Paolo Perazzelli
Pini Swiss Engineers, Zurich

Bolt reinforcement of the tunnel face

Kolloquium
Bauhilfsmassnahmen im Tunnelbau
ETH Zürich

Outline

- Introduction

- Analysis method

- On the effect of the design parameters
  grounds **above the water table**
  grounds **below the water table (drained and undrained)**

- Conclusions

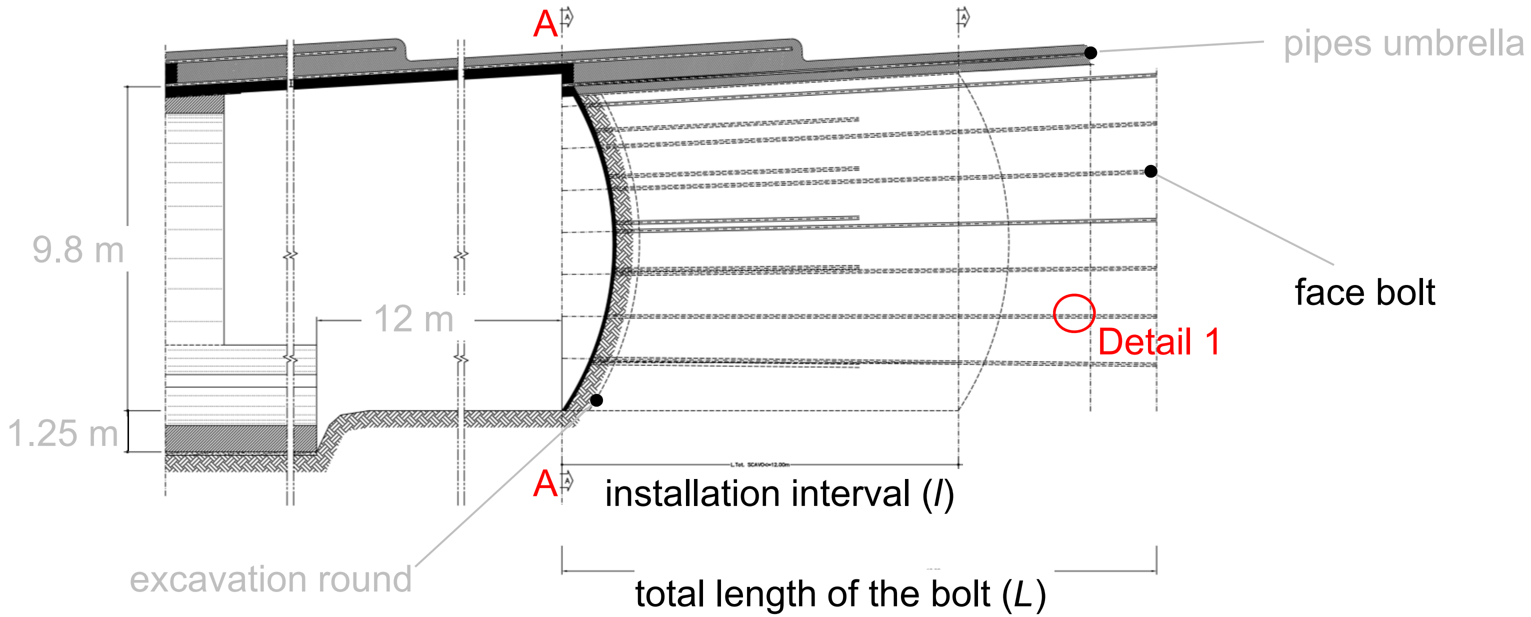
Introduction

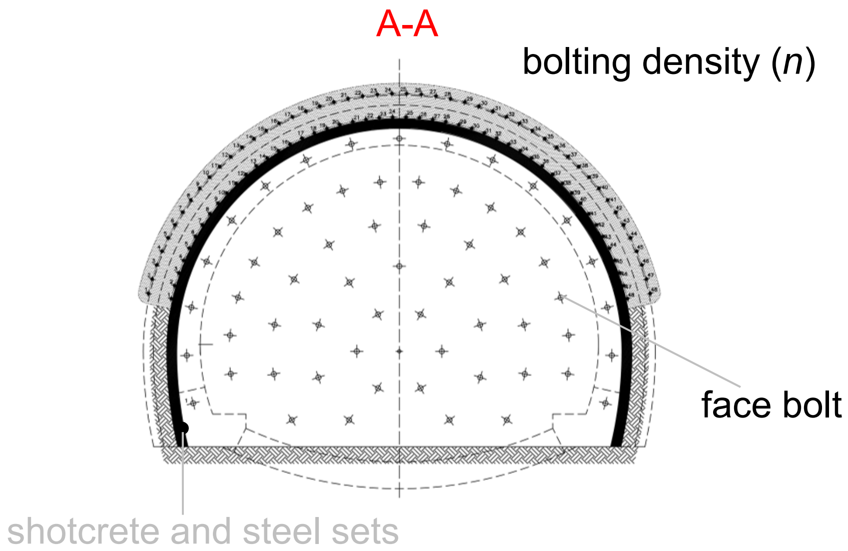
General overview

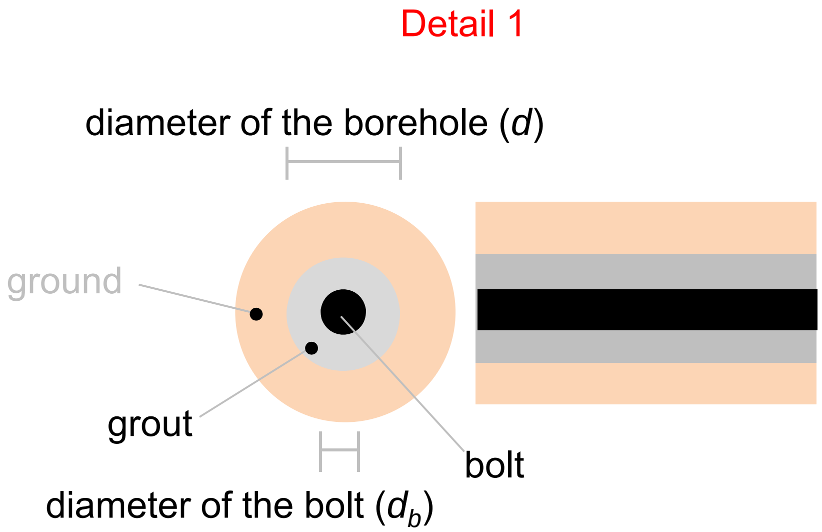
- Ground reinforcement using bolts is a very effective measure for stabilizing the face in **conventional tunnelling**

Introduction

General overview







Introduction

Research at the ETH Zurich

- Anagnostou, G., Serafeimidis, K., 2007. *The dimensioning of tunnel face reinforcement*. World Tunnel Congress 2007 (Prague)

- Serafeimidis, K., Ramoni, M., and Anagnostou, G. (2007). *Analysing the stability of reinforced tunnel faces*. Europ. Conf. on Soil Mech. and Geotech. Eng. (Rotterdam)

- Perazzelli, P., Anagnostou, G., 2013. *Stress analysis of reinforced tunnel faces and comparison with the limit equilibrium method*. Tunnel. Undergr. Space Techn. 38, 87–98

- Anagnostou, G., Perazzelli, P., 2015. *Analysis method and design charts for bolt reinforcement of the tunnel face in cohesive-frictional soils*. Tunnel. Undergr Space Techn. 47, 162–181

- Perazzelli, P., Anagnostou, G., 2017. *Analysis method and design charts for bolt reinforcement of the tunnel face in purely cohesive soils.* Journal of geotechnical and geoenvironmental engineering, 143 (9), American Society of Civil Engineers.

- Perazzelli, P., Cimbali, G., Anagnostou, G., 2017. Stability under seepage flow conditions of a tunnel face reinforced by bolts. EUROCK 2017 (Ostrava)

Introduction

Relevant design parameters

- Surface load
- Unit weight of the ground
- Level of the water table
- Overburden
- Shape and dimension of the tunnel
- Unsupported span

} Load

- Strength of the ground (c', φ', s_u)
- Bond strength of bolt/grout and grout/ground
- Tensile resistance of the bolt
- Bolting density
- Bolting type (diameter, with/without plate,…)
- Bolting length and installation interval

} Resistance

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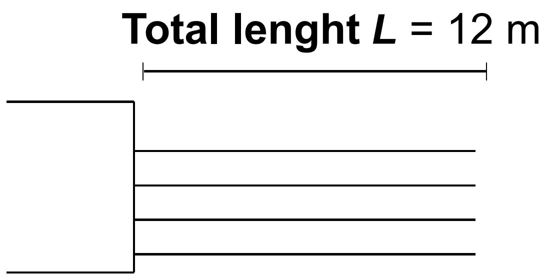
Resistance

Introduction

Relevant design parameters

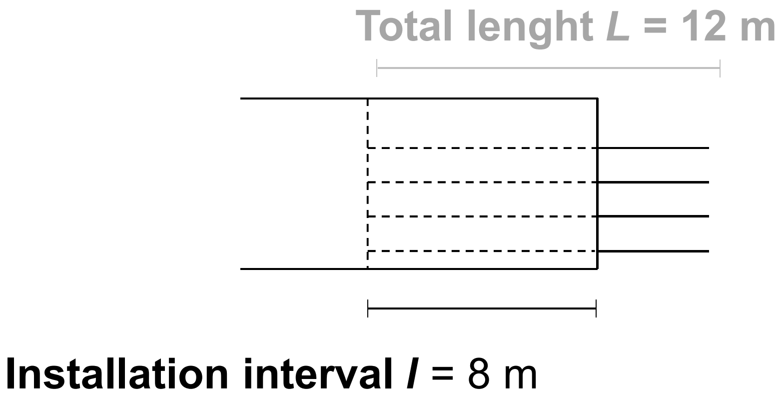
(a) Large installation interval



Introduction

Relevant design parameters

(a) Large installation interval



Introduction

Relevant design parameters

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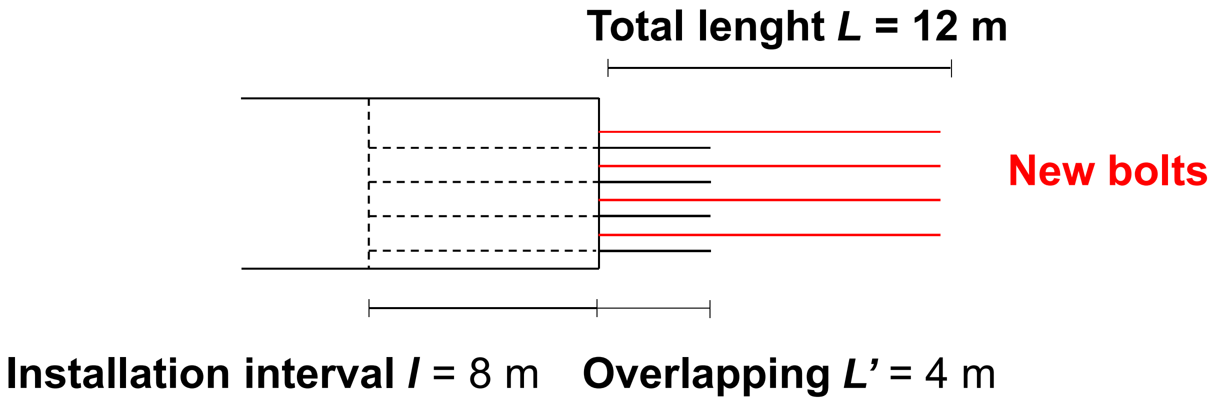
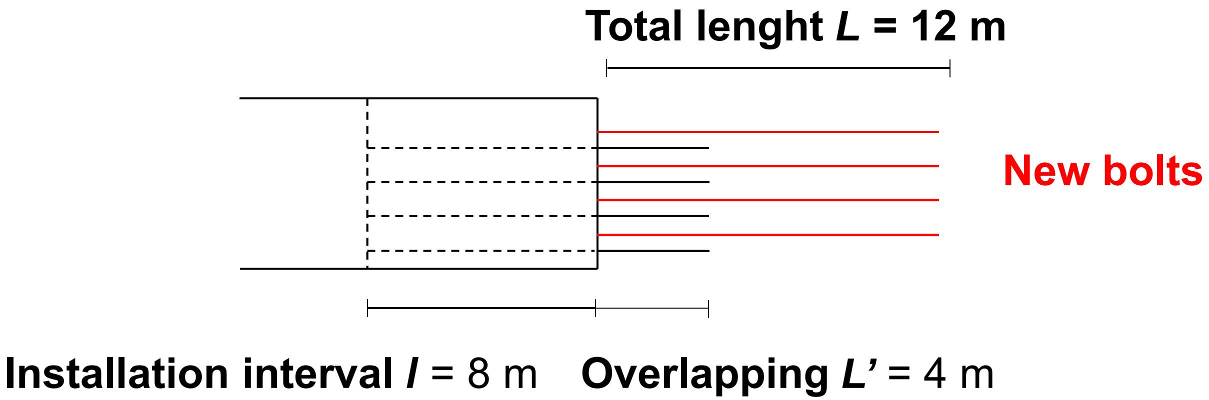


