Minimal flow criterion for RTGC

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1. Minimal flow criterion
2. Flow rate limit and stage target
3. RTGC
4. Inserting MFC into RTGC
5. Application

USA

USDOD

Grouting may be continued…at the maximum grouting pressure …until the hole takes grout at the rate of 1 cu ft or less in 10 min measured over at least a 5-min period

Norway

Follo Line

The injection of hole will be considered finished when at the maximum defined pressure, the injection flows remain below 3lt/min

Sweden

City Line

…at design pressure…grouting could be halted when a grout flow below 1 liter/minute was sustained for 5 minutes ….

Minimal Flow Criterion

Grouting is stopped when

- The flow rate is less than a *given flow rate limit*
- At a *predefined pressure* during a given time period

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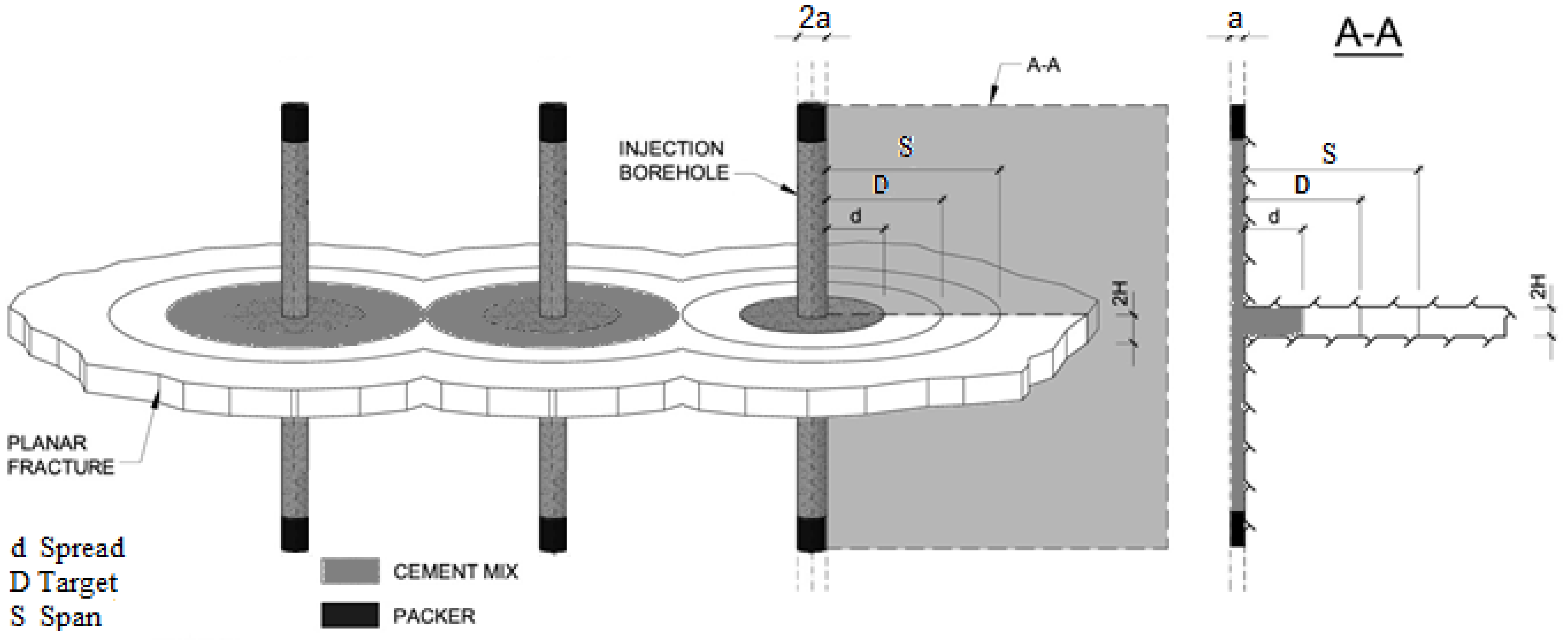
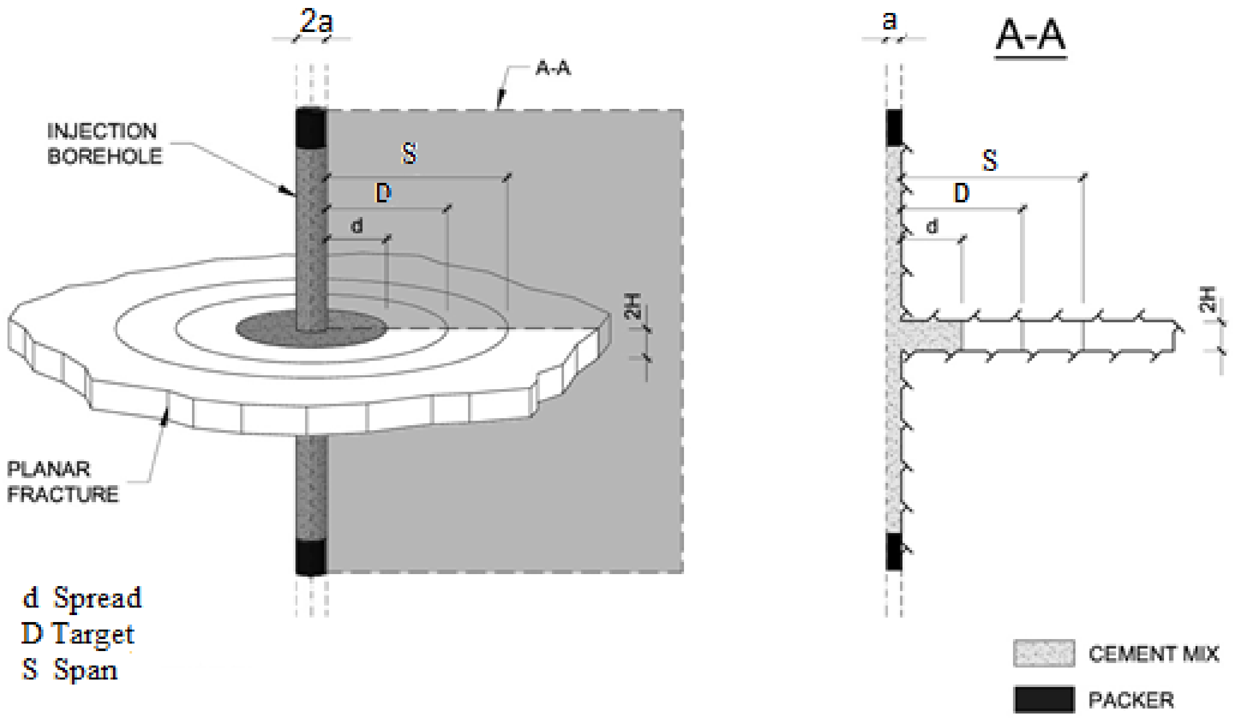
Stage target



