



COMITÉ FRANÇAIS DE MÉCANIQUE  
DES SOLS ET DE GÉOTECHNIQUE



ACADEMIE  
DES SCIENCES  
INSTITUT DE FRANCE



Charles-Augustin COULOMB - A geotechnical tribute

Paris, september 25 & 26, 2023



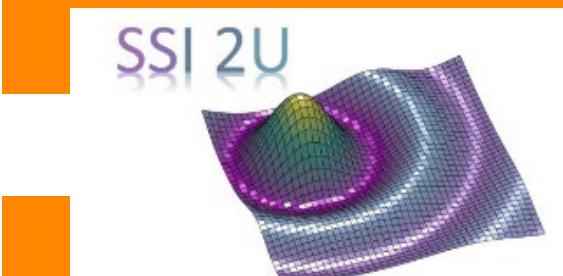
An adaptation of Limit Equilibrium Methods  
for the design of soil-nailed walls facings

J. de Sauvage

Université Gustave Eiffel



BUREAU  
VERITAS



- Context : Soil nailing and PROSPER software
- Centrifuge modeling of soil-nailed walls
- Finite element parametric study
- Adaptation of PROSPER method
- Conclusion

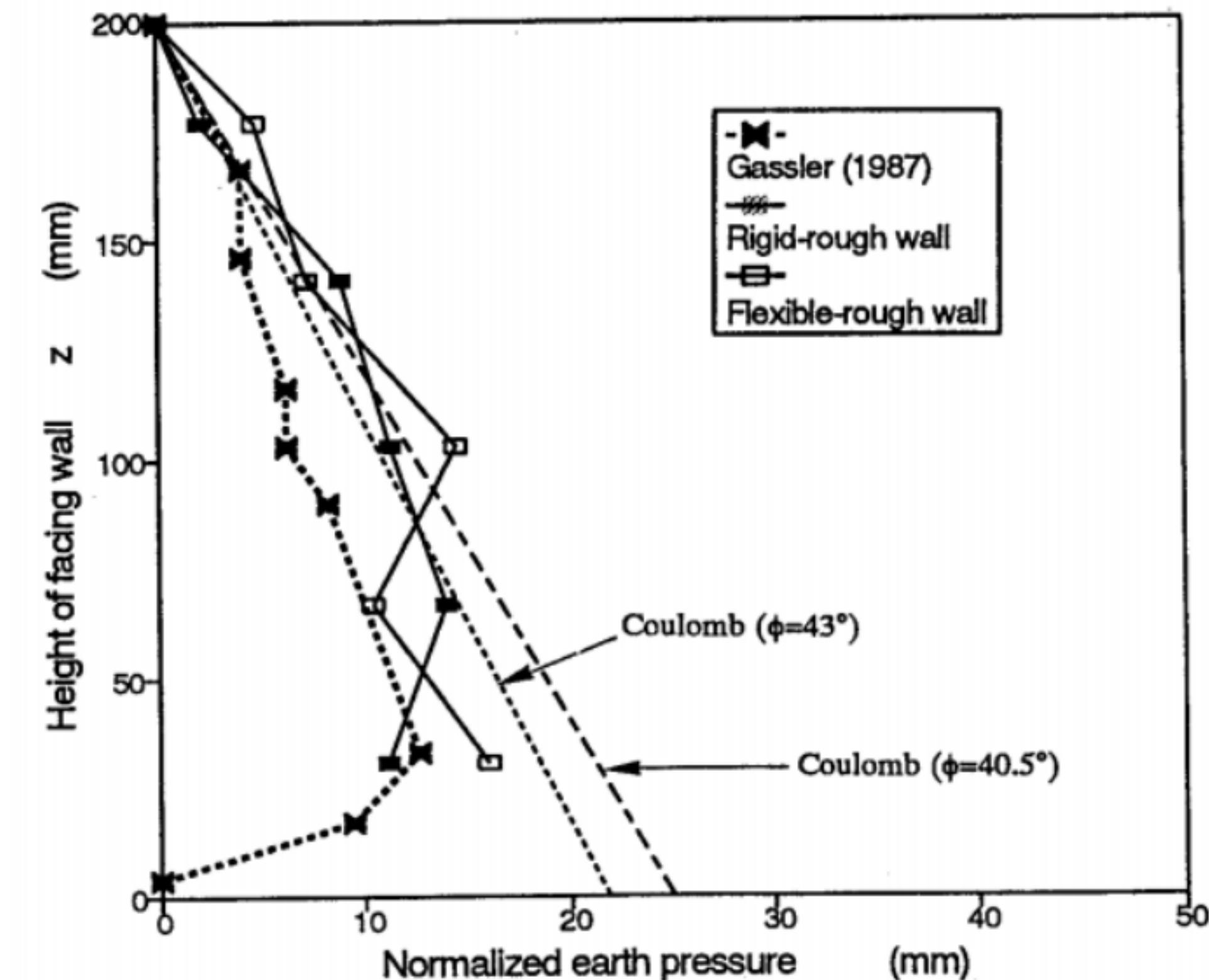


1972 : Enlargement of railway in  
Versailles



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1987 : first monitored soil-nailed wall  
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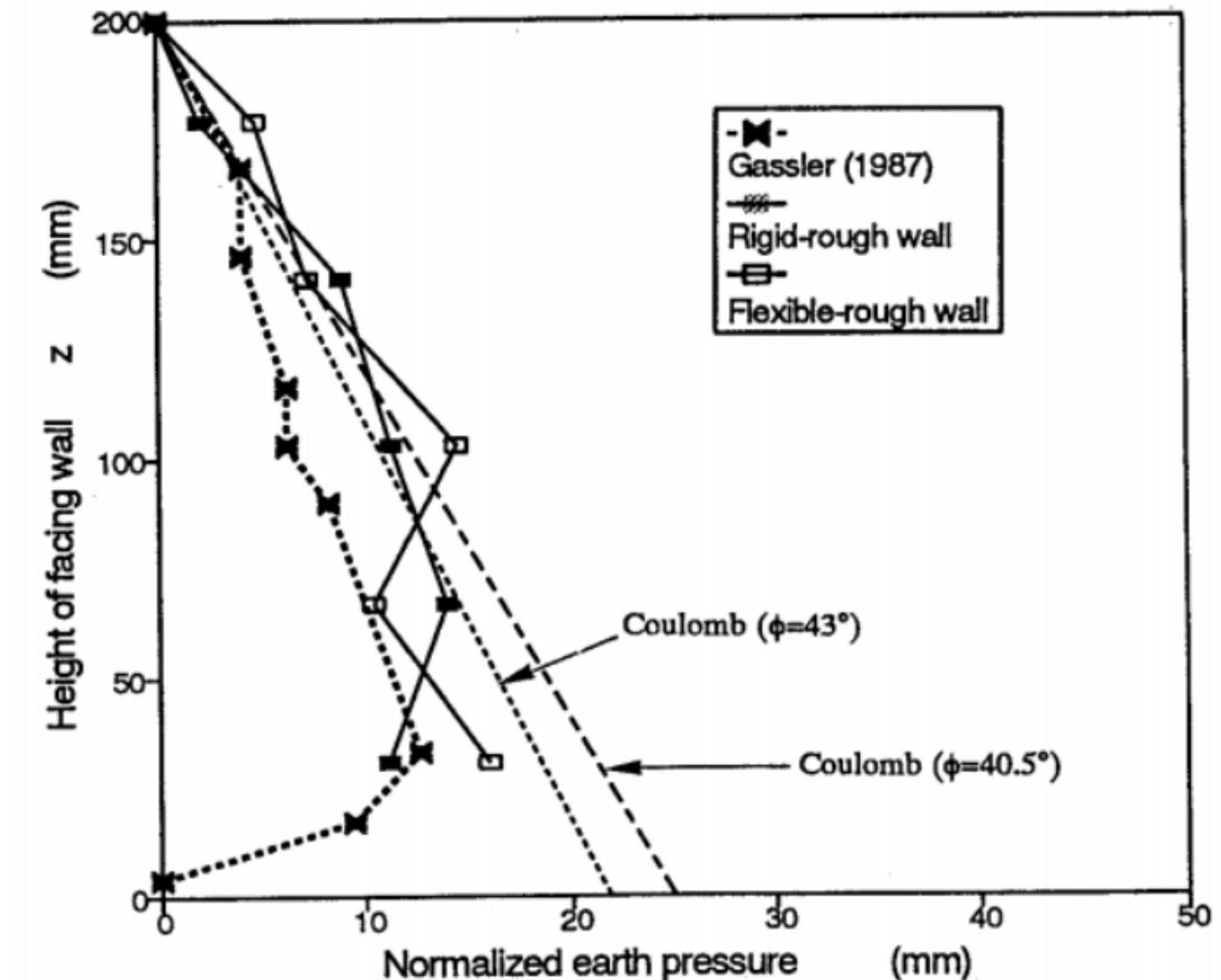
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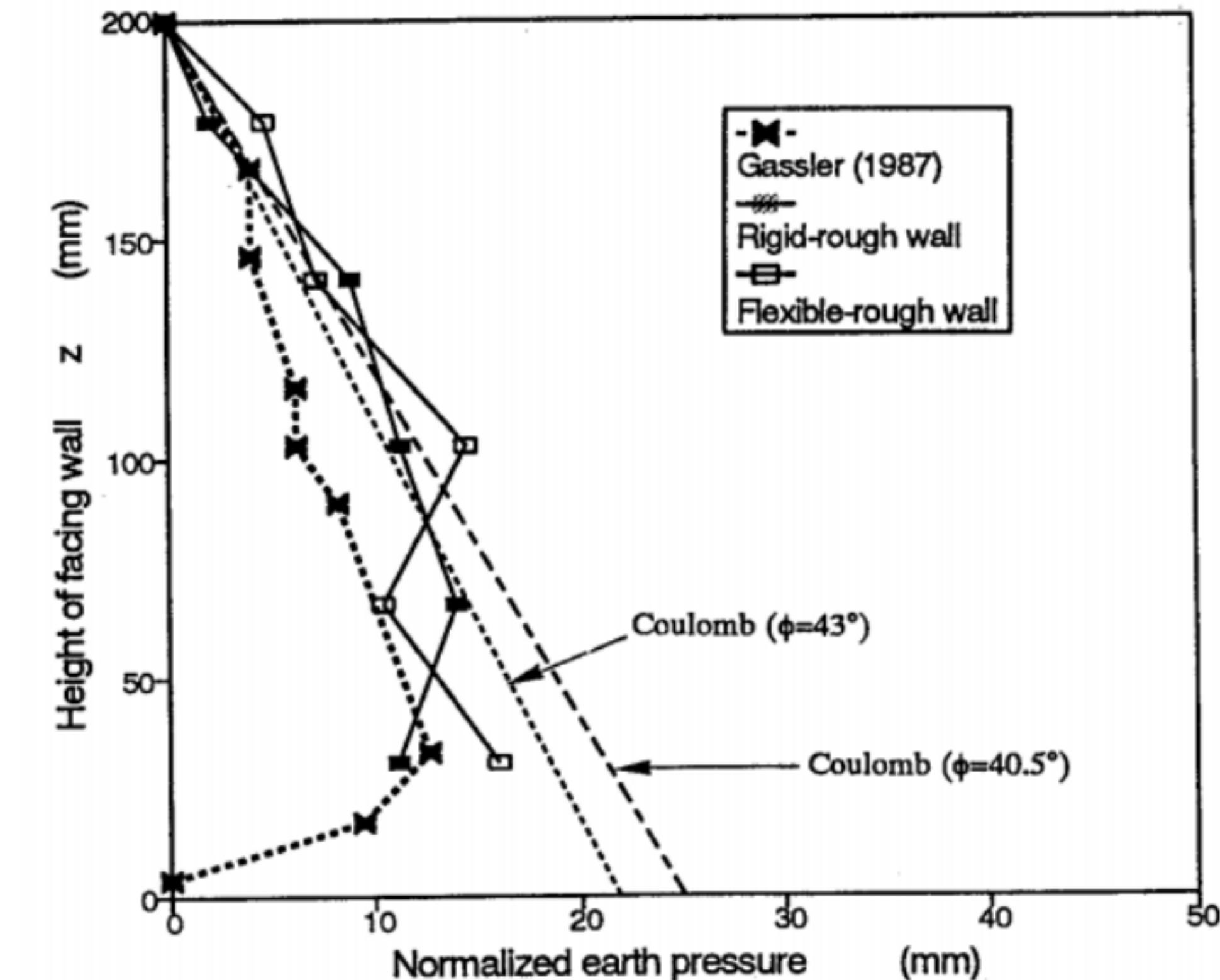