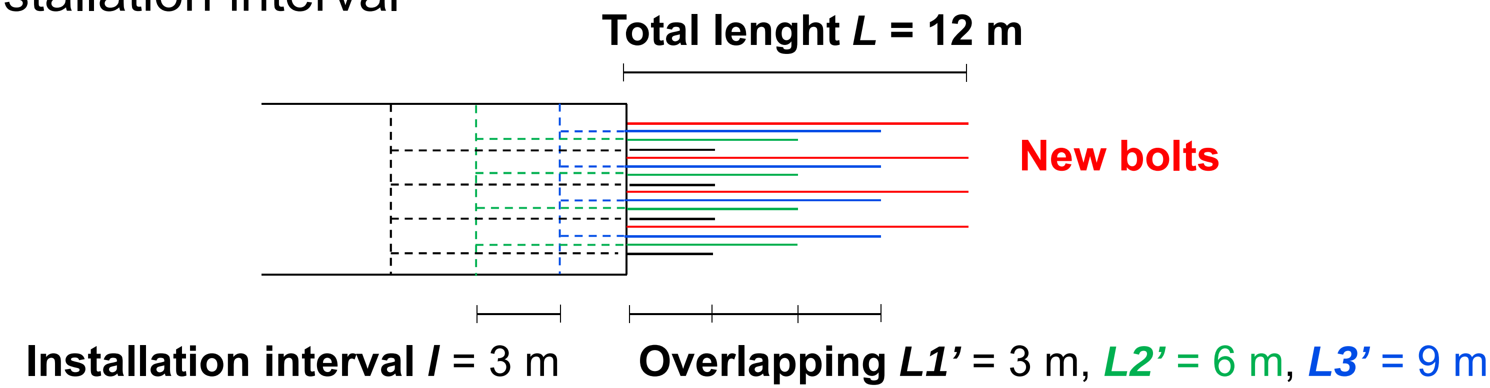
Introduction

Relevant design parameters

(a) Large installation interval



(b) Small installation interval



Analysis method

General concept - Failure mechanism

Ground above the water table

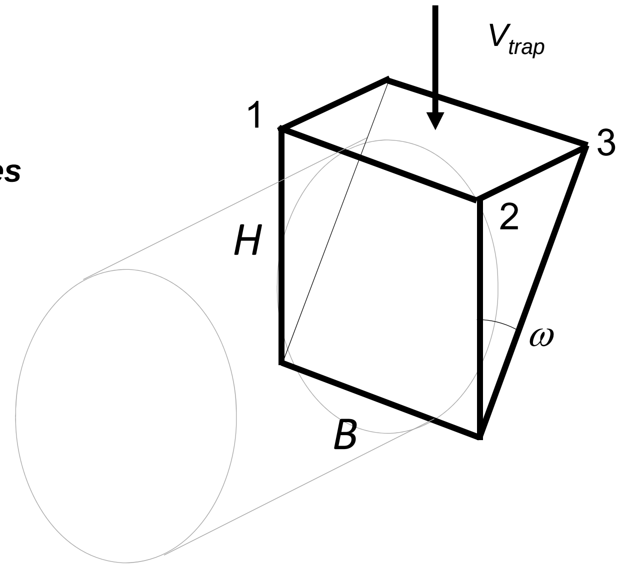
Ground below the water table – drained

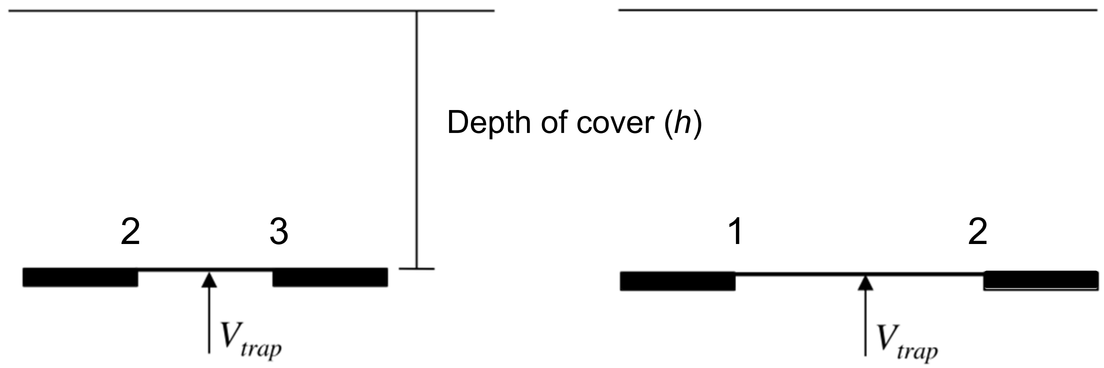
Ground below the water table – undrained

Analysis method

General concept - Failure mechanism

- Limit equilibrium condition
  Trapdoor load V_{trap} = Bearing capacity of wedge V_{res}





Analysis method

General concept - Failure mechanism

Ground above the water table

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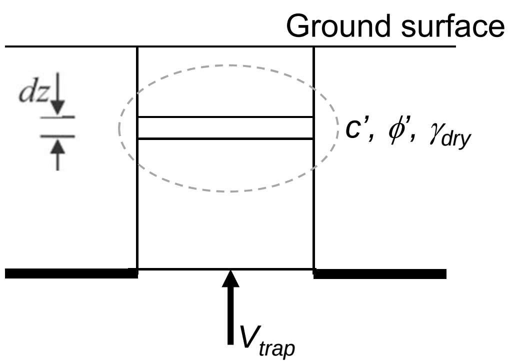
Ground below the water table – undrained

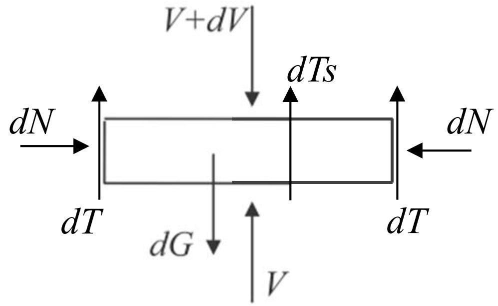
Analysis method

Ground above the water table

- Trapdoor load
  Limit equilibrium of slices
  (silo theory)