a	Radius of the injection hole
H	Half opening of the fracture
d	Spread
D	Stage target
S	Span (Maximal spread)

Flow relation



d Spread
D Target
S Span

$$Q = Q(d, P, H, a, c, \mu)$$

$$Q_L = Q(D, P, H, a, c, \mu)$$

$$P > \frac{Dc}{H}$$

Flow rate limit

$$Q_L = \frac{2\pi}{3\mu}\frac{H^3 P}{\ln(1+\frac{D}{a})}\left(1-\frac{cD}{PH}\right)^2\left(2+\frac{cD}{PH}\right)$$

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RTGC : Basic assumption

There is a distribution of parallel fractures with a dominating largest fracture

The opening of the largest fracture
is determined by a water pressure test

The opening of thinnest injectable fracture
is determined by the designer
based on the cement’s granulometry or d95

RTGC : Stage target

The stage target is a predefined spread

RTGC : Stage target

The stage target is a predefined spread

The target is reached

First in the largest fracture

Second in the second largest one

Last in the thinnest injectable fracture

RTGC : Stop criterion

Grouting is stopped after a time period t(D) the target is attained in the thinnest injectable fracture

Excepting grouting in ideal conditions the time period t(D) is generally unknown

$t(D) = T + \Delta T + \delta T$

T is the ideal time

ΔT is the delay due to uncertainties

δT is the delay due to non conform grouting

Substitutive stop criterion for RTGC

A stop criterion that is unaffected by the delays is needed.