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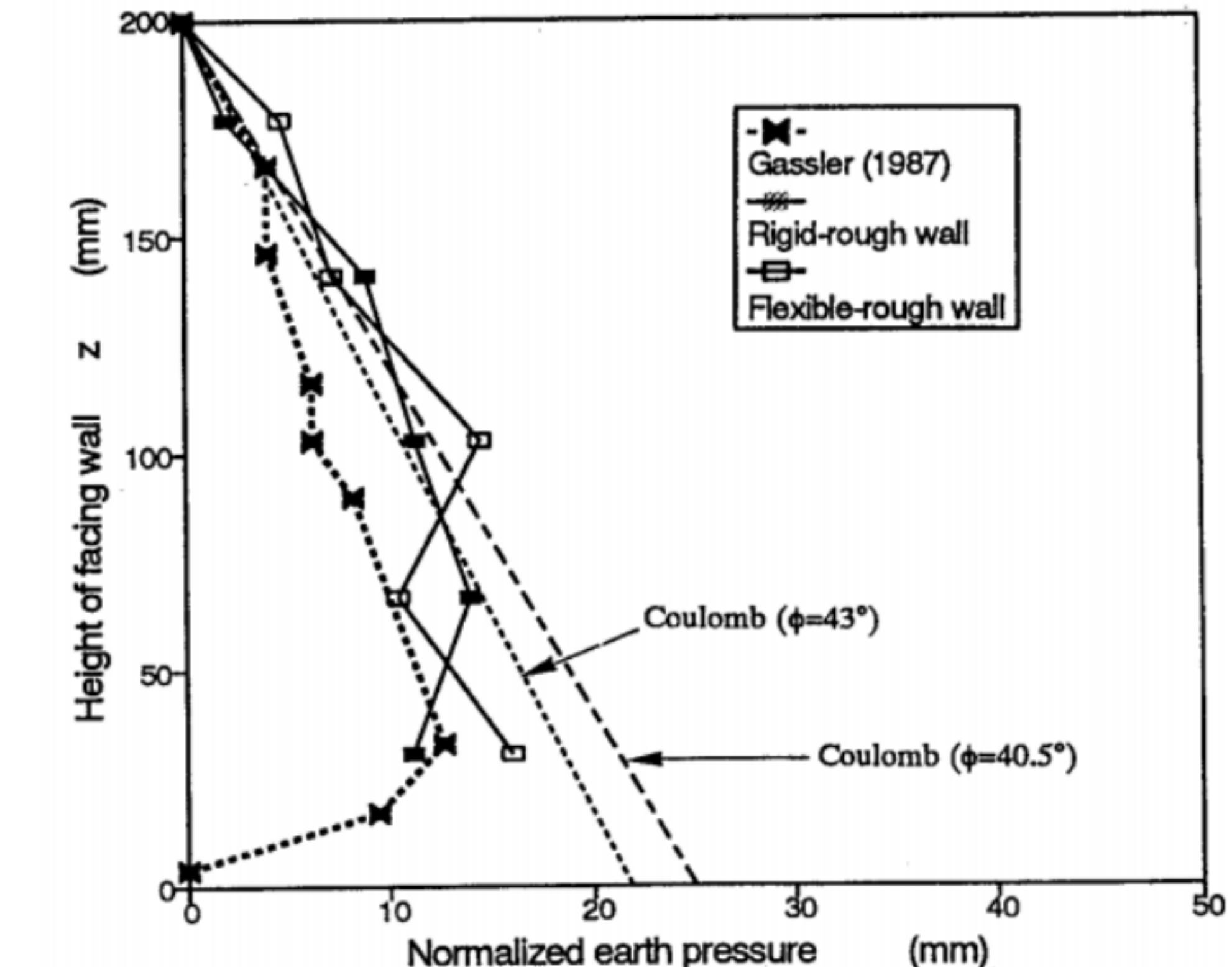
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2018-2020 : reviewing NF P 94-270



Tei, 1991



# Soil-nailed walls ?

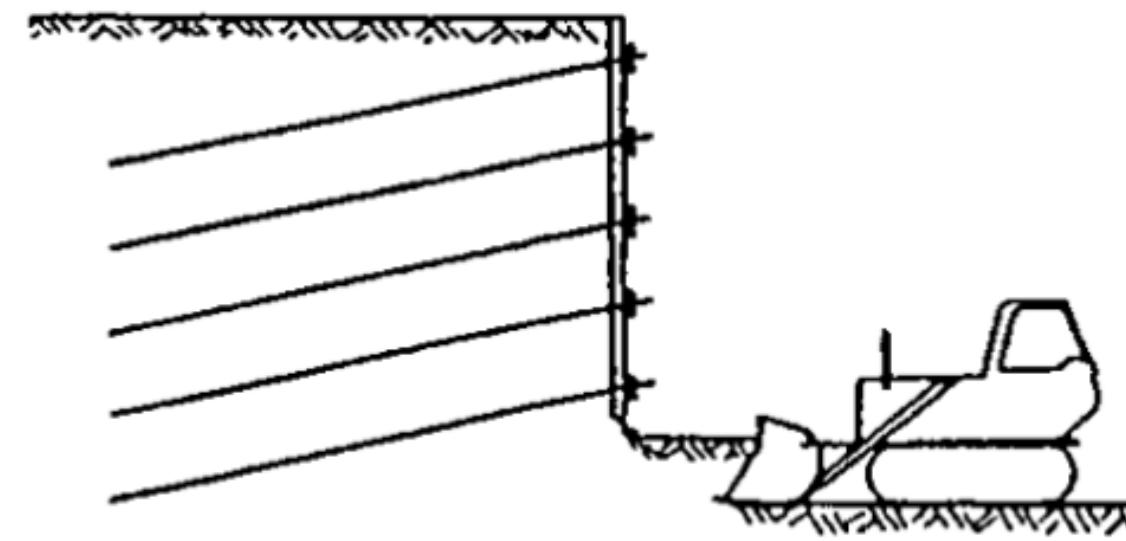
Context

Centrifuge

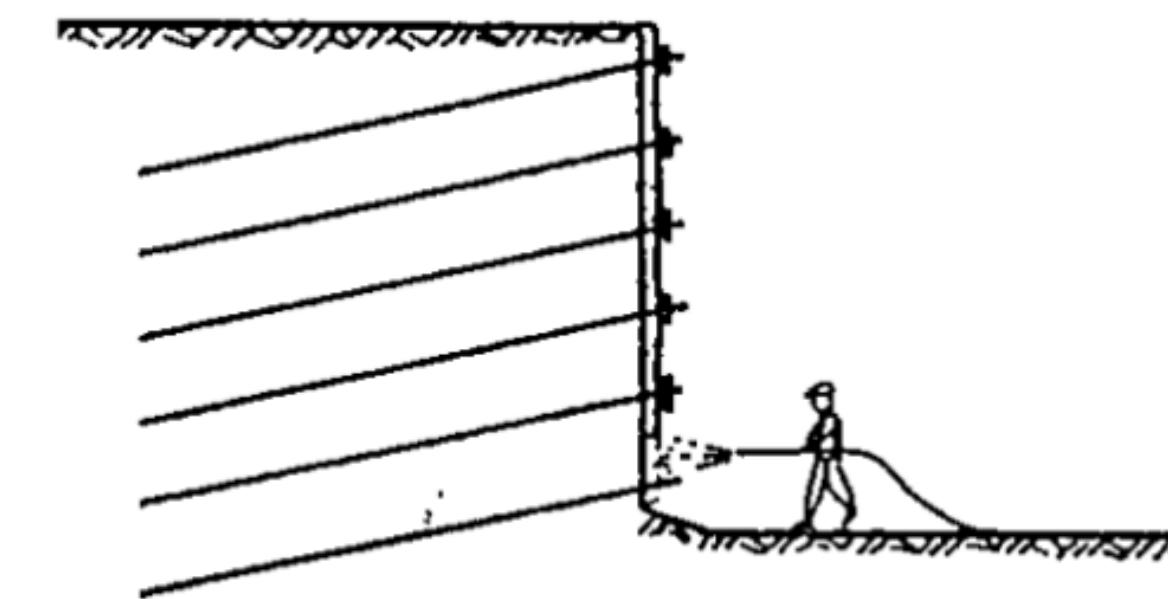
FEM Study

Adaptation

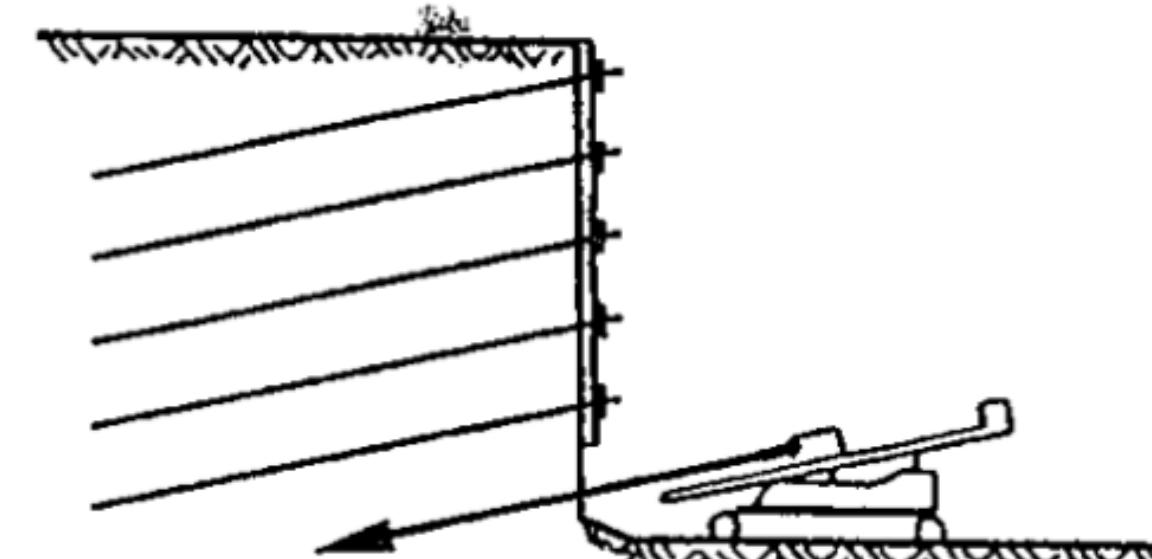
Conclusion



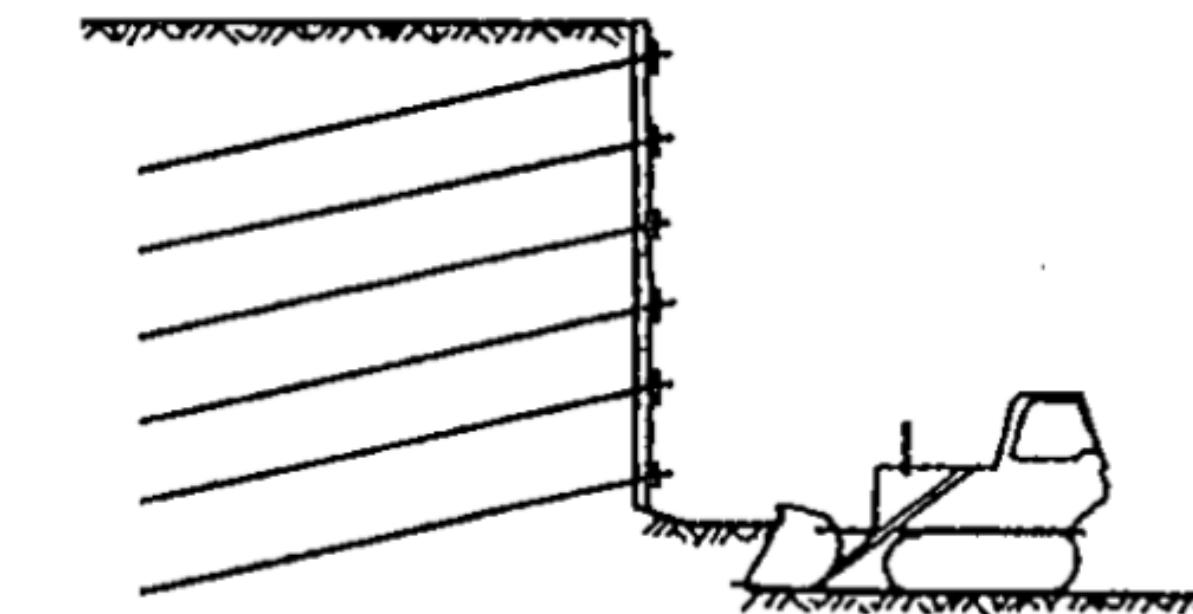
1 . Terrassement



3 . Béton projeté armé  
( ou pose d'éléments préfabriqués )