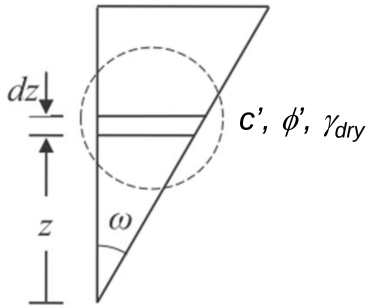
$\sigma_x = \lambda_p \sigma_y$

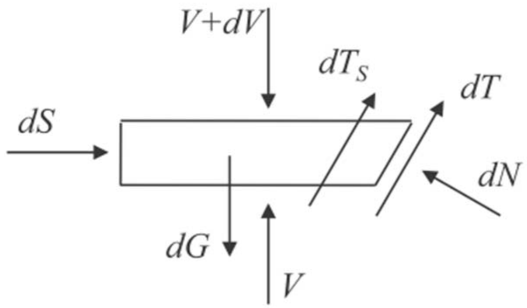




- Bearing capacity of wedge
  Limit equilibrium of slices

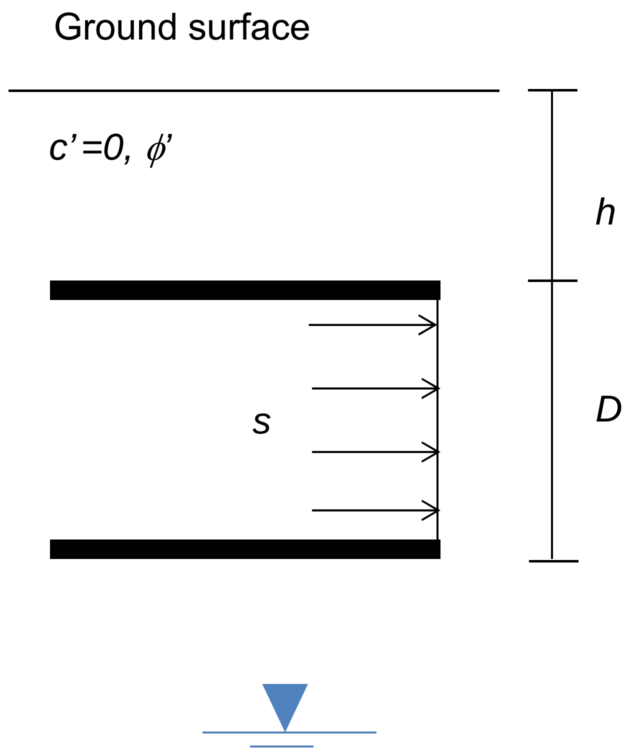
$\sigma_x = \lambda_w \sigma_y$



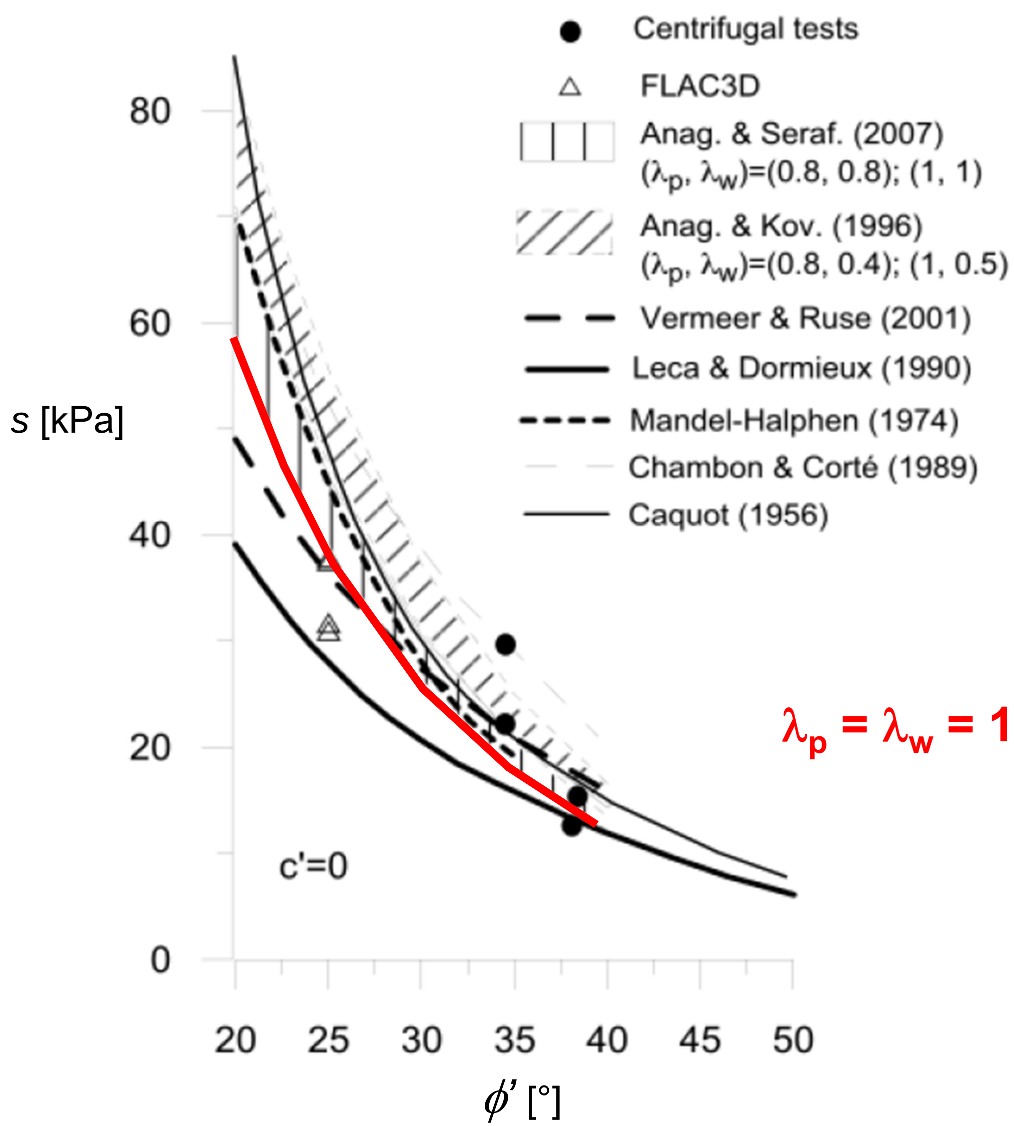


Analysis method

Ground above the water table



Comparison with experimental results and other methods



Analysis method

General concept - Failure mechanism

Ground above the water table

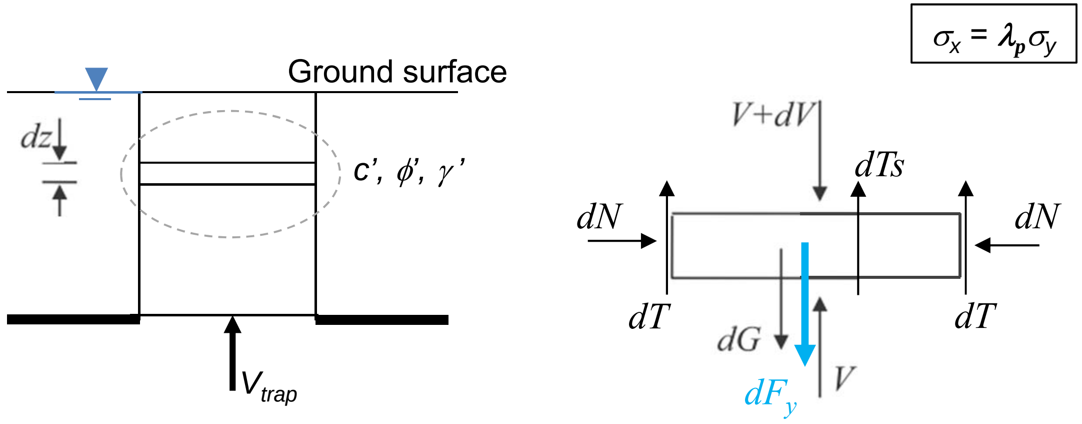
Ground below the water table – drained

Ground below the water table – undrained

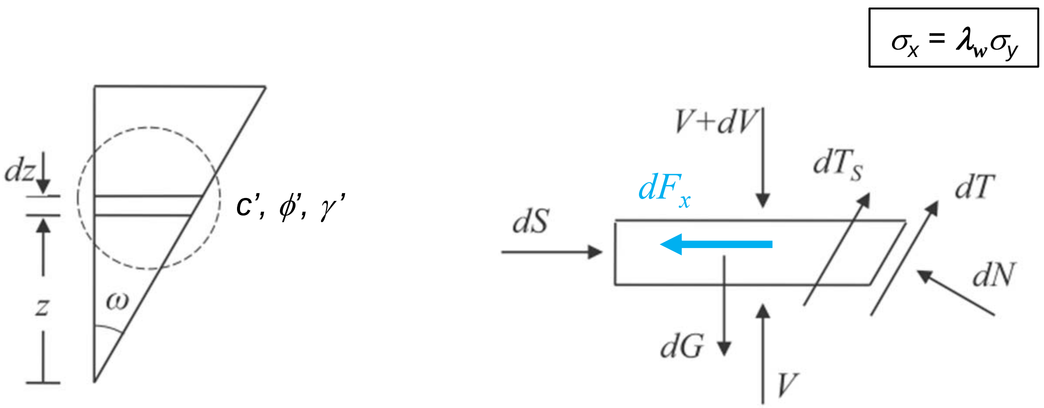
Analysis method

Ground below the water table – drained

- Trapdoor load
  Limit equilibrium of slices
  (silo theory)



- Bearing capacity of wedge
  Limit equilibrium of slices



Analysis method

General concept - Failure mechanism

Ground above the water table

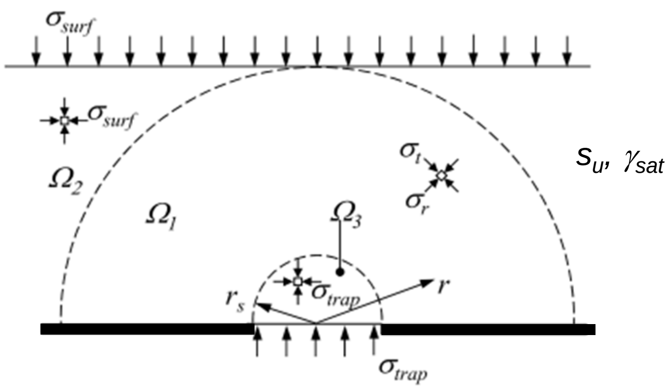
Ground below the water table – drained

Ground below the water table – undrained

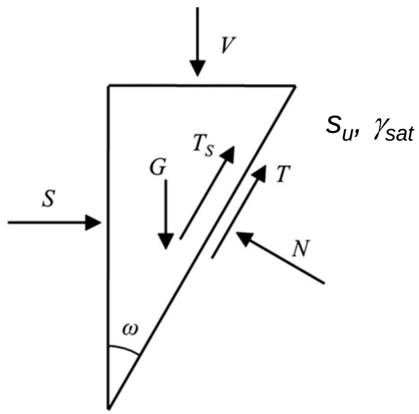
Analysis method

Ground below the water table – undrained

- Trapdoor load
  Upper bound approach

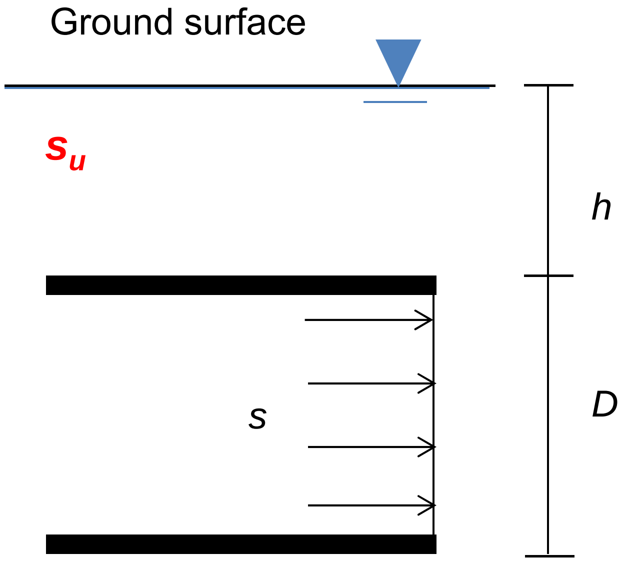


- Bearing capacity of wedge
  Limit equilibrium of the entire wedge



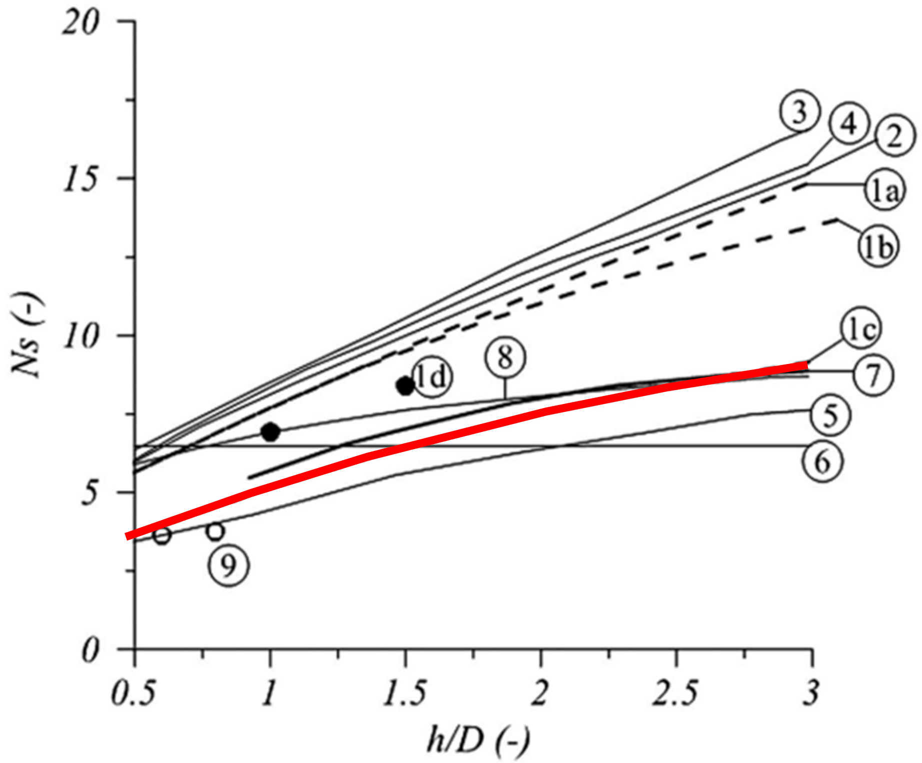
Analysis method

Ground below the water table – undrained



$$N_s = \frac{\sigma_{v0} - s}{s_u}$$

Comparison with experimental results and other methods



- (1a) V_{trap} by silo theory
- (1b) V_{trap} by kinematic approach based upon Gunn (1980)
- (1c) V_{trap} by static approach based upon Gunn (1980)
- (1d) Numerical stress analysis (Appendix III)

Other methods

- (2) Mollon et al. (2010) (kinematic approach)
- (3) Mollon et al. (2009) (kinematic approach)
- (4) Davis et al. (1980) (kinematic approach)
- (5) Davis et al. (1980) (static approach)
- (6) Broms and Bennermark (1967)
- (7) Kimura and Mair (1981) (centrifuge tests)
- (8) Ellstein (1986)
- (9) Bezuijen and Van Seters (2006) (centrifuge tests)

Analysis method

Support pressure given by the bolts

Analysis method

Support pressure given by the bolts

$s = n*\min\,[F_t,\ \max(\min(d\tau_m,\ d_b\tau_g)\pi a,\ F_p),\ \min(d\tau_m,\ d_b\tau_g)\pi a(L'-a)]$