The time period was substituted with an observational one based on water ingress during the construction of the City Line

In case the observational method is not applicable the Minimal Flow Criterion is a potential substitute.

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Immersion

The flow rate limit needs to be adapted to RTGC

A dominating fracture

The objective is the target in the thinnest injectable fracture

$$Q_L = Q(d_g(t(D)), P, H_g, a, c, \mu)$$

t(D) is unknown and so far are $d_g(t(D))$ and Q_L

H_g is half the opening of the largest fracture

d_g is the spread in the largest fracture

Shortcut

A shortcut to the time problem is obtained from the governing equations

$$\frac{d_g(t)}{H_g} \le \frac{d_t(t)}{H_t}$$

The consequence of which is

$$Q(\frac{H_g}{H_t} D, P, H_g, a, c, \mu) \le Q(d_g(t(D)), P, H_g, a, c, \mu)$$

H_t is half the opening of the thinnest fracture

d_t is the spread in the thinnest fracture

H_g is half the opening of the largest fracture

d_g is the spread in the largest fracture

Flow rate limit for RTGC

$$Q_L = \frac{2\pi}{3\mu} \frac{H_g^3 P}{\ln\left(1 + \frac{H_g}{H_t} \frac{D}{a}\right)} \left(1 - \frac{Dc}{PH_t}\right)^2 \left(2 + \frac{Dc}{PH_t}\right)$$