2 . Mise en place des barres



4 . Terrassement

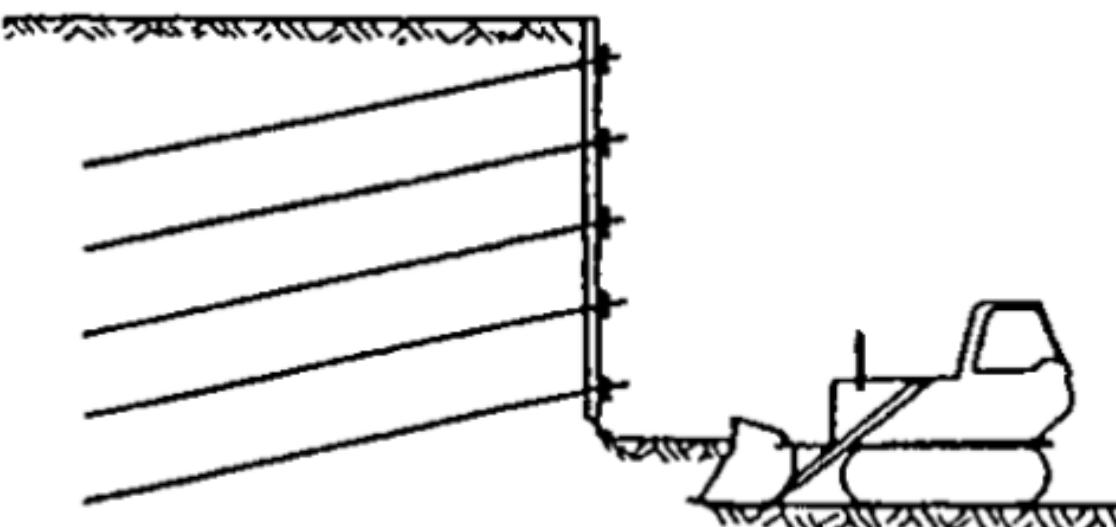
**Clouterre, 1991**



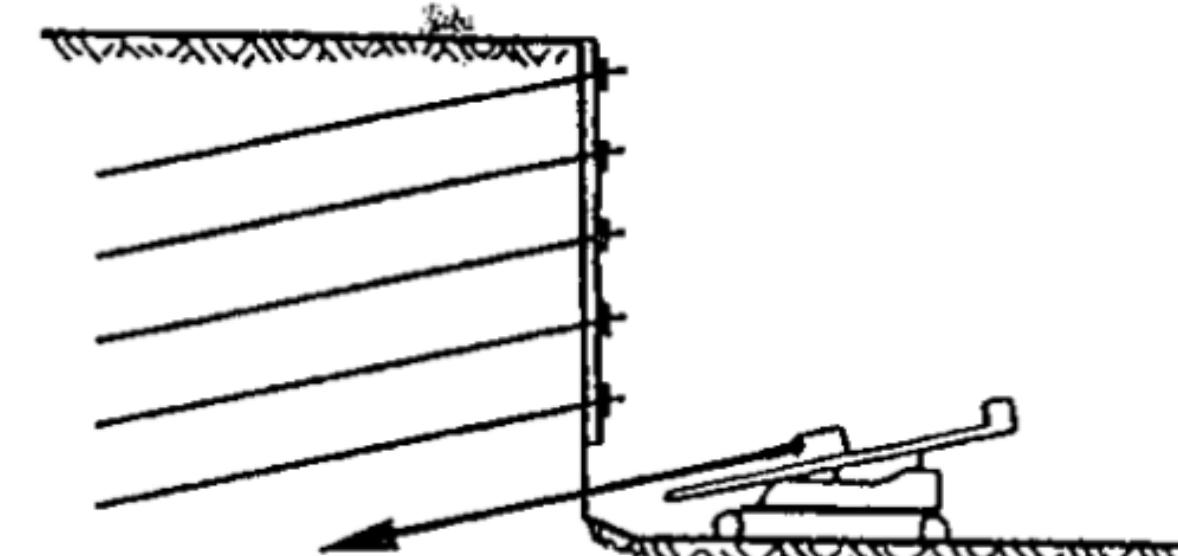
A specific type of reinforced soil (cf P. de Buhan)

Soil-nailed walls are not MSE walls.

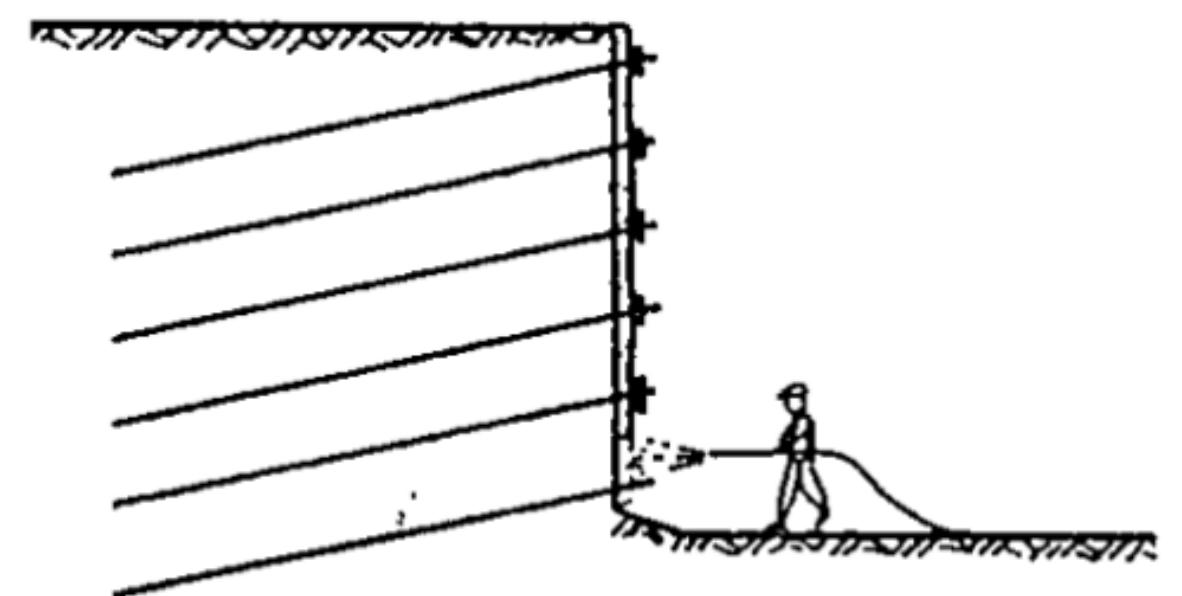
The nails are passive anchors, activated by the excavation of next lifts.



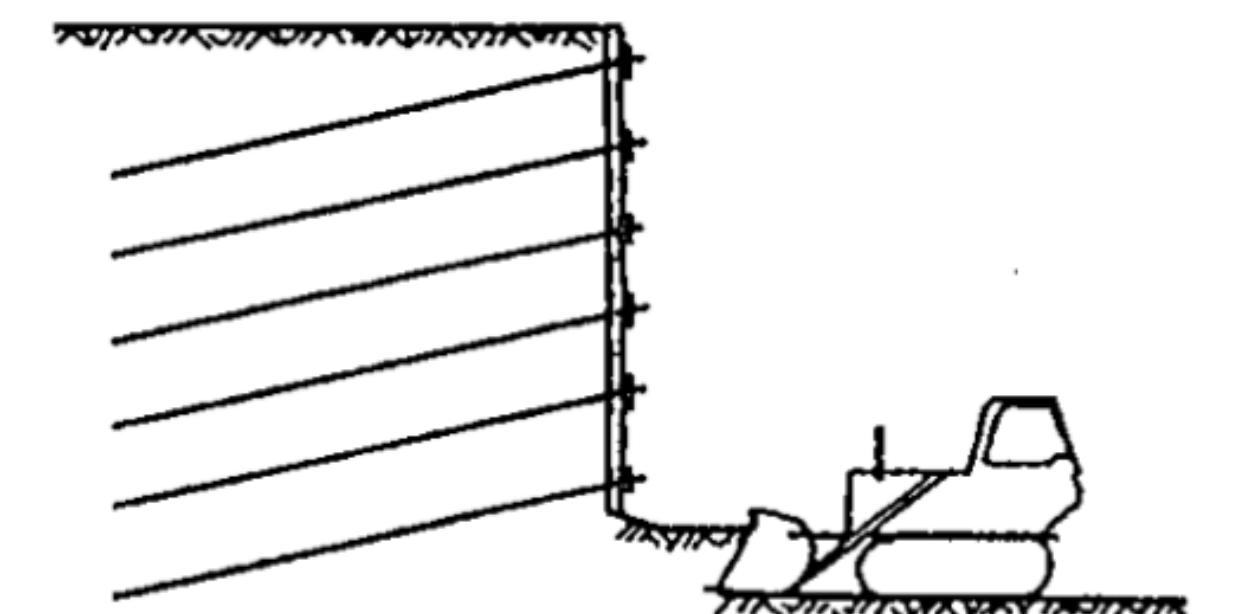
1 . Terrassement



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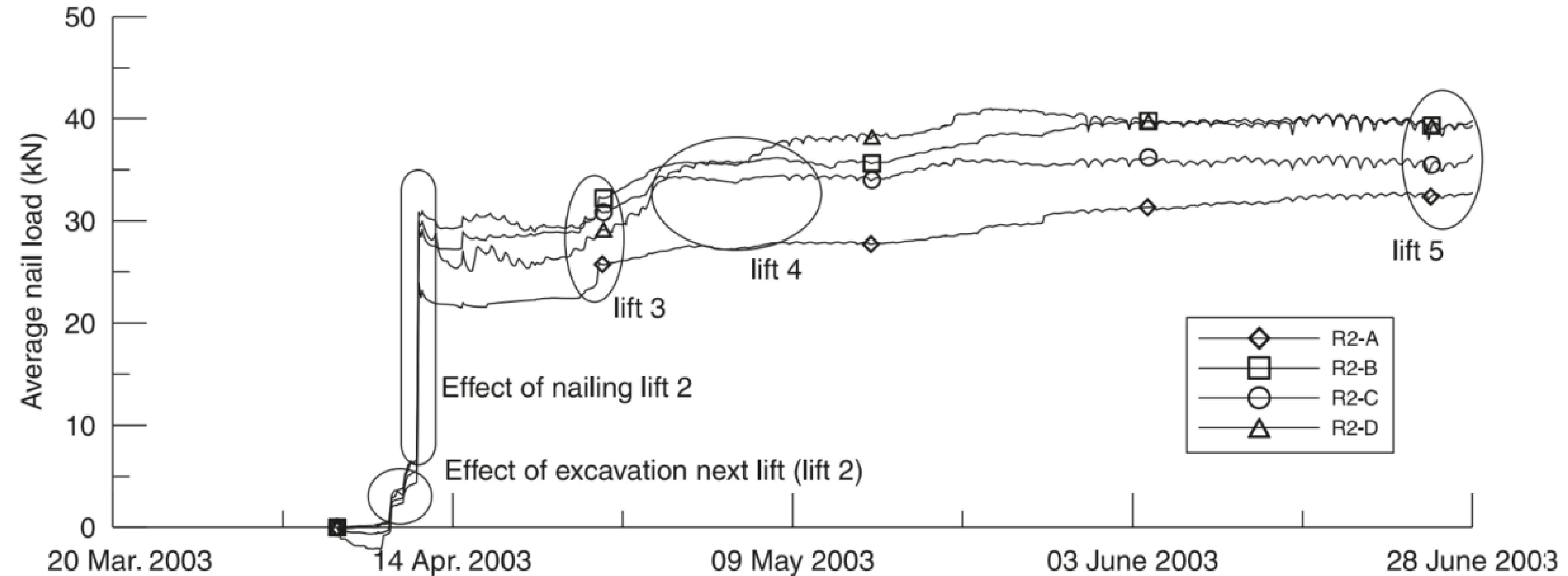
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**Clouterre, 1991**