Bearing capacity of the bolt plate

Tensile resistance of the bolt

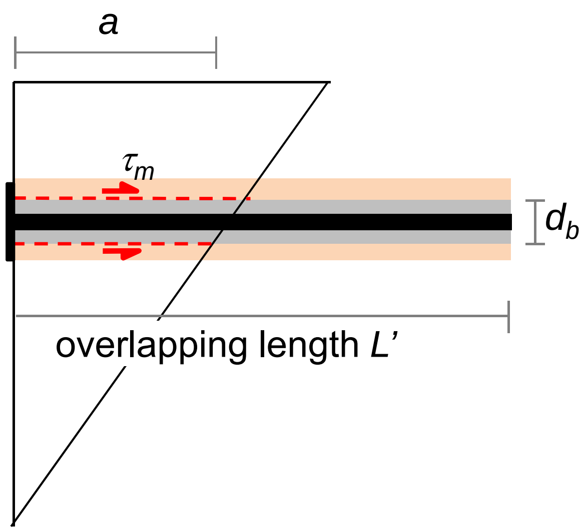
Bolting density

Analysis method

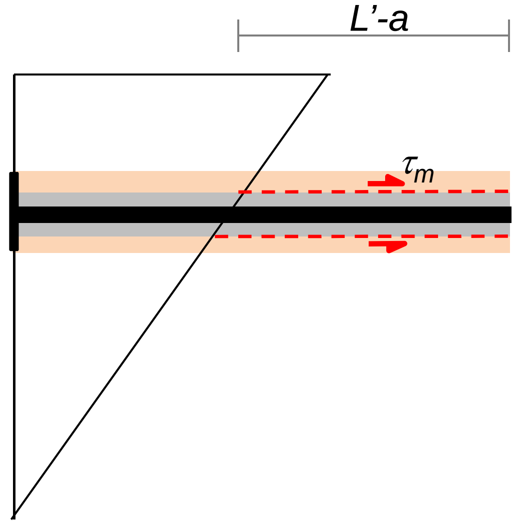
Support pressure given by the bolts

$$s = n^{*}\min\left[F_t,\ \max\left(\min(d\tau_m,\ d_b\tau_g)\pi a,\ F_p\right),\ \min(d\tau_m,\ d_b\tau_g)\pi a(L'-a)\right]$$

Pull-out resistance inside the sliding wedge

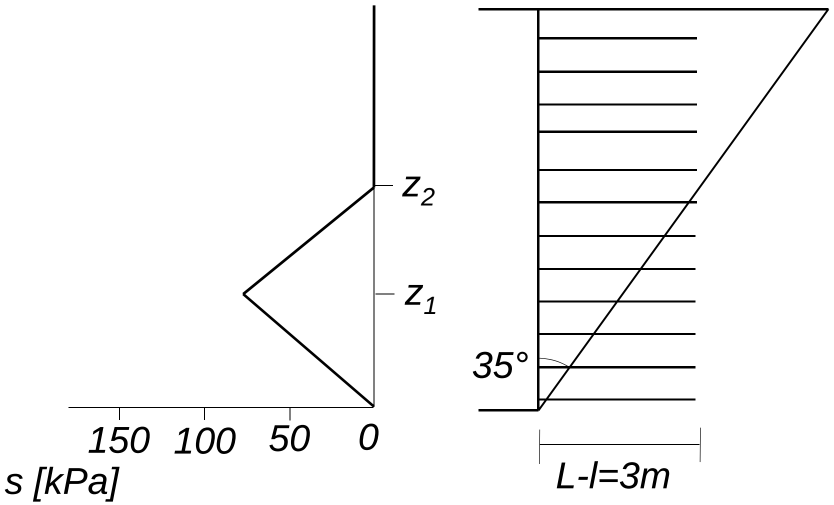


Pull-out resistance outside the sliding wedge



Analysis method

Support pressure given by the bolts



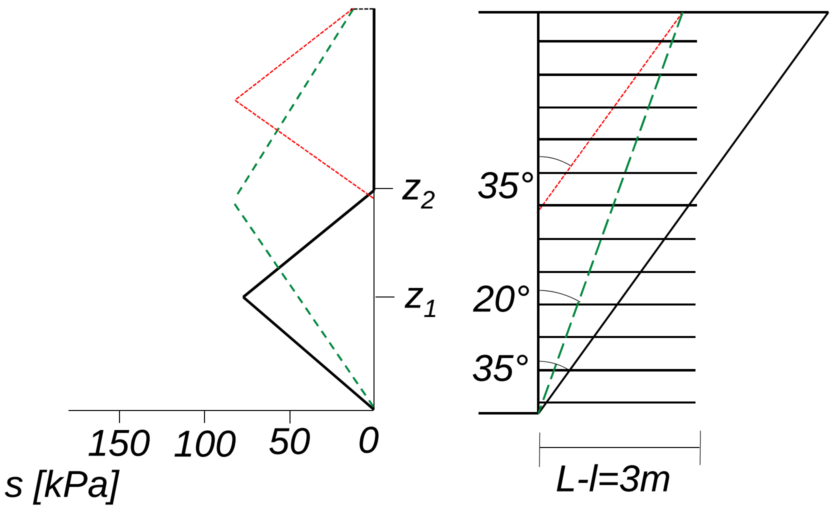
n=1 bolt/m²

L=12 m

l=9 m

Analysis method

Support pressure given by the bolts



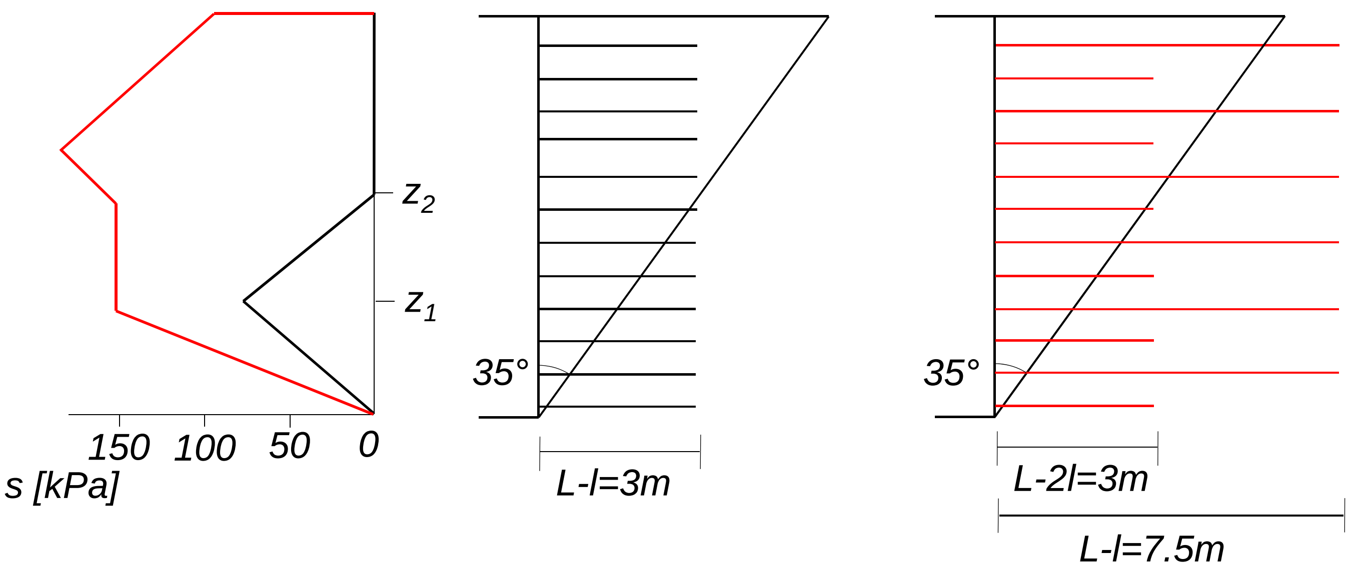
n=1 bolt/m^2

L=12 m

l=9 m

Analysis method

Support pressure given by the bolts



n=1 bolt/m²
L=12 m
l=9 m

n=1 bolt/m²
L=12 m
l=4.5 m

Analysis method

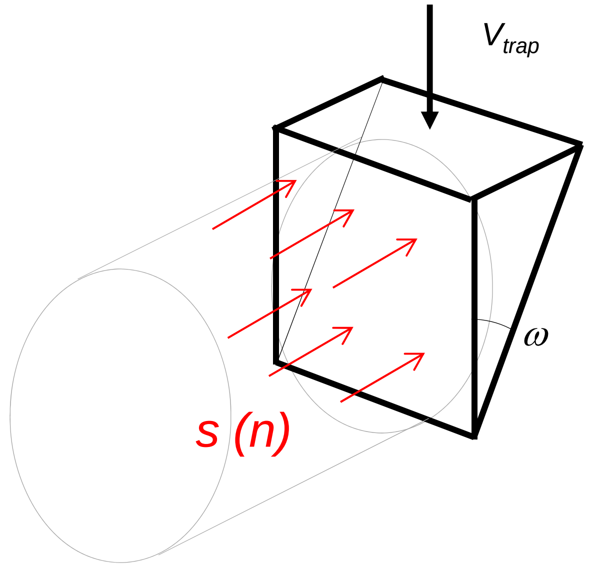
Computation of the minimum required number of bolts

Analysis method

Computation of the minimum required number of bolts

- For fixed failure mechanism i, required density of bolts $\boldsymbol{n_i}$ is such that limit equilibrium condition fulfilled

- **Minimum required number of bolts n_{cr} = $max\ (n_i)$**



Analysis method

Computation of the minimum required number of bolts

For the special case of a **homogeneous ground with uniform face reinforcement**

- Limit equilibrium condition

↓

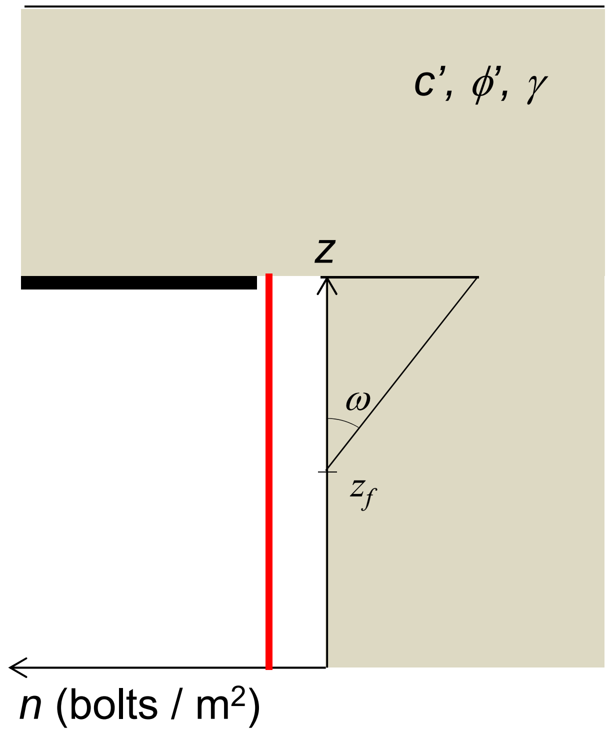
- $n = n(\omega, z_f)$ (closed form solution)

↓

- $n_{cr} = \max [n(\omega, z_f)]$

↓

→ **simple optimization problem (one-variable)**



Analysis method

Computation of the minimum required number of bolts

For the most **general case of heterogeneous ground and arbitrary bolt distribution**