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City Line : Access tunnel

Data

c	6	Pa
μ	20	mPas
a	32	mm
$2H_g$	0.20	mm
$2H_t$	0.07	mm
D	2.5	m

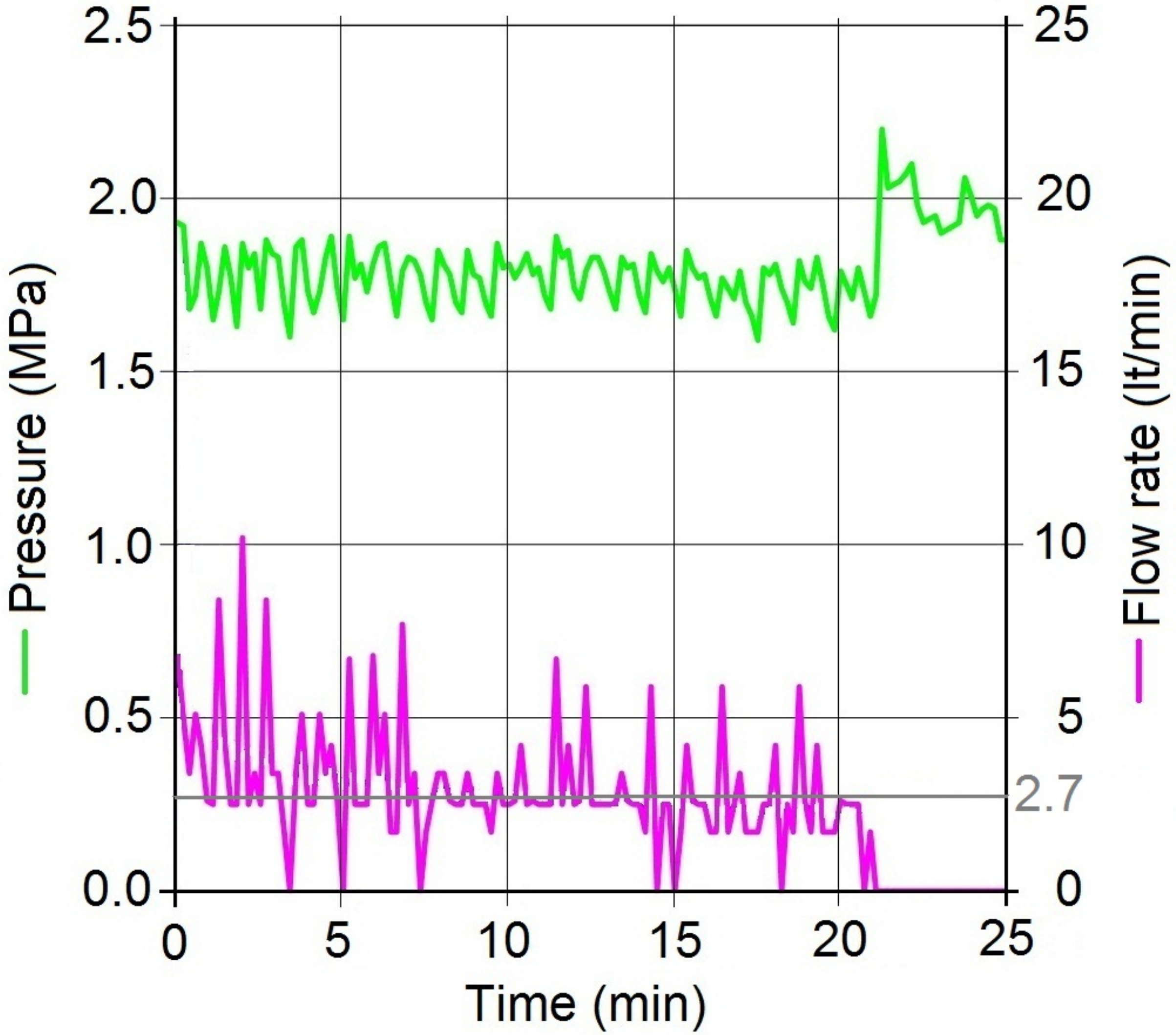
Injection Pressure

P 1.8 MPa

Flow rate limit

Q_L 2.7 lt/min

$d_g(t(D))$ 7.1 m



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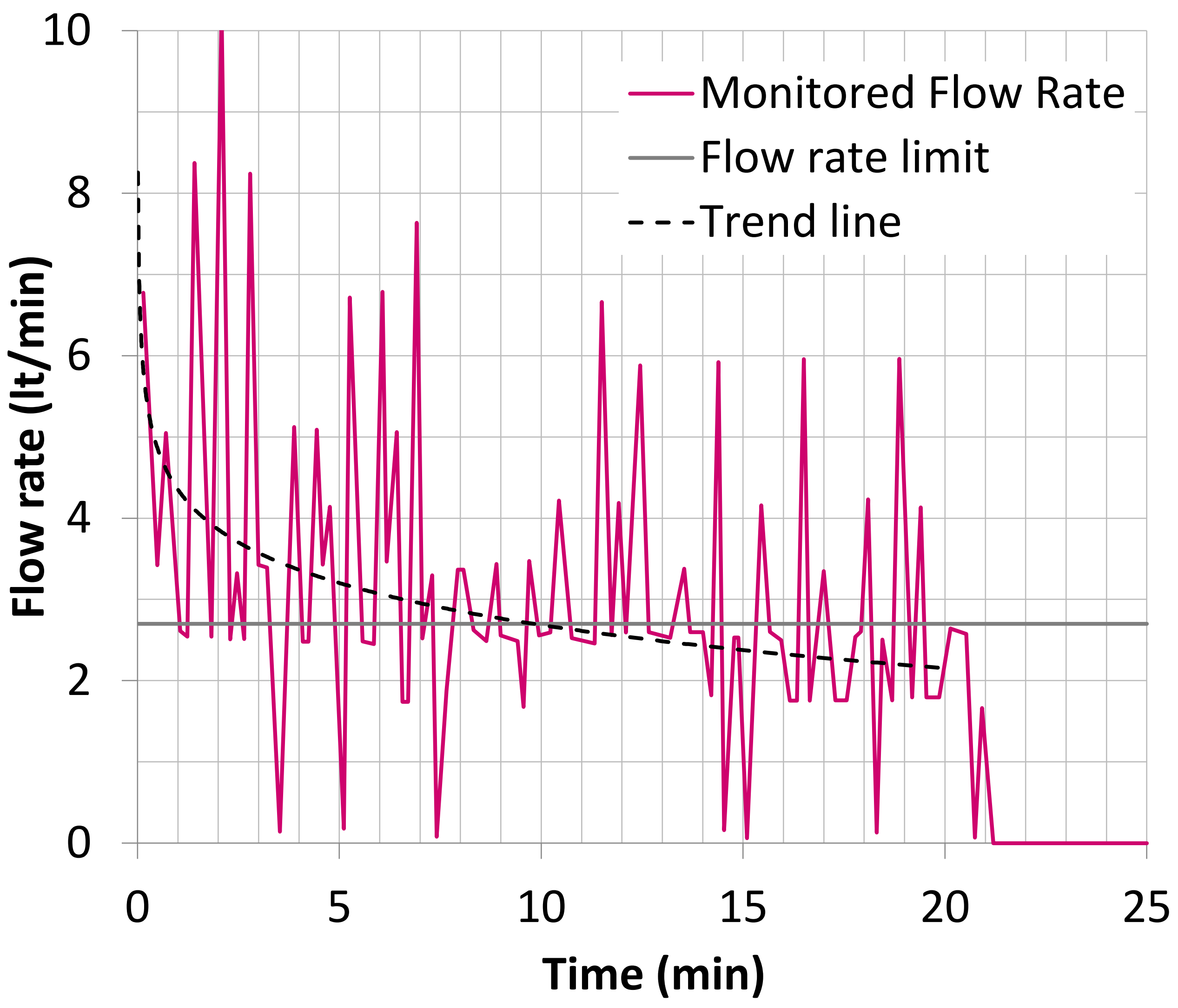
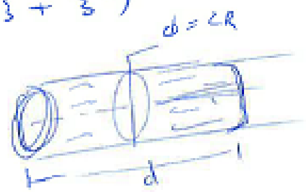


Pipe

$$Q = \frac{\pi R^4}{24\eta} \frac{P}{d} (1-\zeta)^2 (3 + 2\zeta + \zeta^2)$$

$$\zeta = \frac{2cd}{PR}$$

$$S = \frac{PR}{2c}$$



- Q flow rate
- P Excess pressure
- R Pipe radius