Dublin glacial till, Menkiti and Long, 2008



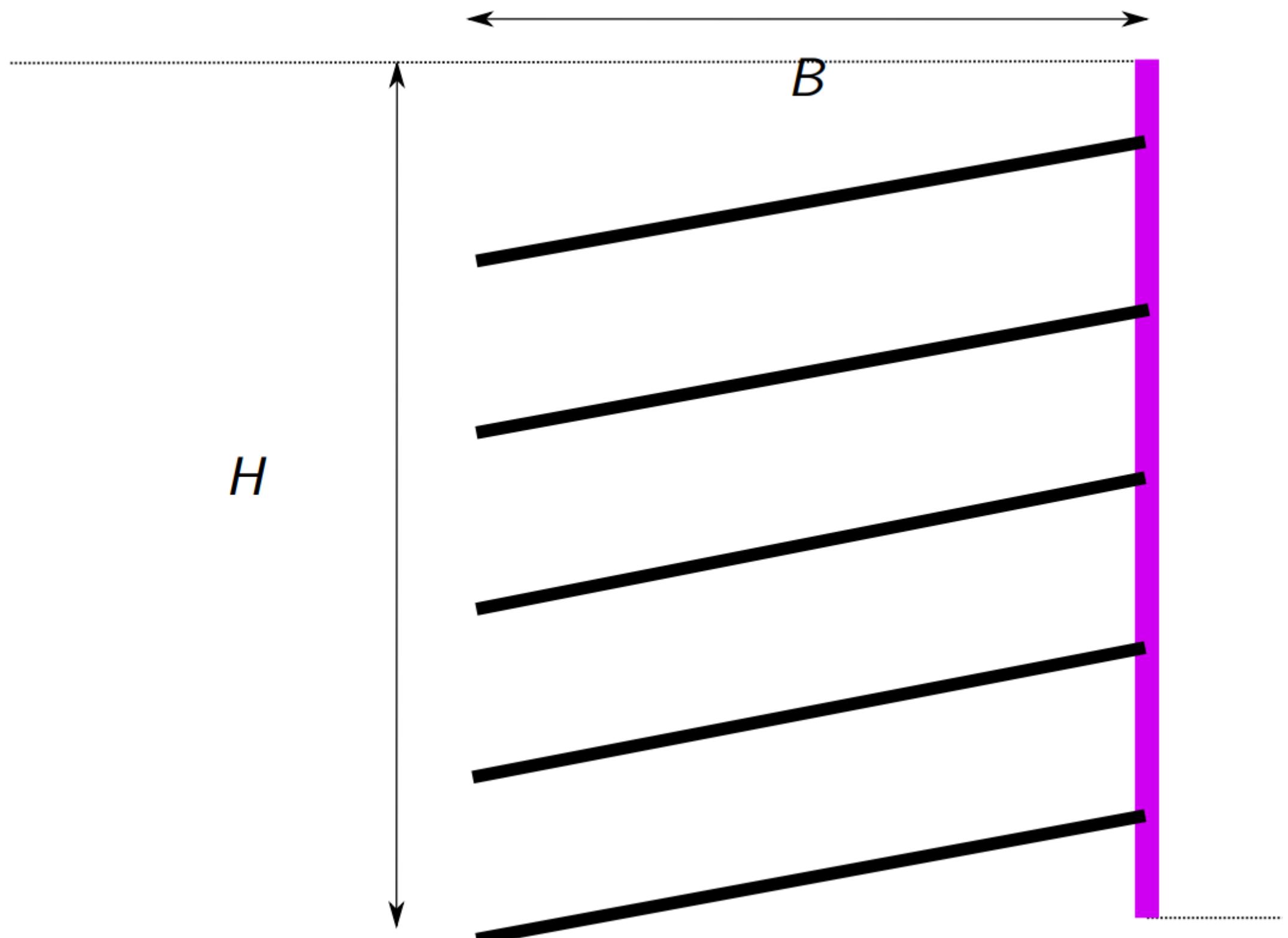
**Traditionnal design uses Limit Equilibrium ...**

**... not in the rigorous framework of yield design but in the Coulomb rationale :**

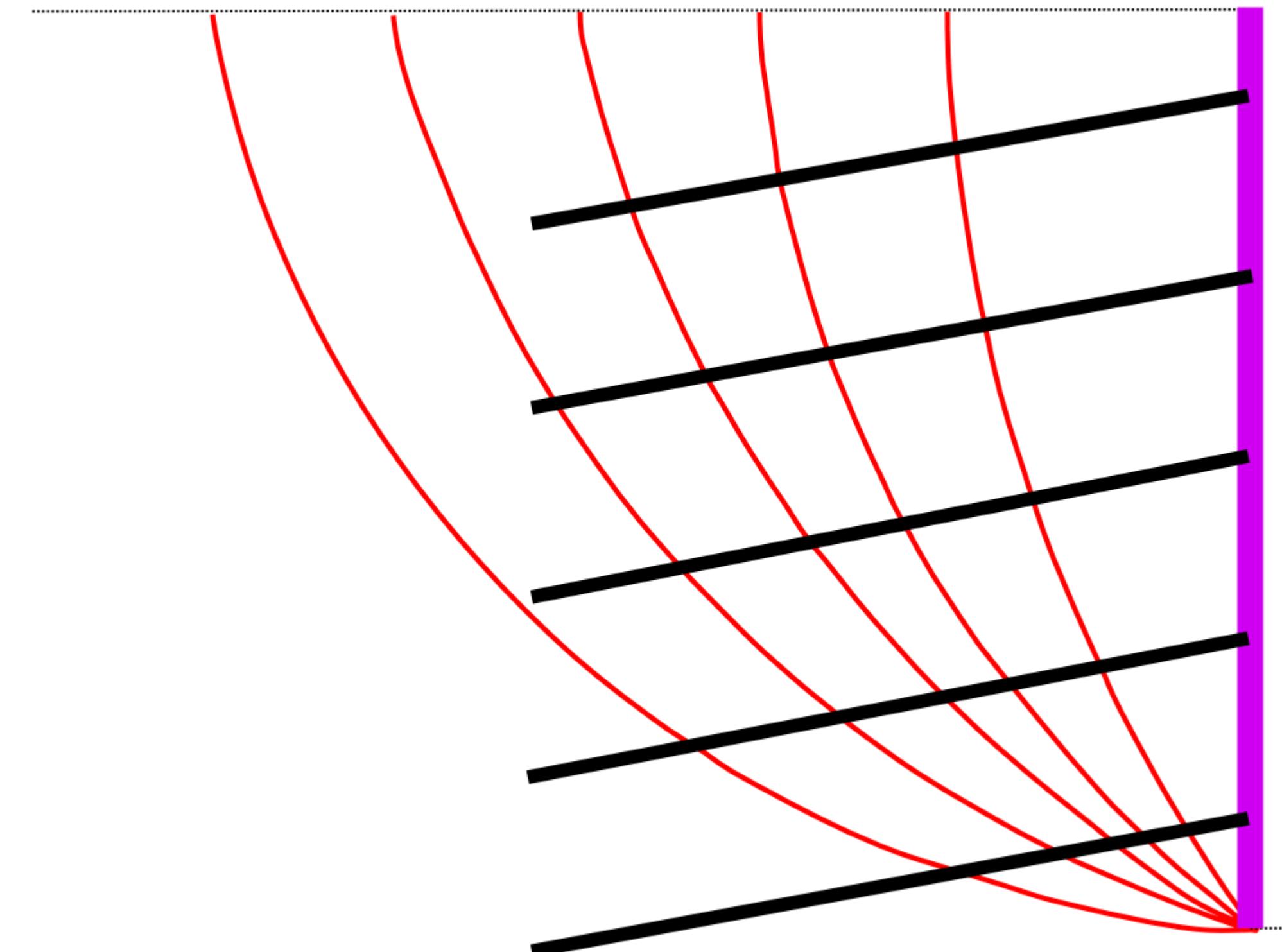
- Distinguish driving forces and resisting strength
- State that equilibrium must be compatible with strength
- Derive constraints from this condition
- Optimize to tighten the constraints