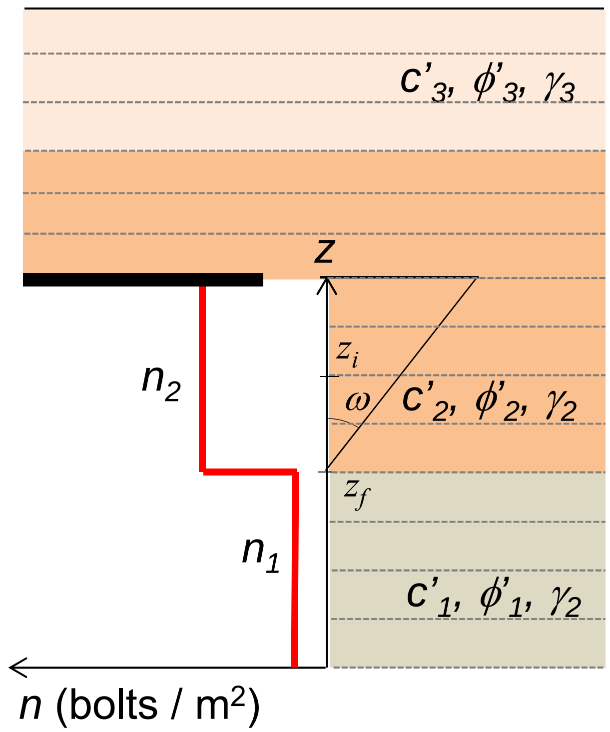
- $N = \min \sum n_k A_k$

  $V_{res}(\omega, z_f) \geq V_{trap}(\omega, z_f)$

  $V(\omega, z_f, z_i) \geq 0$

↓

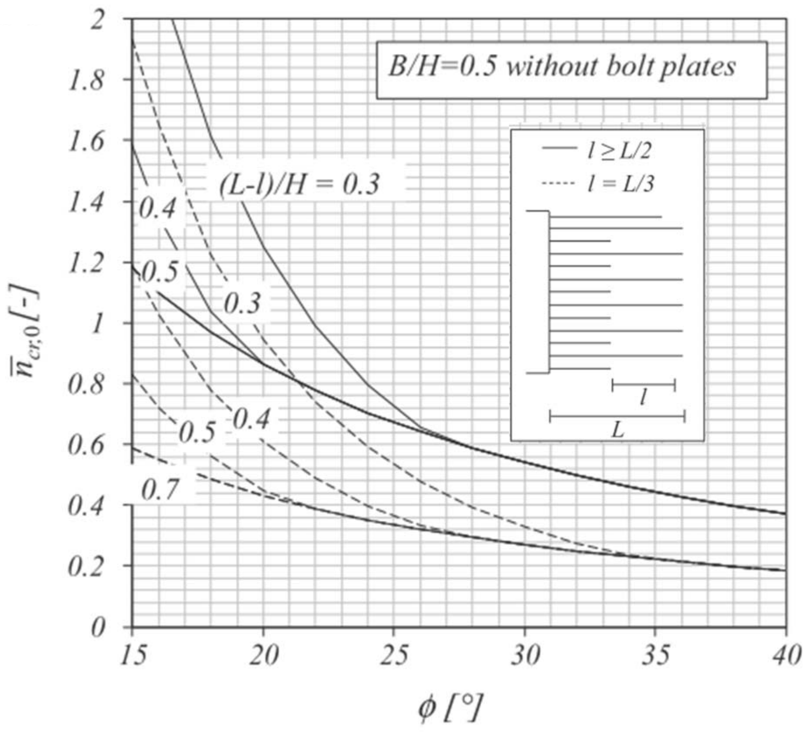
→ **complex optimization problem (multi-variable): numerical solution based on the simplex method**

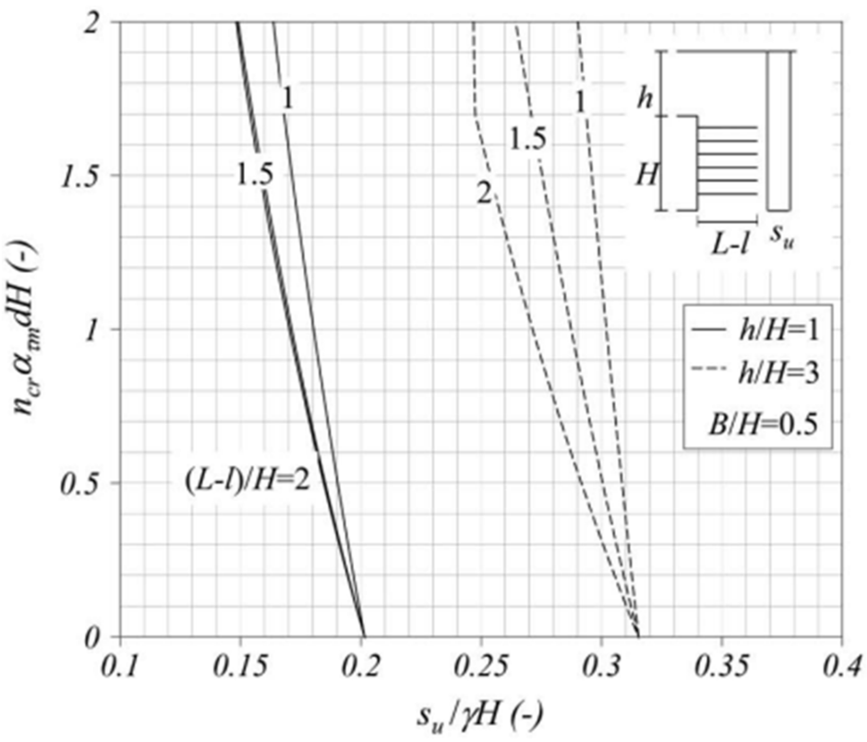


Analysis method
Design tools

For the special case of a homogeneous ground with uniform face reinforcement

- **Design charts**





Analysis method

Design tools

For the special case of a homogeneous ground with uniform face reinforcement

- **Tunnel+ (free App for smartphones)**

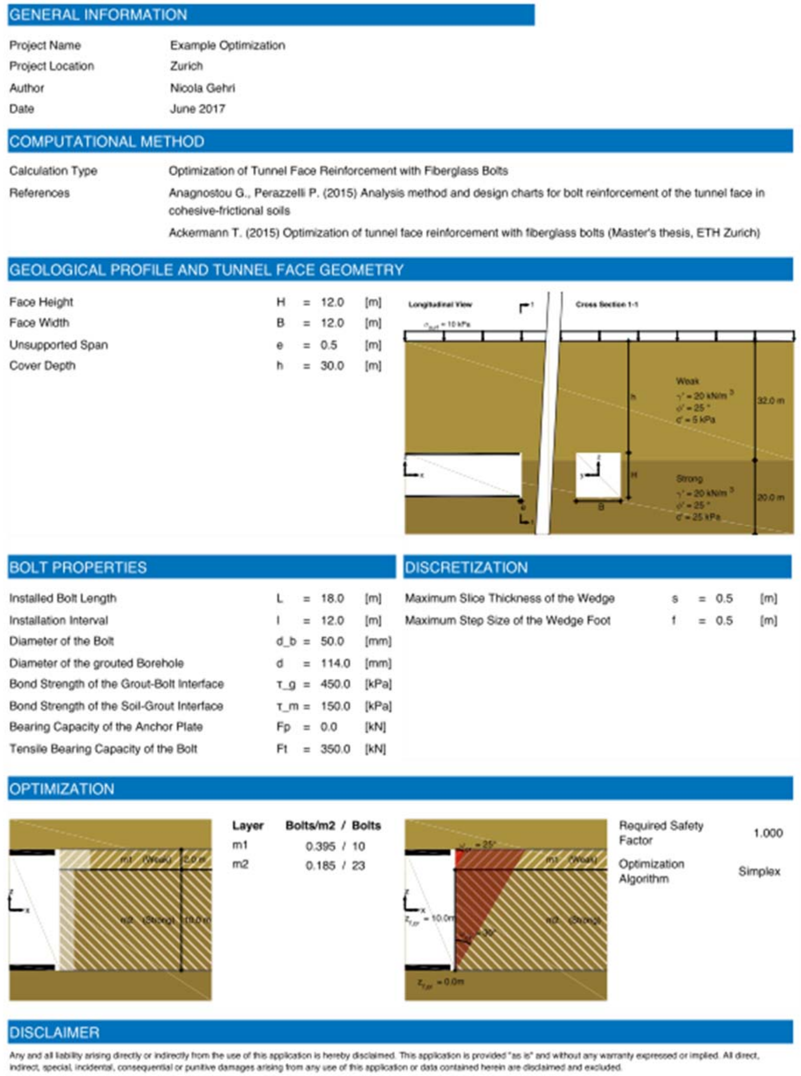
Tunnel+

Analysis method

Design tools

For the most general case of heterogeneous ground and arbitrary bolt distribution

- **Standalone computer application with Graphical User Interface**



GENERAL INFORMATION

Project Name	Example Optimization
Project Location	Zurich
Author	Nicola Gehri
Date	June 2017

COMPUTATIONAL METHOD

Calculation Type	Optimization of Tunnel Face Reinforcement with Fiberglass Bolts
References	Anagnostou G., Perazzelli P. (2015) Analysis method and design charts for bolt reinforcement of the tunnel face in cohesive-frictional soils
	Ackermann T. (2015) Optimization of tunnel face reinforcement with fiberglass bolts (Master's thesis, ETH Zurich)

GEOLOGICAL PROFILE AND TUNNEL FACE GEOMETRY

Face Height	H	=	12.0	[m]
Face Width	B	=	12.0	[m]
Unsupported Span	e	=	0.5	[m]
Cover Depth	h	=	30.0	[m]

BOLT PROPERTIES

Installed Bolt Length	L	=	18.0	[m]
Installation Interval	l	=	12.0	[m]
Diameter of the Bolt	d_b	=	50.0	[mm]
Diameter of the grouted Borehole	d	=	114.0	[mm]
Bond Strength of the Grout-Bolt Interface	τ_g	=	450.0	[kPa]
Bond Strength of the Soil-Grout Interface	τ_m	=	150.0	[kPa]
Bearing Capacity of the Anchor Plate	Fp	=	0.0	[kN]
Tensile Bearing Capacity of the Bolt	Ft	=	350.0	[kN]

DISCRETIZATION

Maximum Slice Thickness of the Wedge	s	=	0.5	[m]
Maximum Step Size of the Wedge Foot	f	=	0.5	[m]

OPTIMIZATION

Layer	Bolts/m2 / Bolts
m1	0.395 / 10
m2	0.185 / 23

Required Safety Factor	1.000
Optimization Algorithm	Simplex

DISCLAIMER

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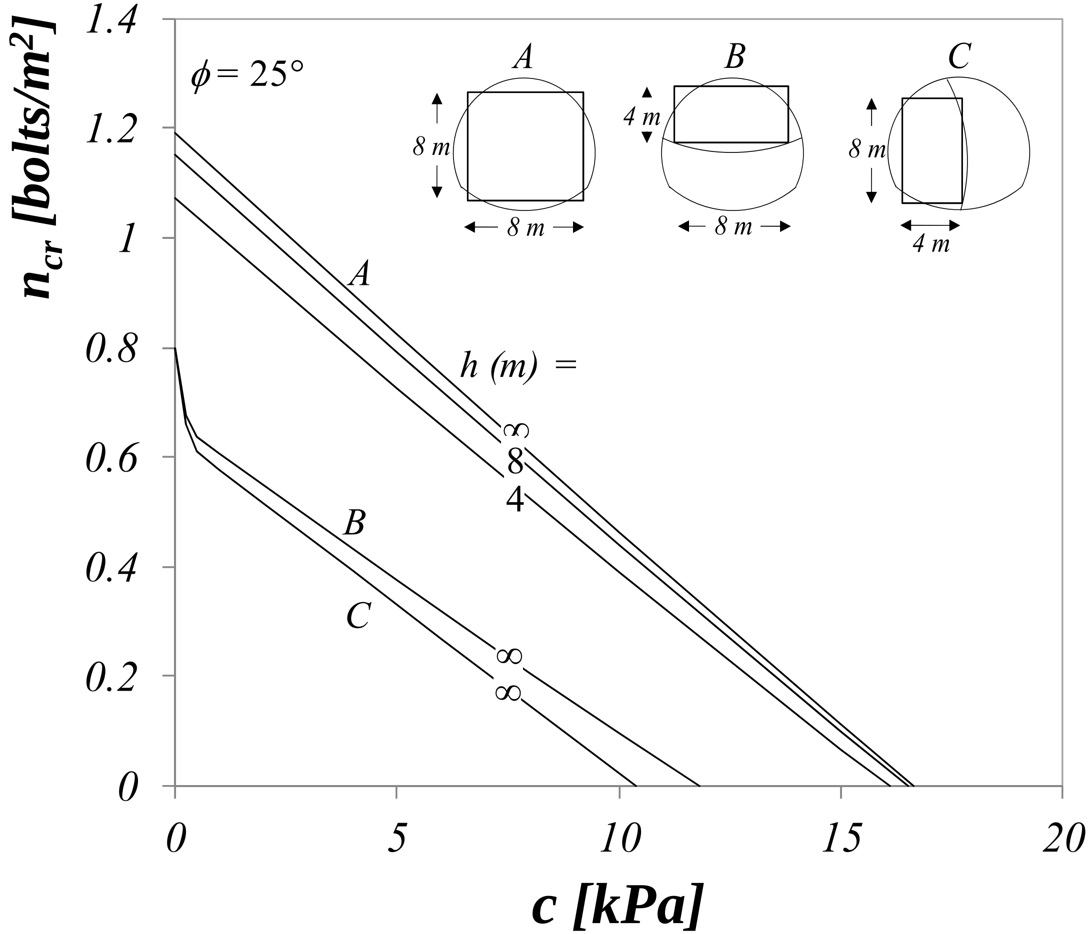
On the effect of the design parameters

