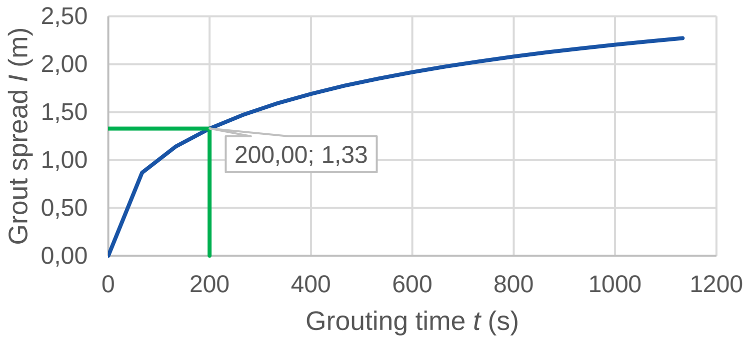
$$F_{up} = \left[\frac{H_{down}(W - T)}{2} + \frac{(H_{down} + H_w)T}{2} \right] \cdot \rho g$$

$$i_g = \frac{H_w - H_{down}}{T}$$

$$= \frac{k_3^3 k_4^3 b_{mh}^3}{b_{crit}^3 (W - T) + k_3^3 k_4^3 b_{mh}^3 T} H_w$$

Design example

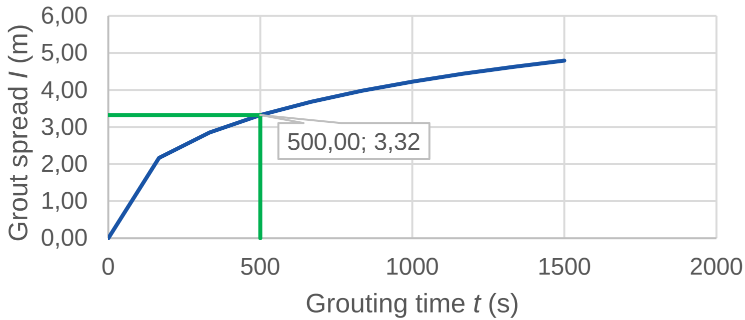
Stop criteria



section 0-4m
with effective grouting
pressure of 0.2MPa

Stille et al. 2009

Stop criteria



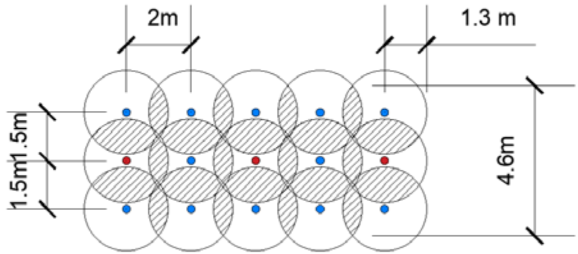
sections below 4m
with effective grouting
pressure of 0.5MPa

Stille et al. 2009

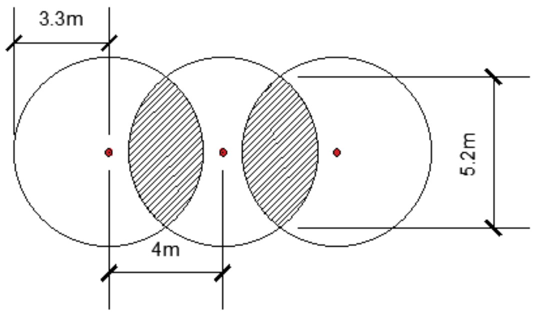
Stop criteria

Design example

Grout hole layout (from above)



section 0-4m

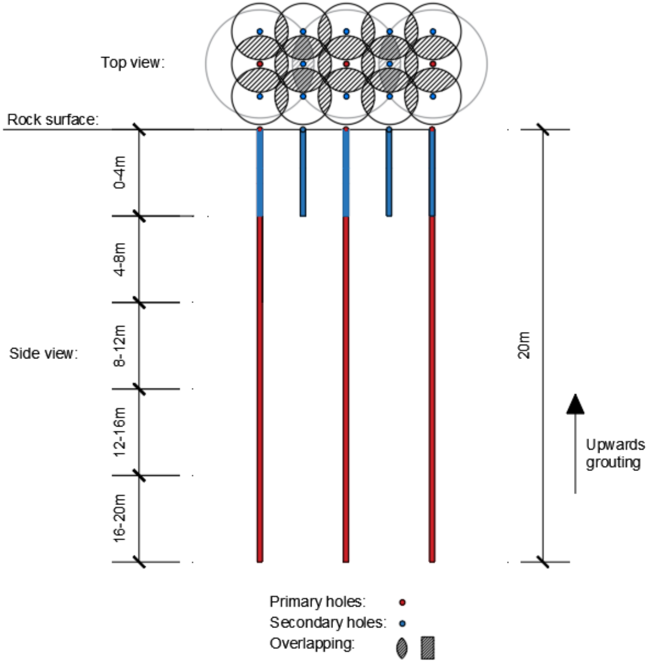


sections below 4m

Primary holes:
Secondary holes:
Overlapping:

Design example

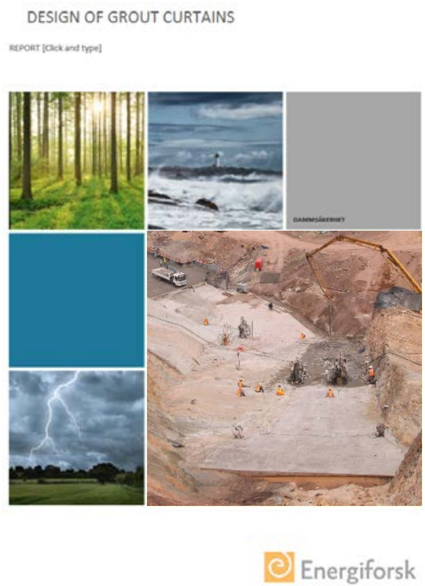
Grouting plan



Grout mix	Grouting section (upwards grouting)	Grouting pressure (MPa)	Grouting time (s)	Injected volume per hole per section (liter)
INJ30 w:c=0.8	16-20 m	0.7	500	24
	12-16 m	0.6	500	45
	8-12 m	0.6	500	105
	4-8 m	0.6	500	92
	0-4 m	0.2	200	19

SVC report- Design of grout curtains

- In-detail description and discussion on the new design concept
- In the process of being published on the Energiforsk website



Future work

- Remedial grouting design
- Grout erosion during remedial grouting (laboratory study)
- Case study on grouting project:
  - ➢ To investigate the grout spread vs time in natural rock mass;
  - ➢ To investigate the grouting’s effect on the uplift pore pressure and hydraulic gradient;
  - ➢ To evaluate the applicability of the design concept.

Thank you!