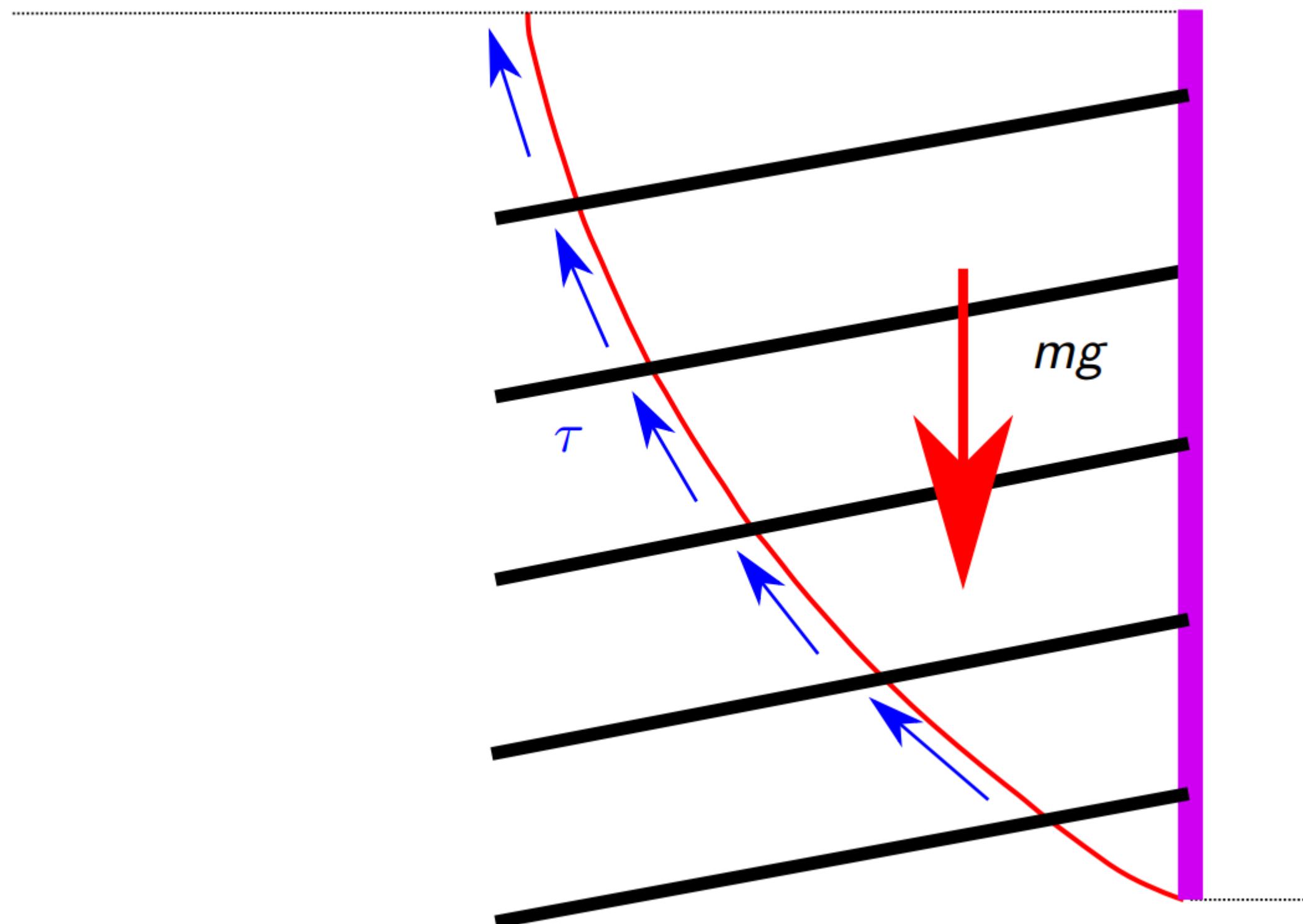
➤ Let us consider a given wall



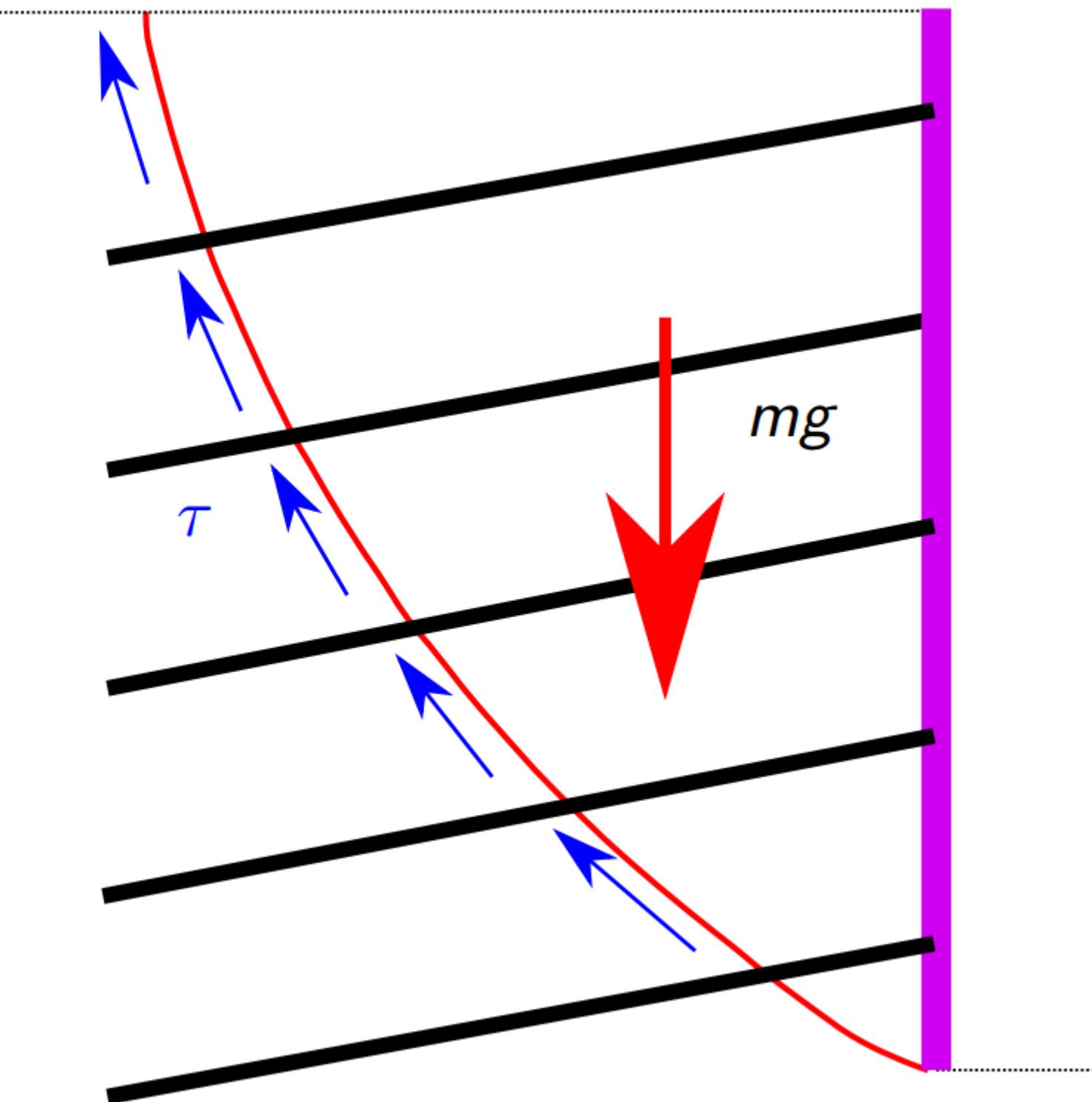
- Let us consider a given wall
- Let us consider failure surfaces
  - ❖ Line (Coulomb, 1773)
  - ❖ Circle (Fellenius, 1927)
  - ❖ Log-Spiral (Rendulic, 1935)
  - ❖ ...



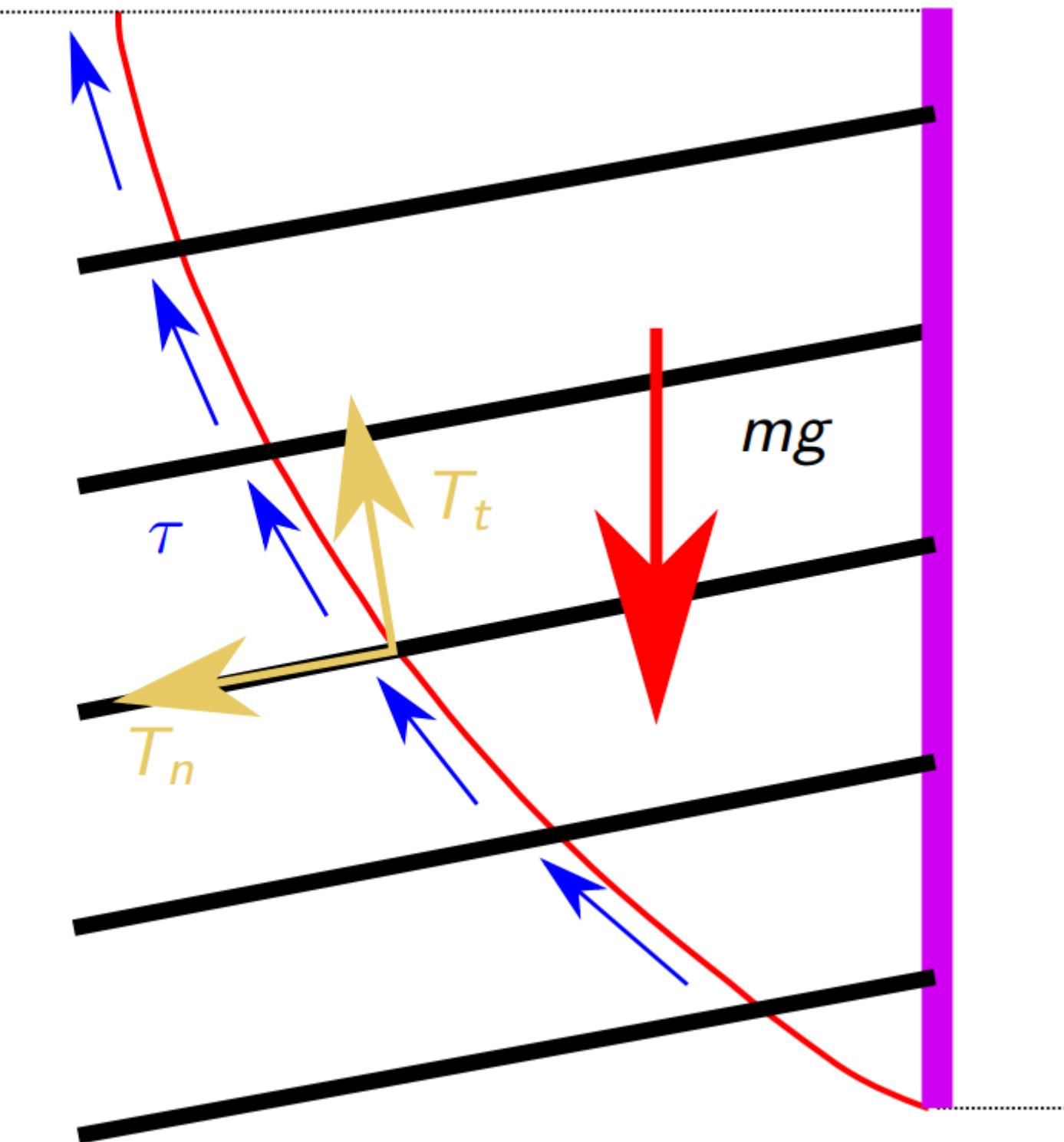
- Let us consider a given wall
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- Driving force : self weight



- Let us consider a given wall
- Let us consider failure surfaces
  
- Driving force : self weight
- Strength :
  - ❖ Mohr-Coulomb in the soil



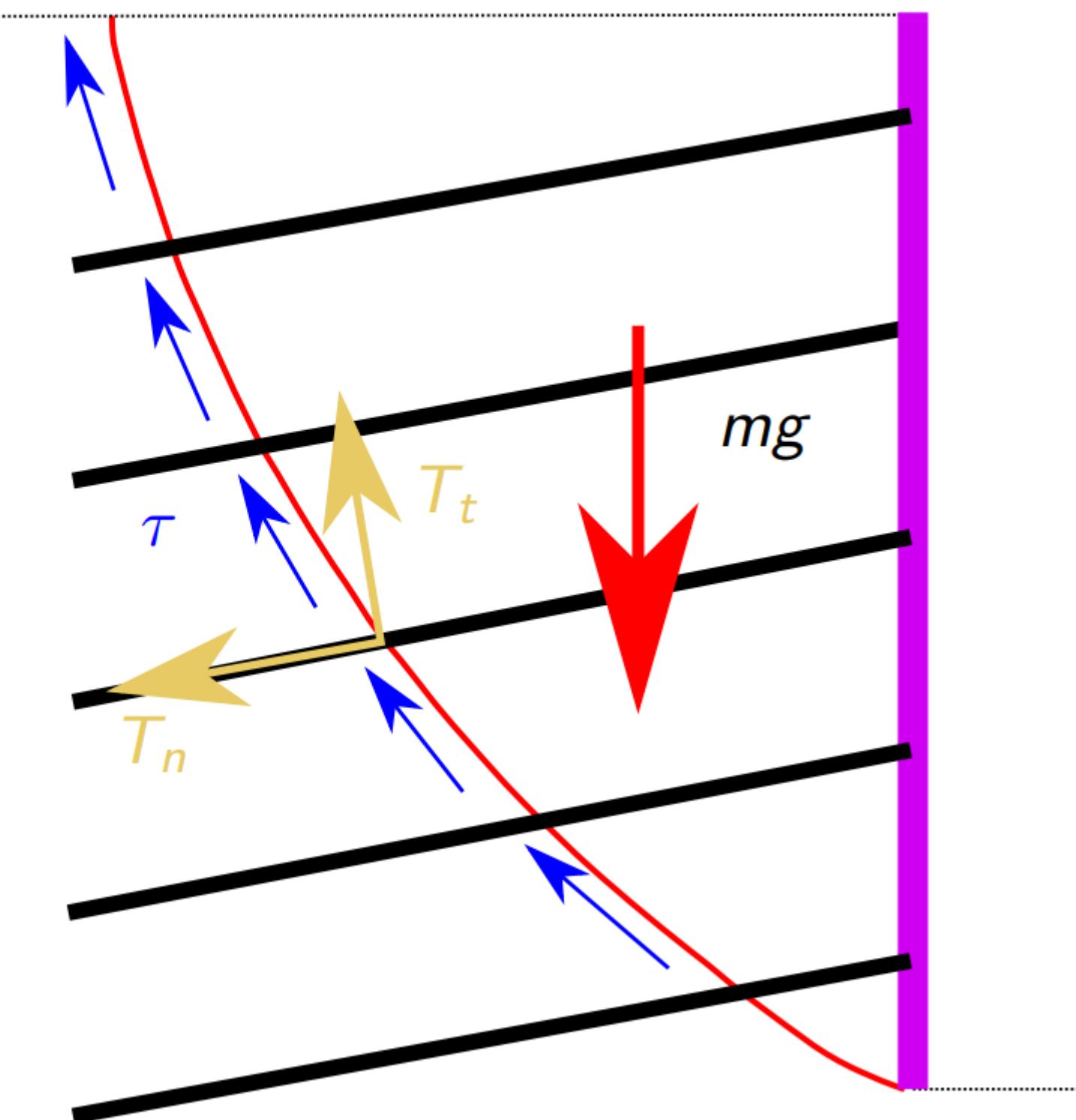
- Let us consider a given wall
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- Driving force : self weight
- Strength :
  - ❖ Mohr-Coulomb in the soil
  - ❖ What about the nails ?