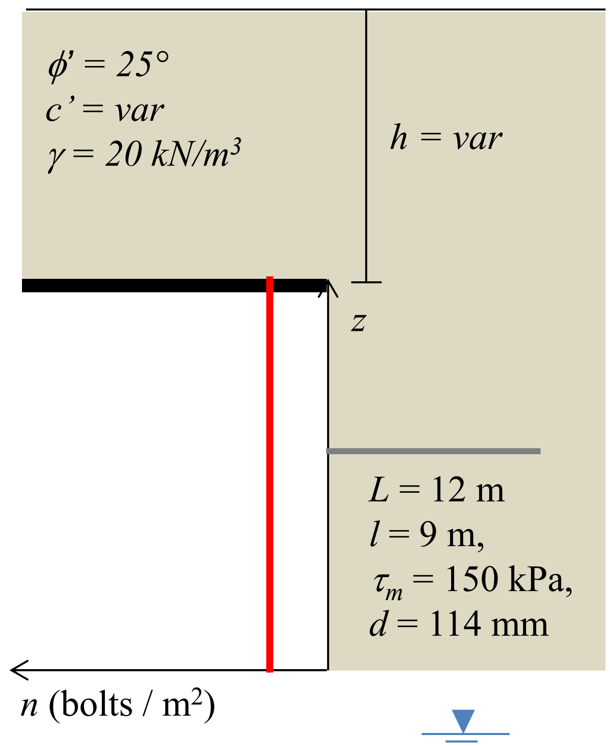
Grounds above the water table

On the effect of the design parameters

Grounds above the water table

Overburden and shape of the face

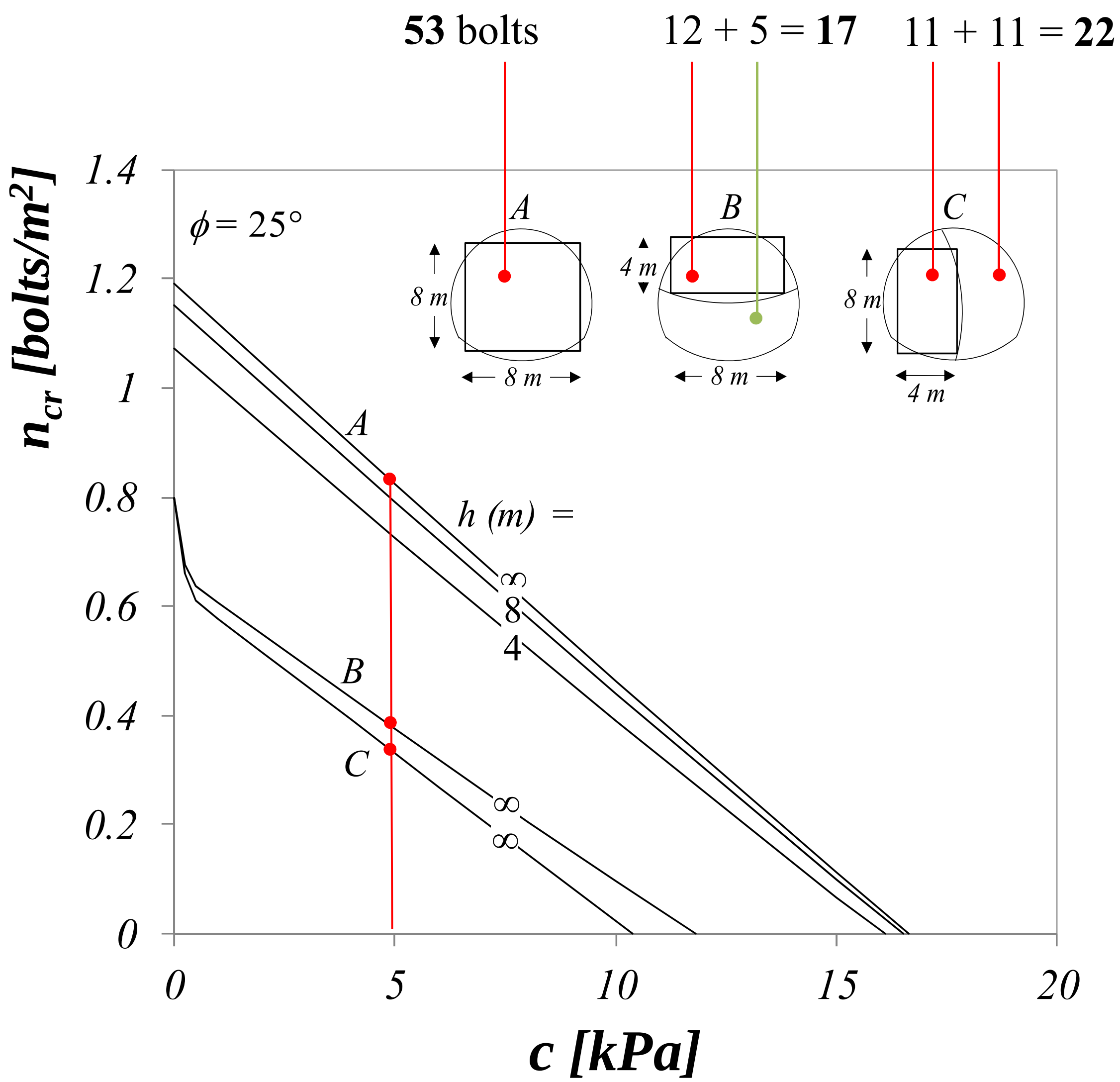


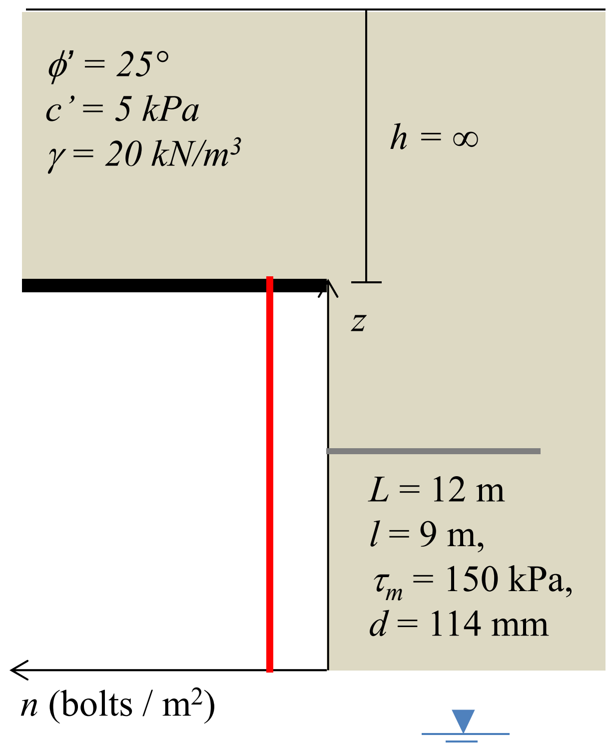


On the effect of the design parameters

Grounds above the water table

Overburden and shape of the face

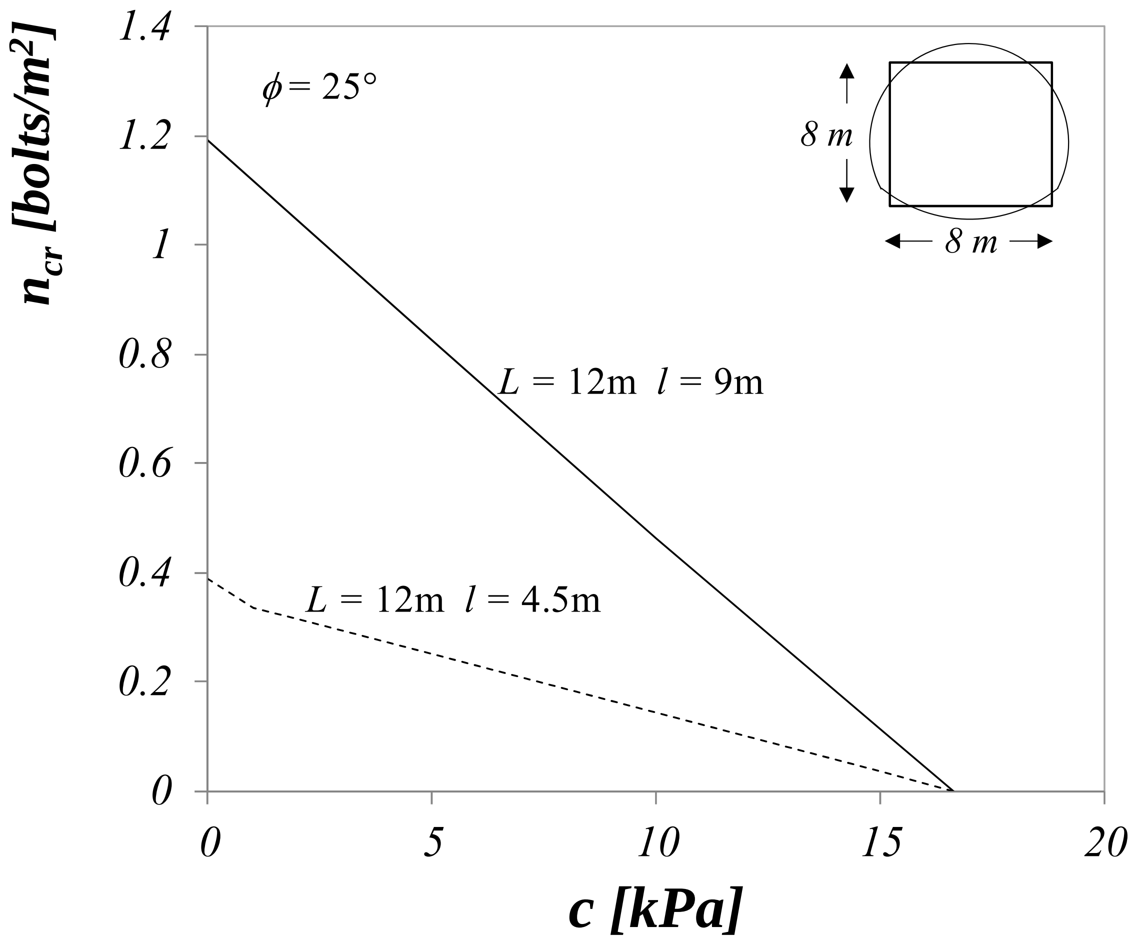


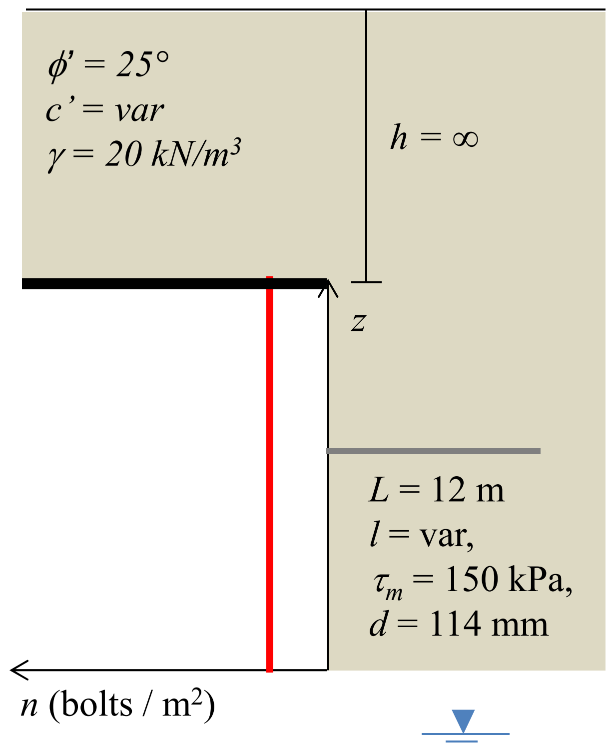


On the effect of the design parameters

Grounds above the water table

Installation interval



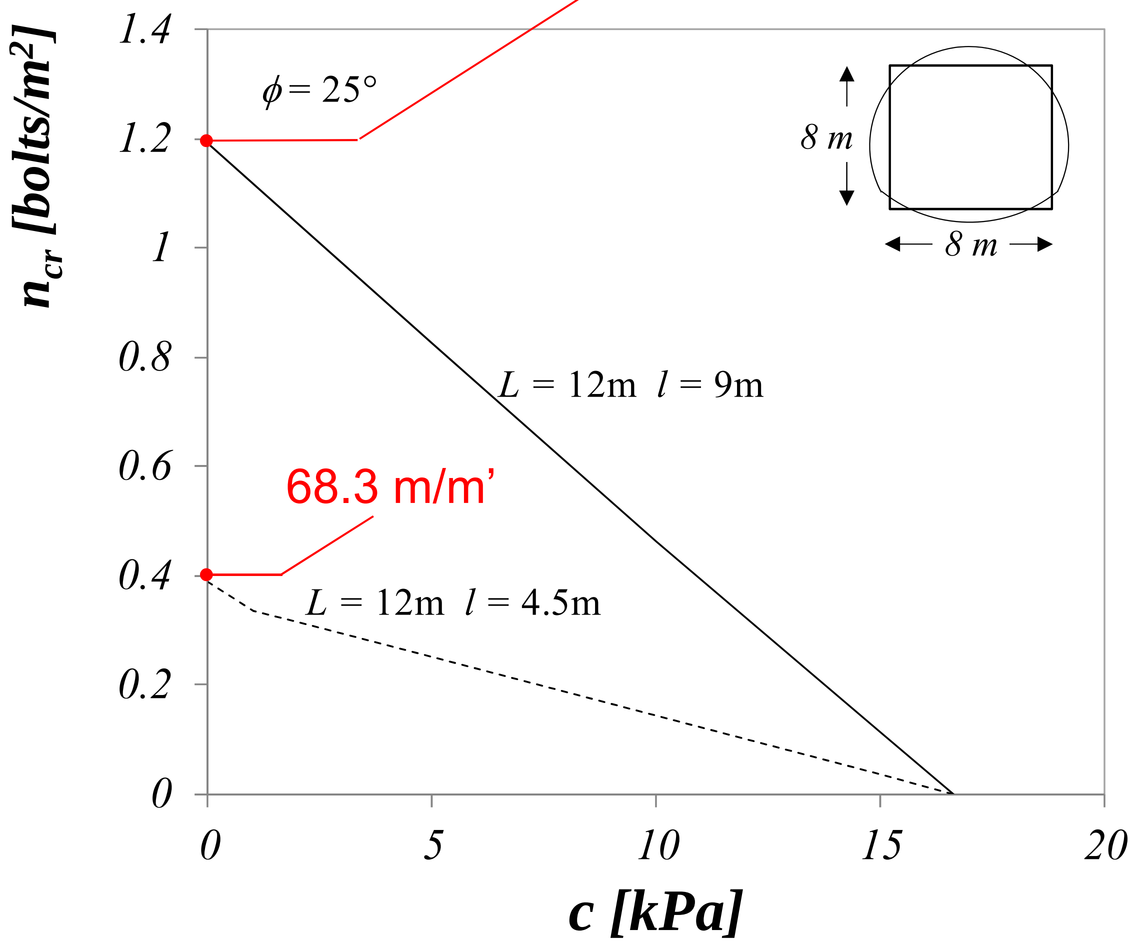


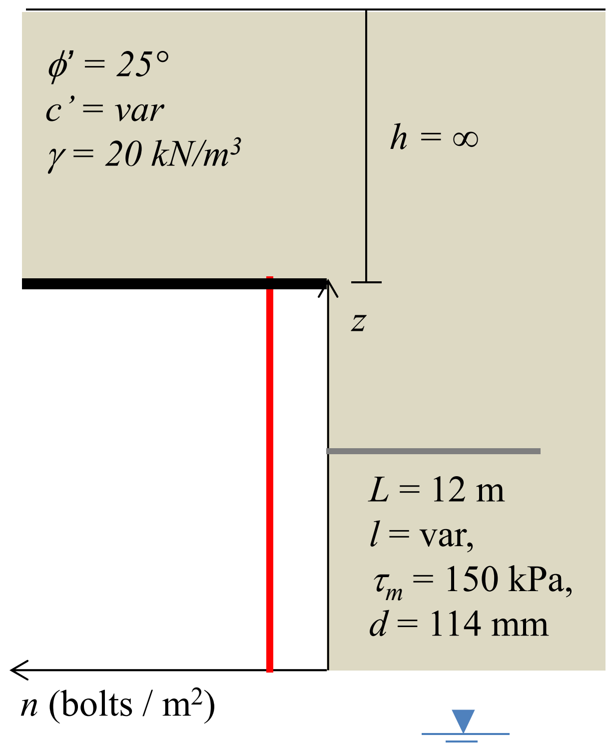
On the effect of the design parameters

Grounds above the water table

Installation interval

meters of bolts installed per linear meter of tunnel
102.4 m/m'