- d Current advance (penetration)
- c cohesion
- η viscosity
- ζ advance ratio ($= \frac{d}{S}$)
- S Span (Max penetration at P)

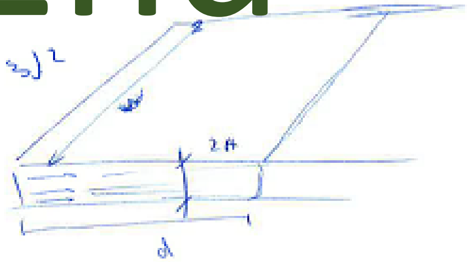
End

Planar 1D

$$Q = \frac{wH^3}{3\eta} \frac{P}{d} (2+\zeta)(1-\zeta)^2$$

$$\zeta = \frac{cd}{PH}$$

$$S = \frac{PH}{c}$$



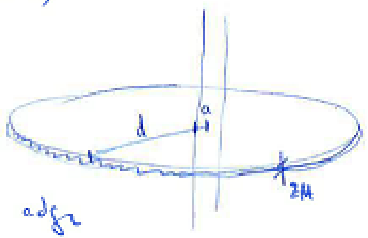
- w width of the fracture
- H half thickness of the fracture

Planar radial

$$Q = \frac{2\pi}{3\eta} \frac{H^3 P}{\ln(1+\frac{d}{a})} (1-\zeta)^2 (2+\zeta)$$

$$\zeta = \frac{cd}{PH}$$

$$S = \frac{PH}{c}$$



- d is measured from the borehole edge
- a radius of the borehole