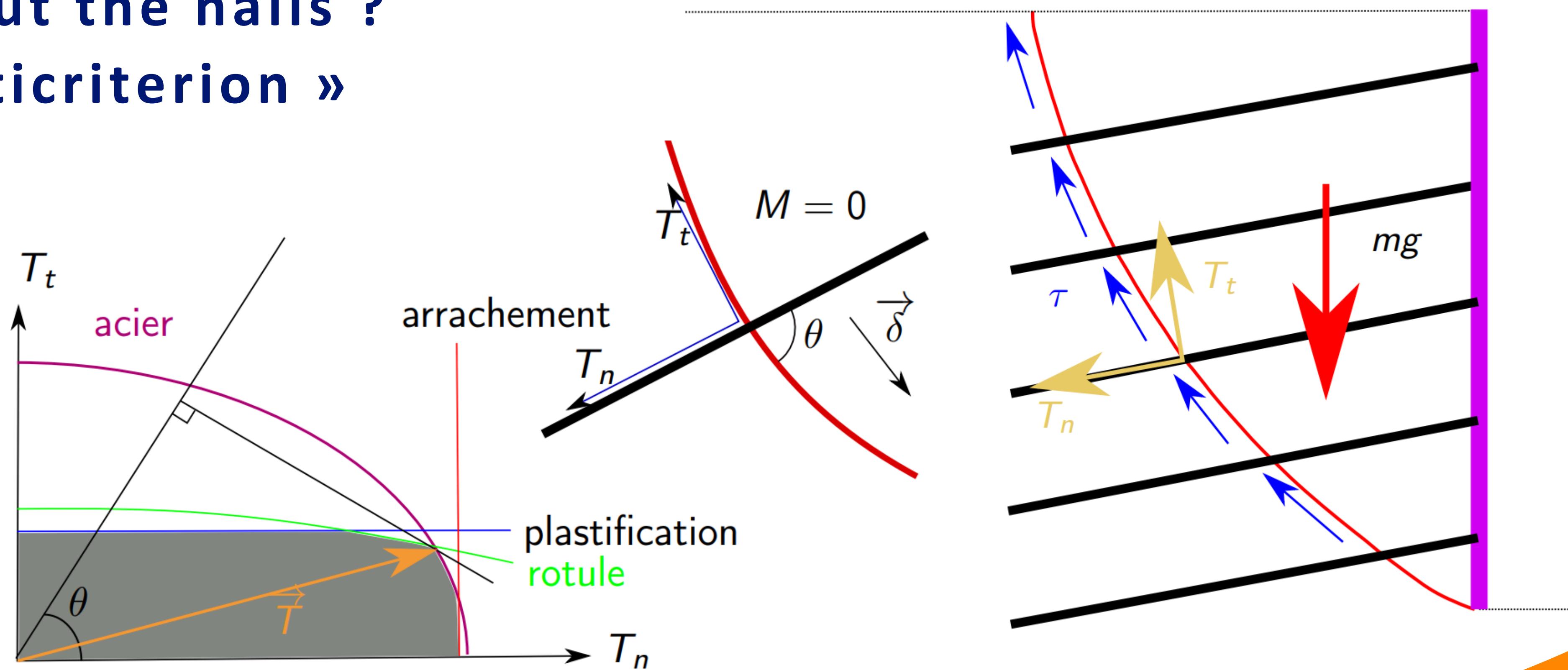
## ❖ What about the nails ?

In common softwares,  
homogenisation and multiphase  
models are not very often used.

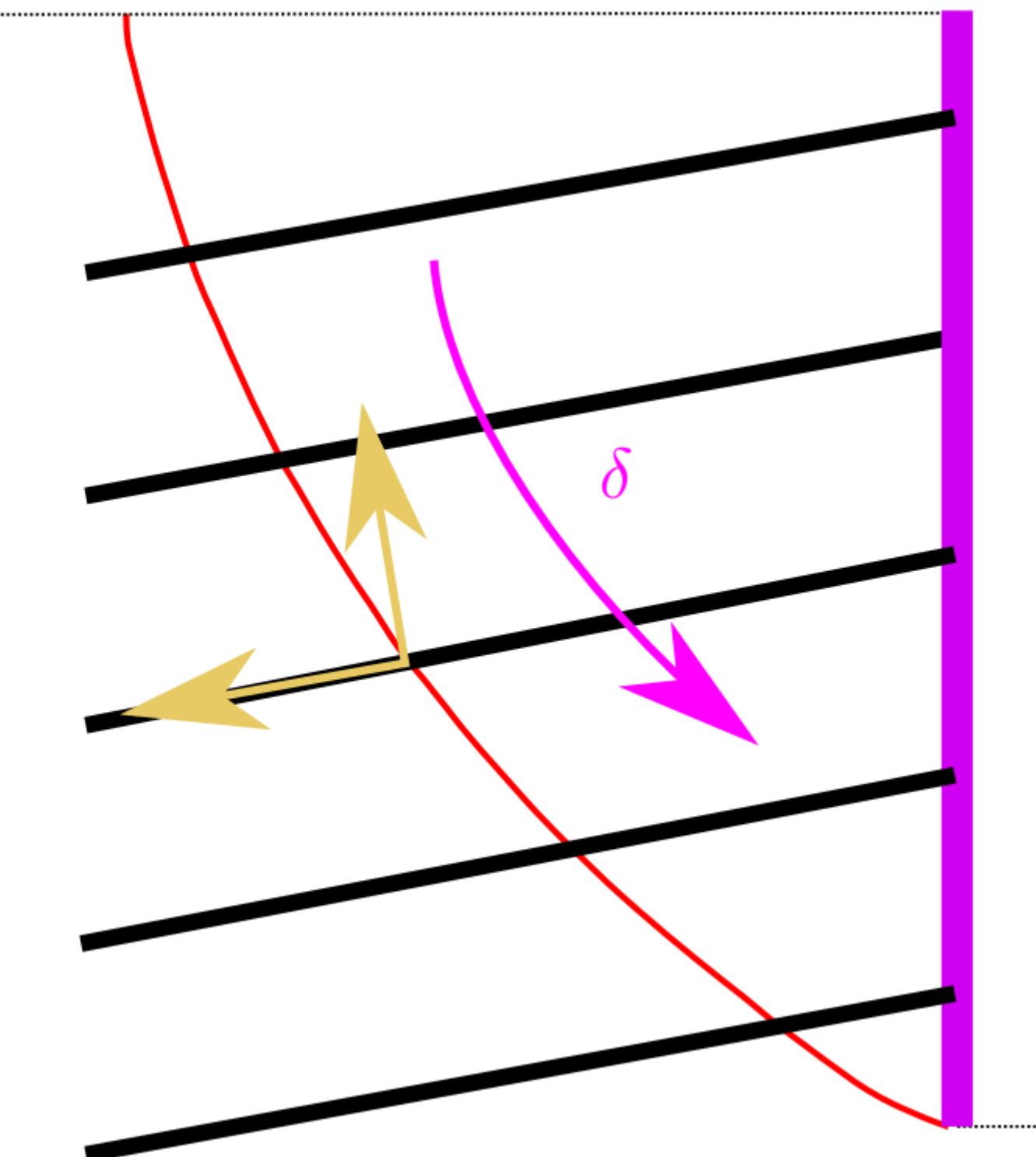
General approach is mixed  
modelling where efforts  
considered in nails are N,V,M



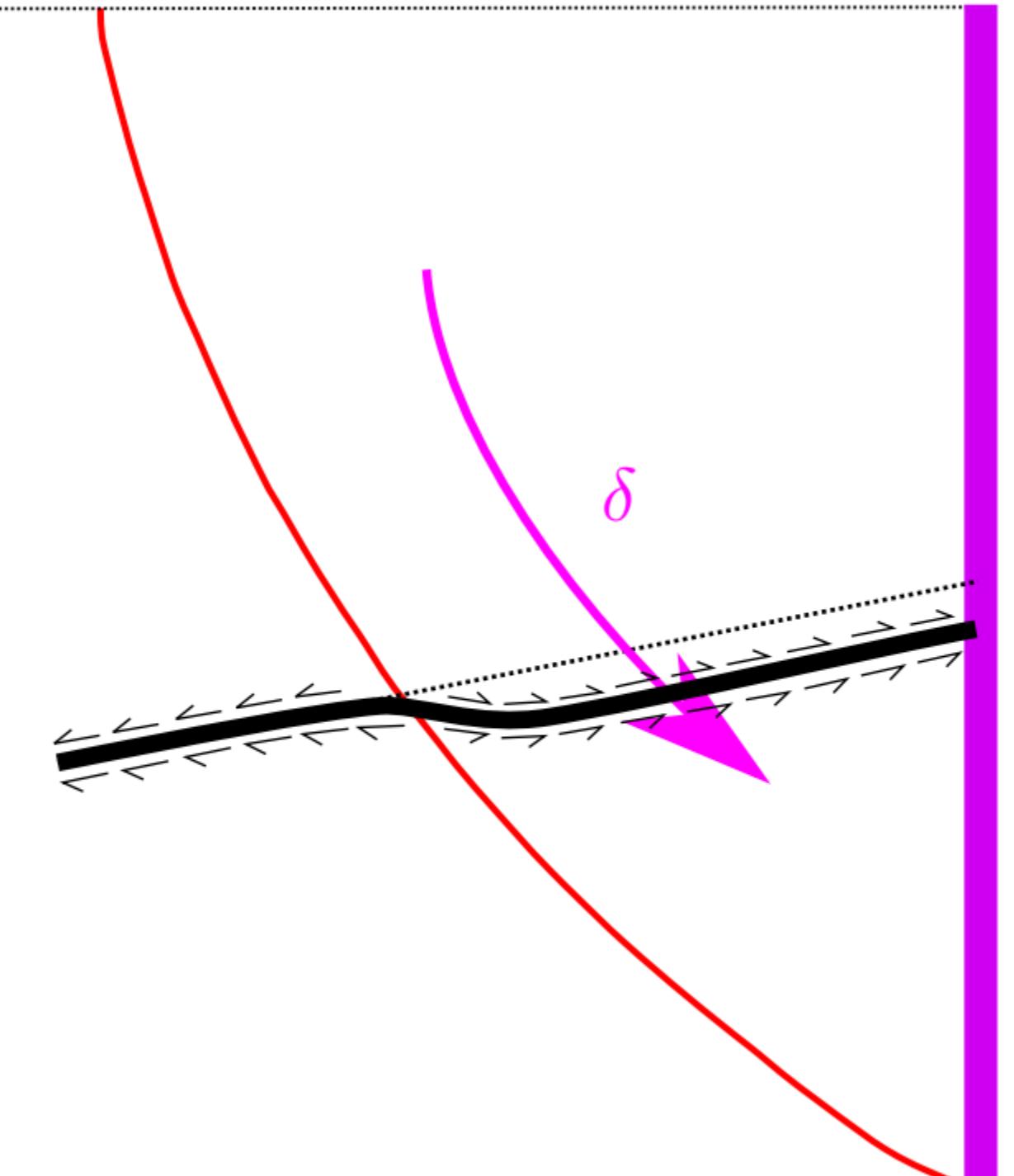
❖ What about the nails ?  
➤ « Multicriterion »