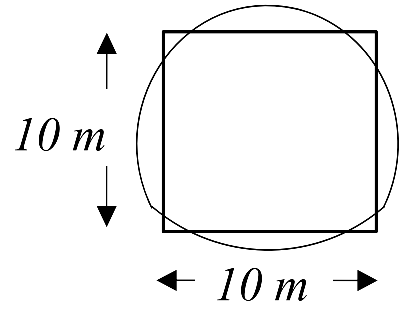


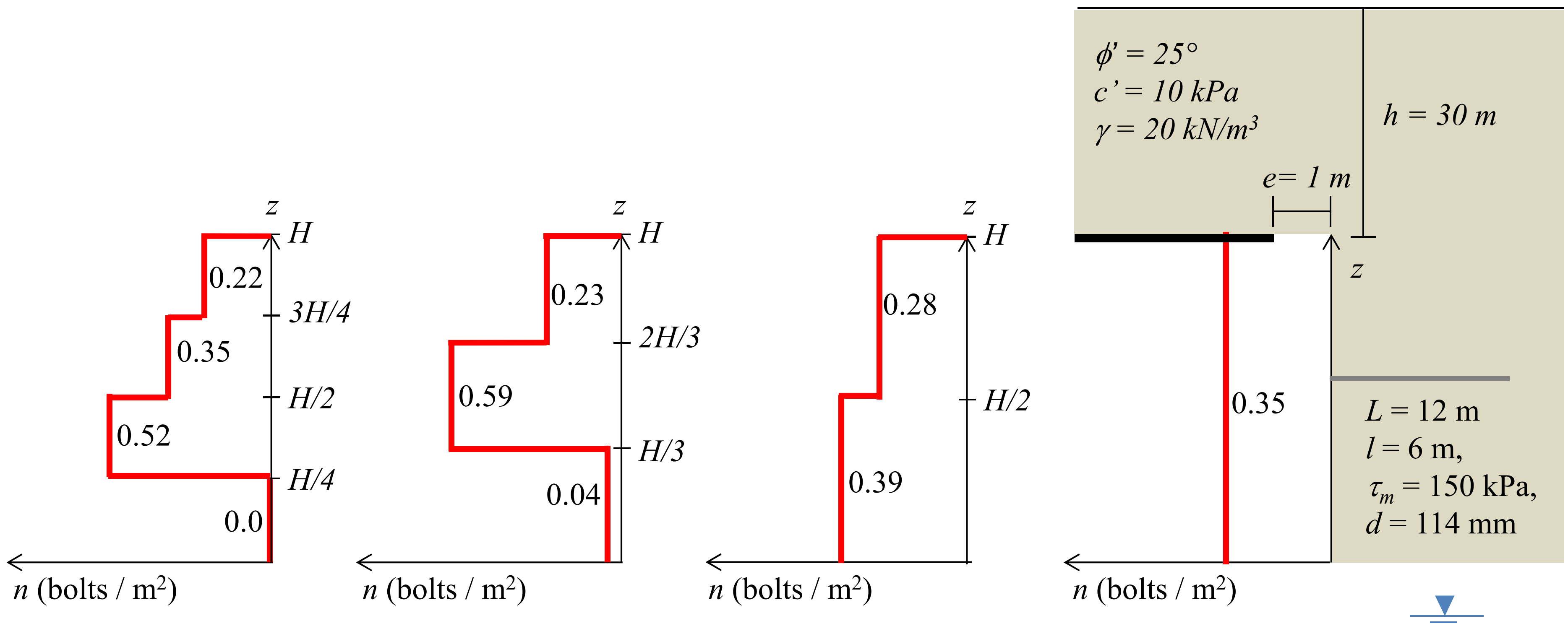


On the effect of the design parameters

Grounds above the water table

Spatial bolt distribution





28 bolts **29 bolts** **34 bolts** **35 bolts**

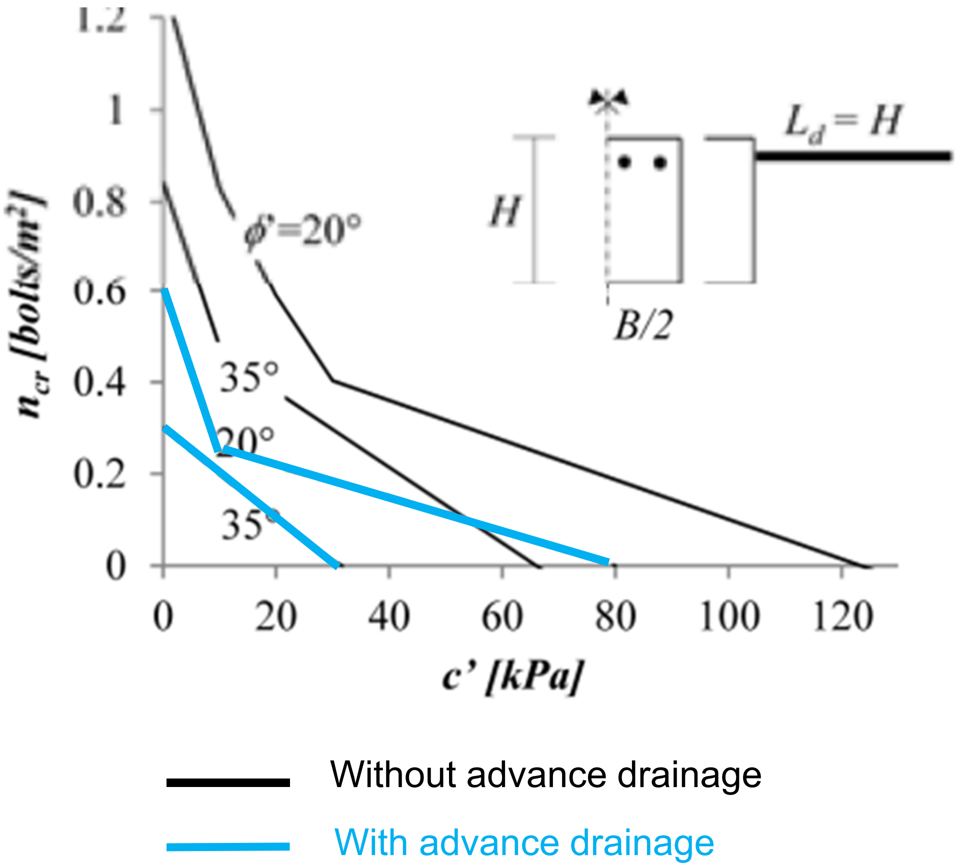
On the effect of the design parameters

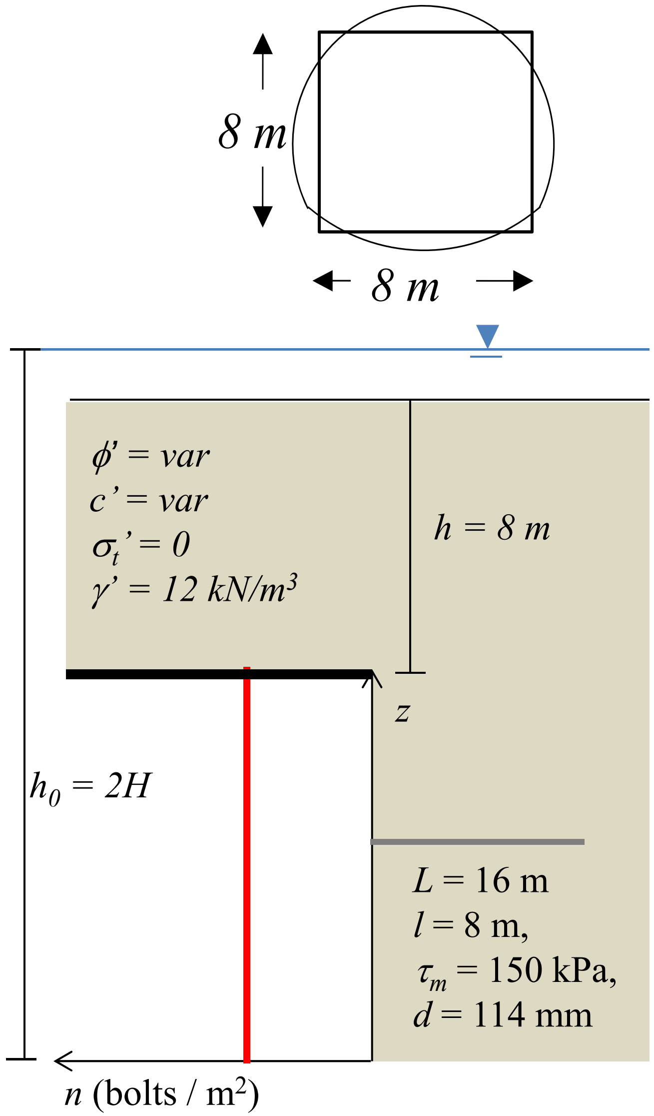
Grounds below the water table - drained

On the effect of the design parameters

Grounds below the water table - drained

Drainage boreholes





35 bolts

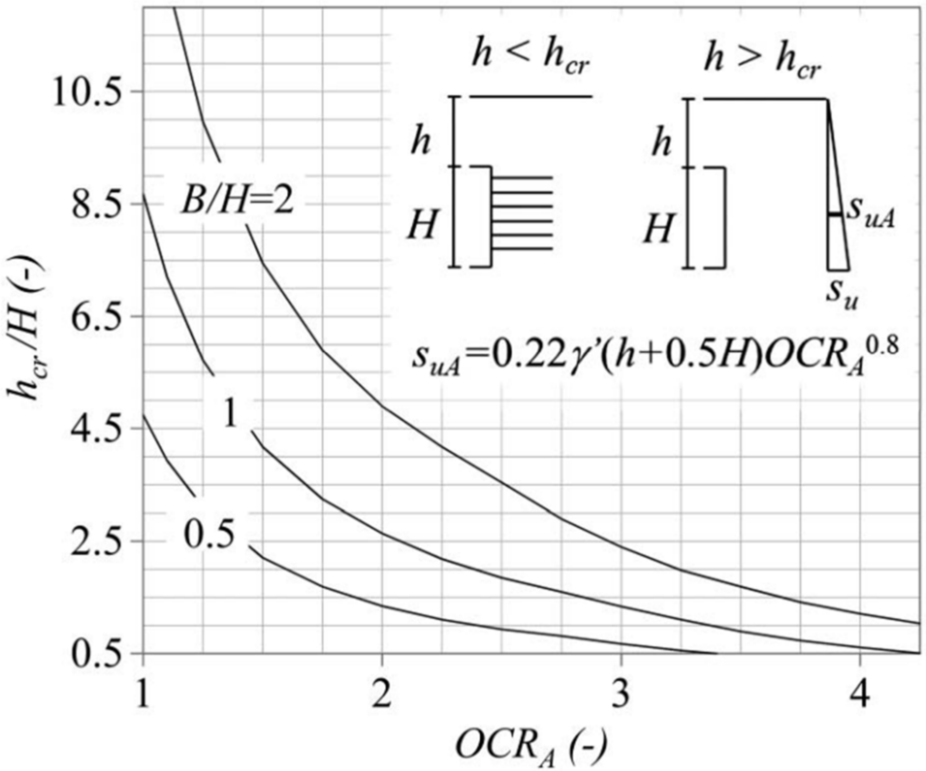
On the effect of the design parameters

Grounds below the water table - undrained

On the effect of the design parameters

Grounds below the water table - undrained

Over-consolidation ratio

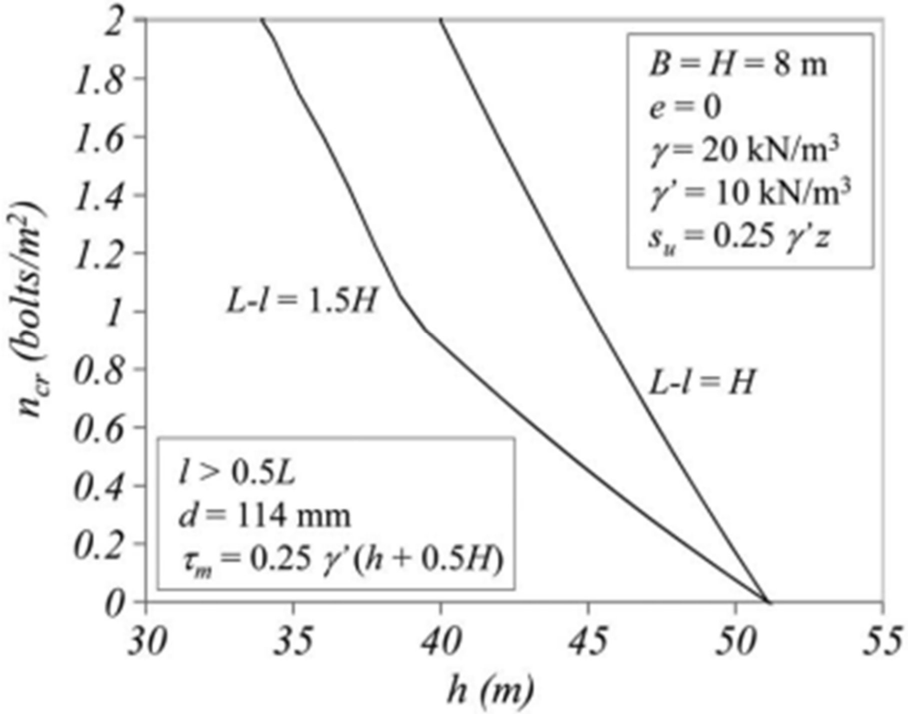


On the effect of the design parameters

Grounds below the water table - undrained

Overburden

OCR = 1.0

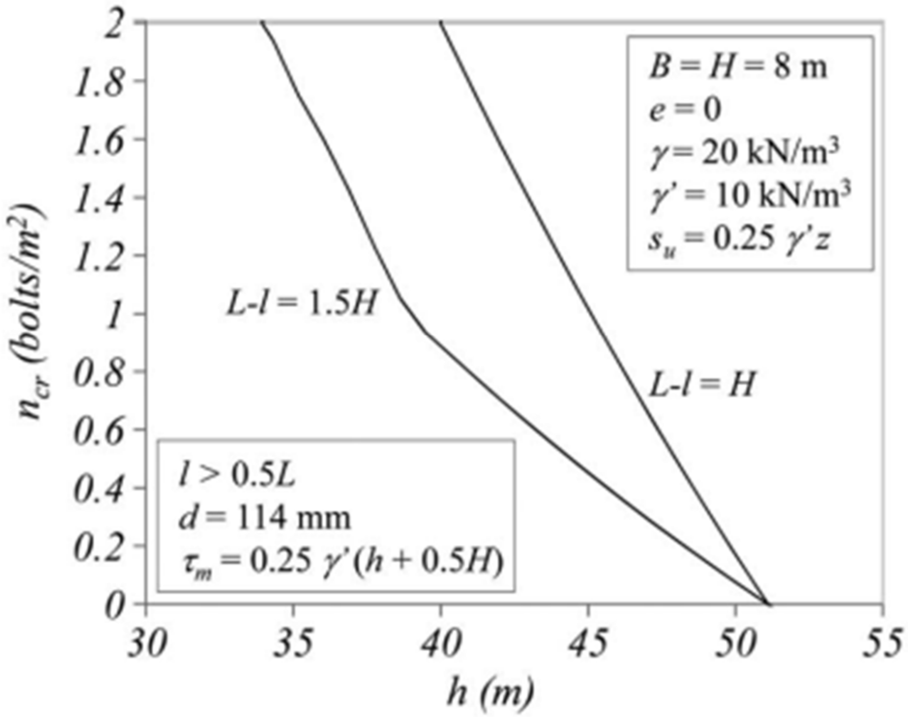


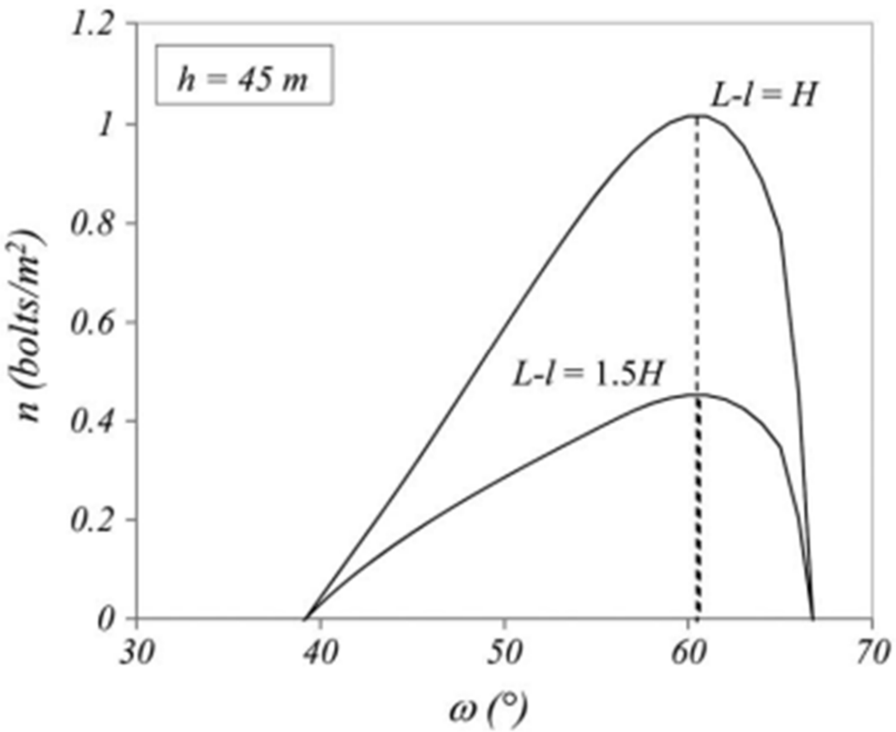
On the effect of the design parameters

Grounds below the water table - undrained

Overlapping length

OCR = 1.0





Conclusions

- Experience and predictions prove that ground reinforcement using bolts is a very effective measure for stabilizing the tunnel face

- Excavation method and installation interval of the bolts affect significantly the required quantity of bolts (Top heading and Bench excavation method and small installation intervals allow to reduce the quantity of bolts)

- Big overlapping length are required in undrained soils

- Drainage boreholes are required in soils below the water table under drained conditions

- The uniform distribution is not the optimal one. A computational method was developed for the optimization of the face reinforcement

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Thank you for the attention!