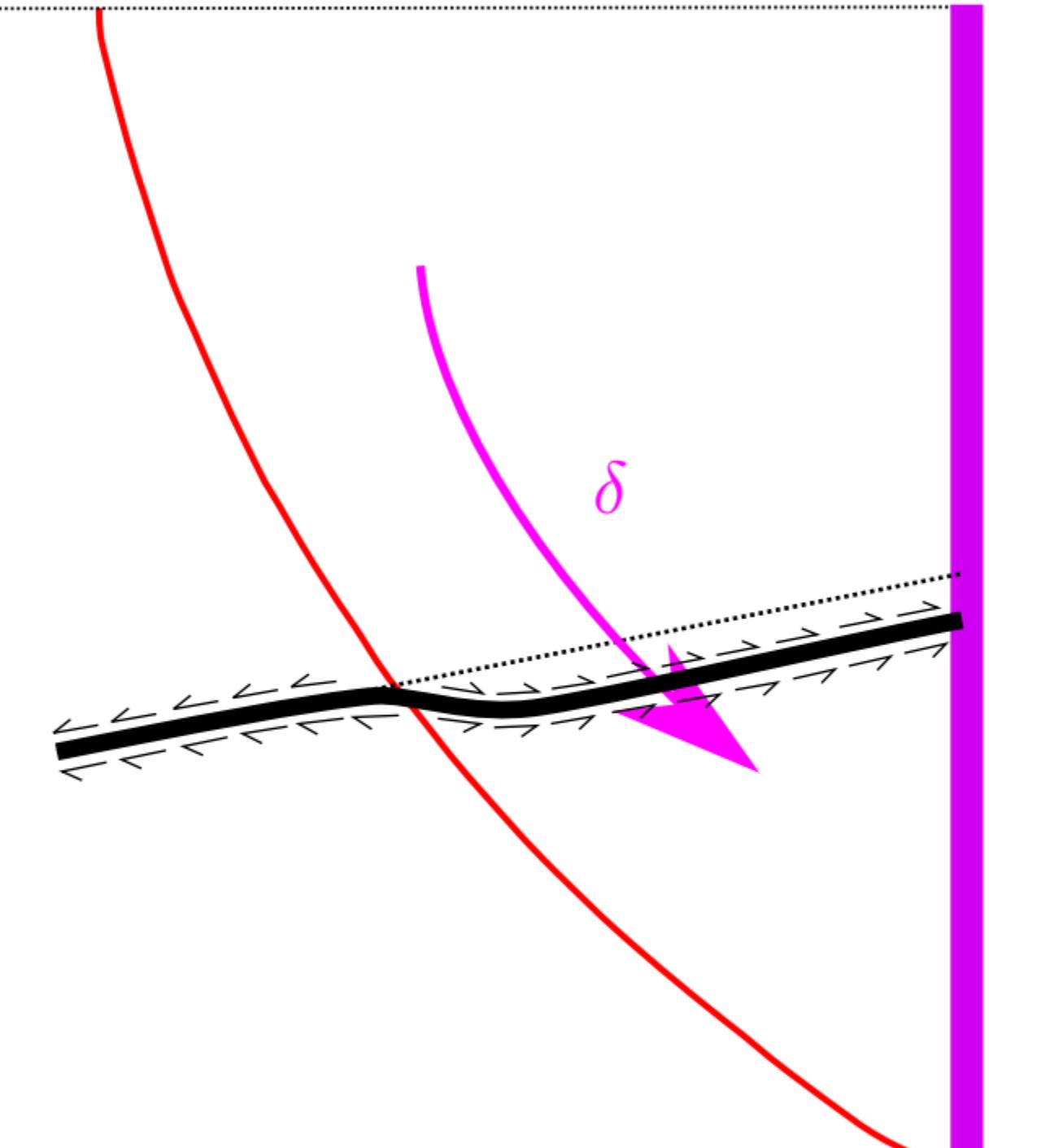
- « Displacement Method » developed in LCPC in 90s
- Idea : toggle the mobilization of nails by considering a displacement of the failing mass



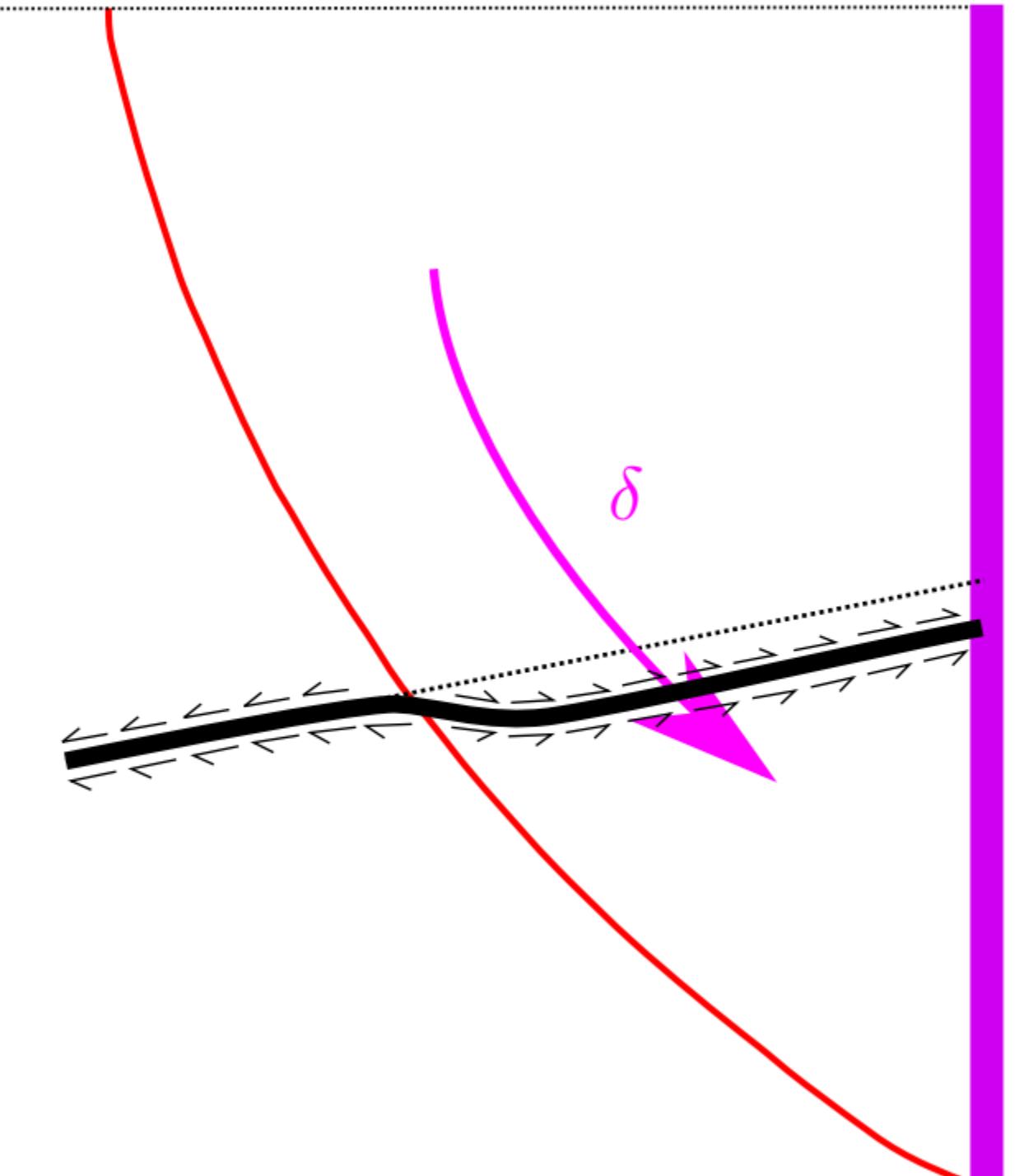
- « Displacement Method » developed in LCPC in 90s
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- Integration of beam equations



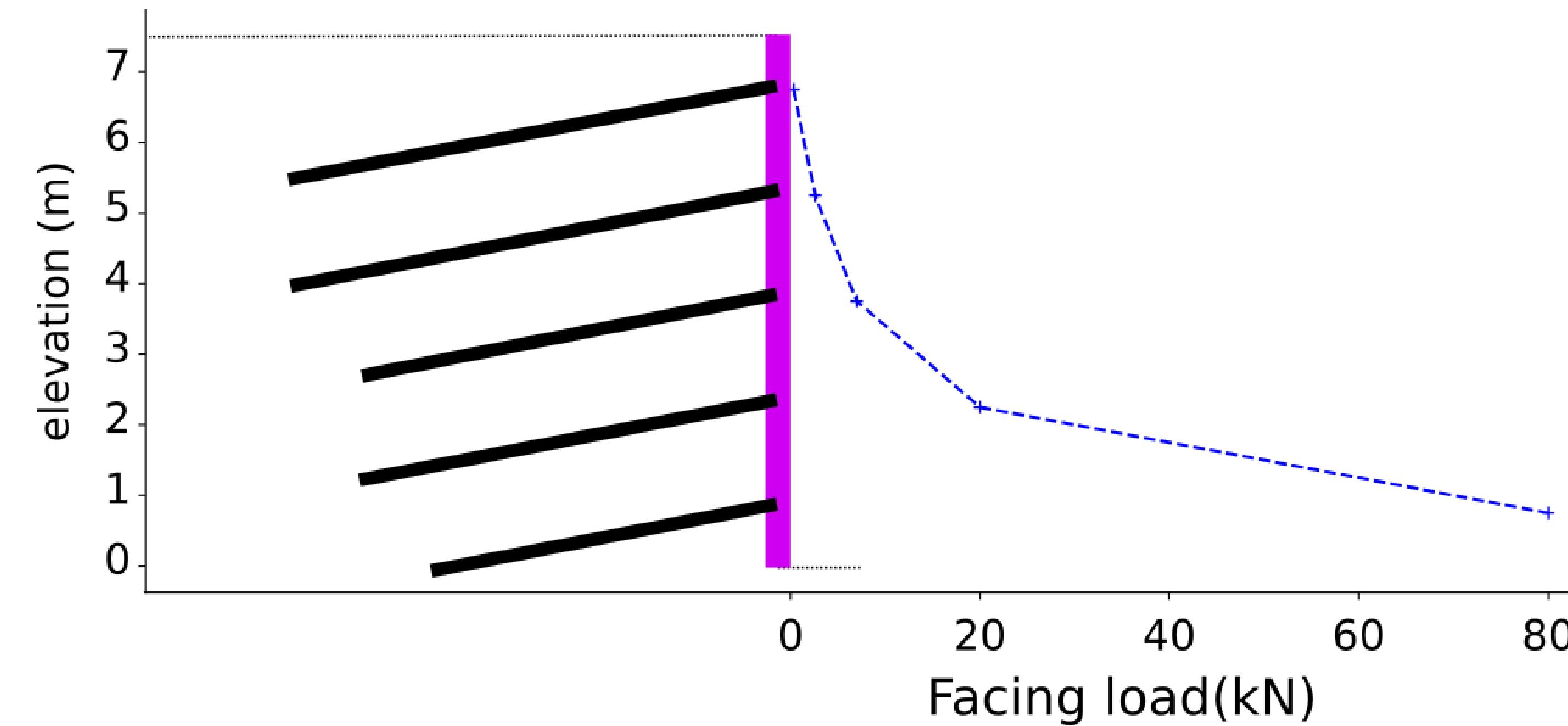
- Idea : toggle the mobilization of nails by considering a displacement of the failing mass
- Integration of beam equations
- Efforts in the nails used to write the limit analysis constraints
- Not a kinematic method !!



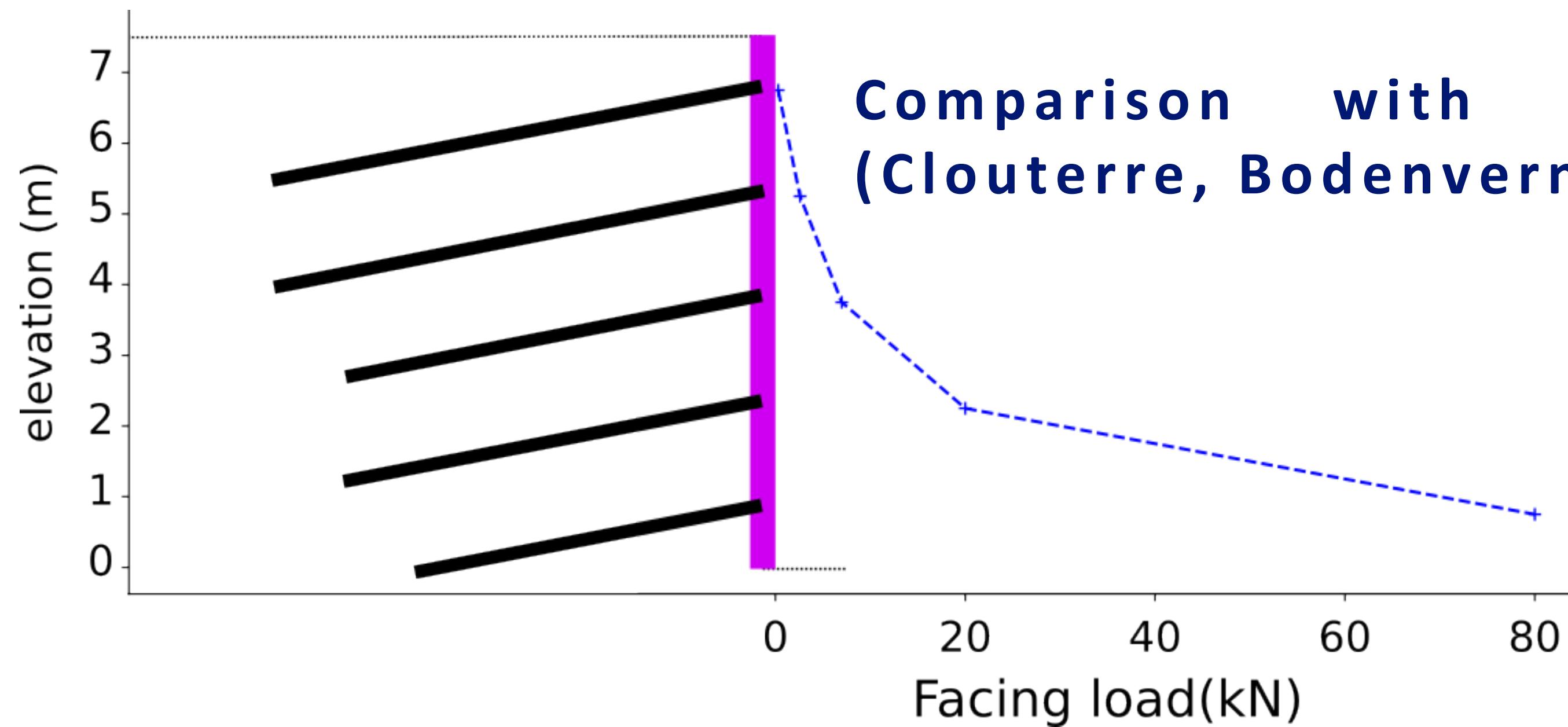
- **Integration of beam equations**
- **Beam equation can be integrated until the facing**
- **Loads on the facing can be estimated**



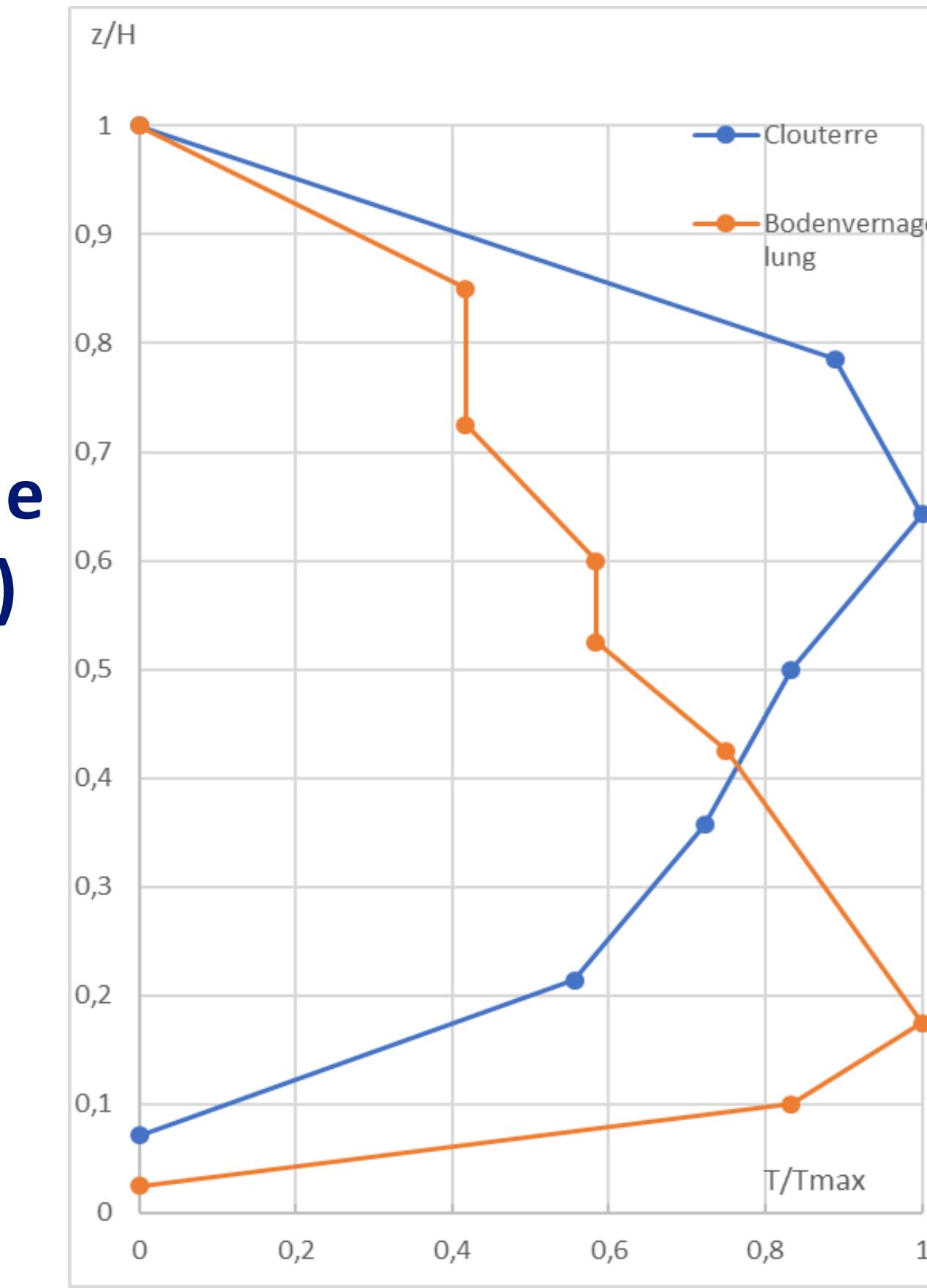
➤ Loads on the facing can be estimated

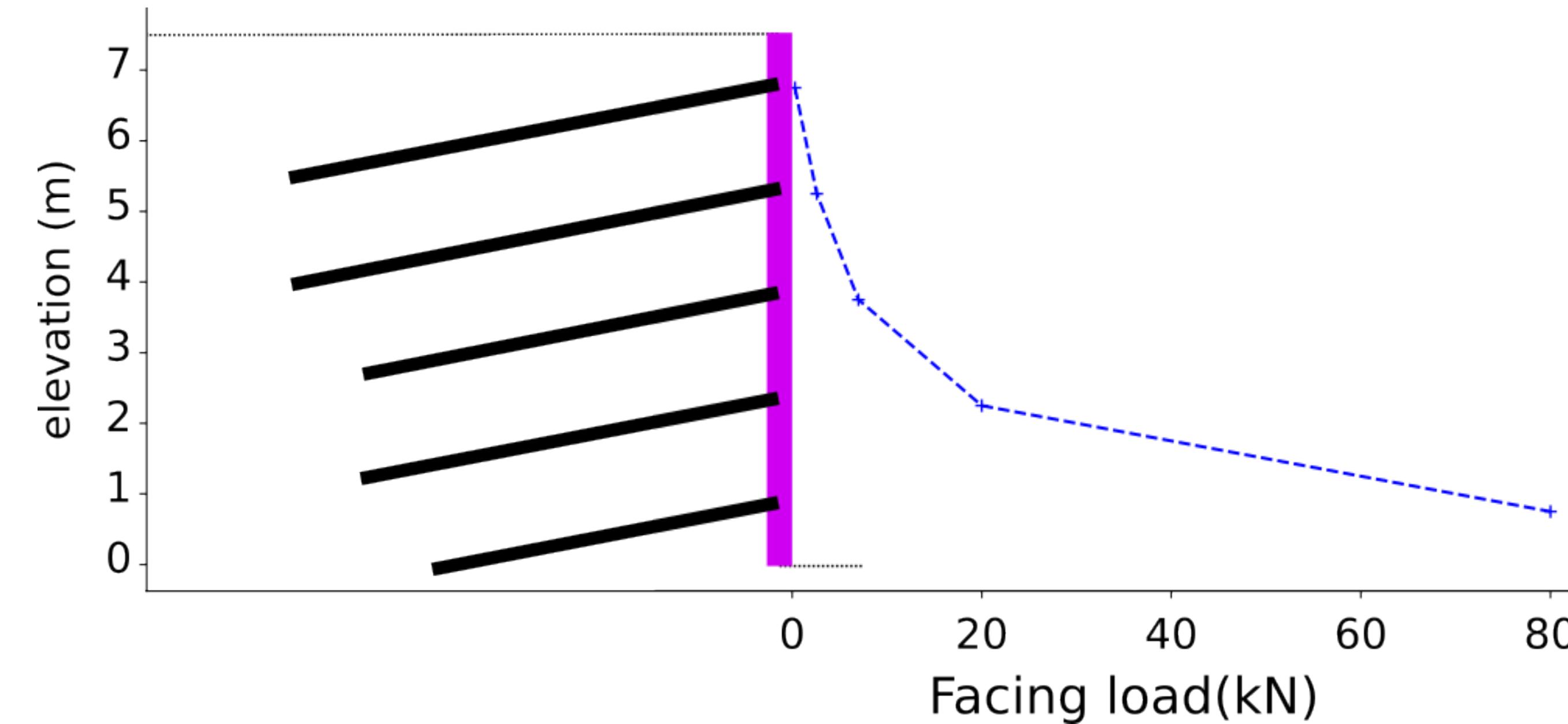


➤ Loads on the facing can be estimated ??



Comparison with literature  
(Clouterre, Bodenvernagelung)



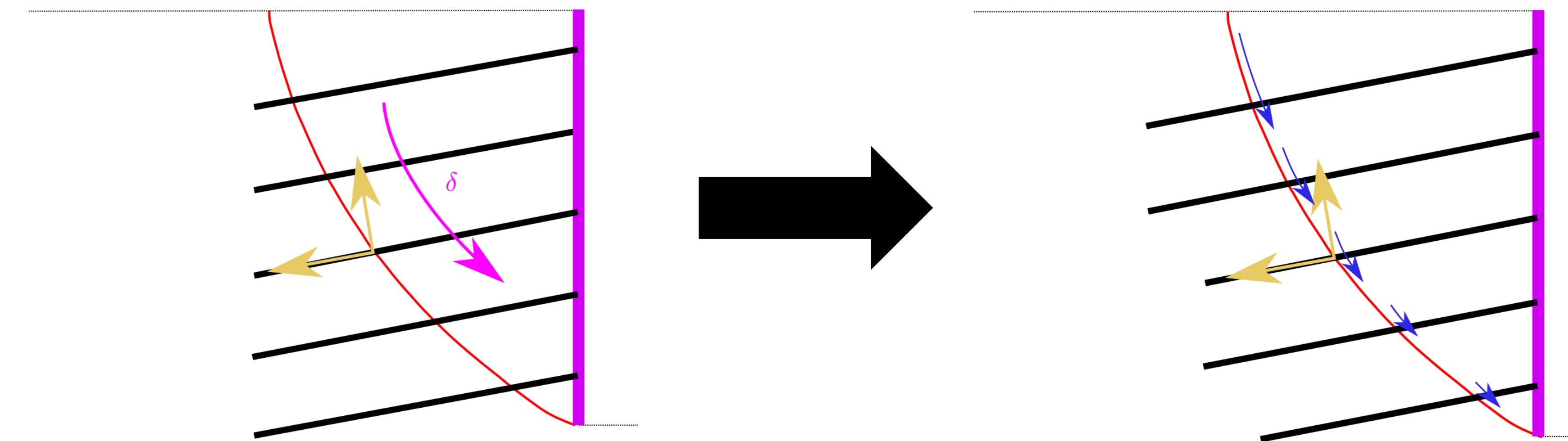


**Tension of the bottom nail very high ...  
but no further lift activates it !**



**Tension of the bottom nail very high ...  
but no further lift activates it !**

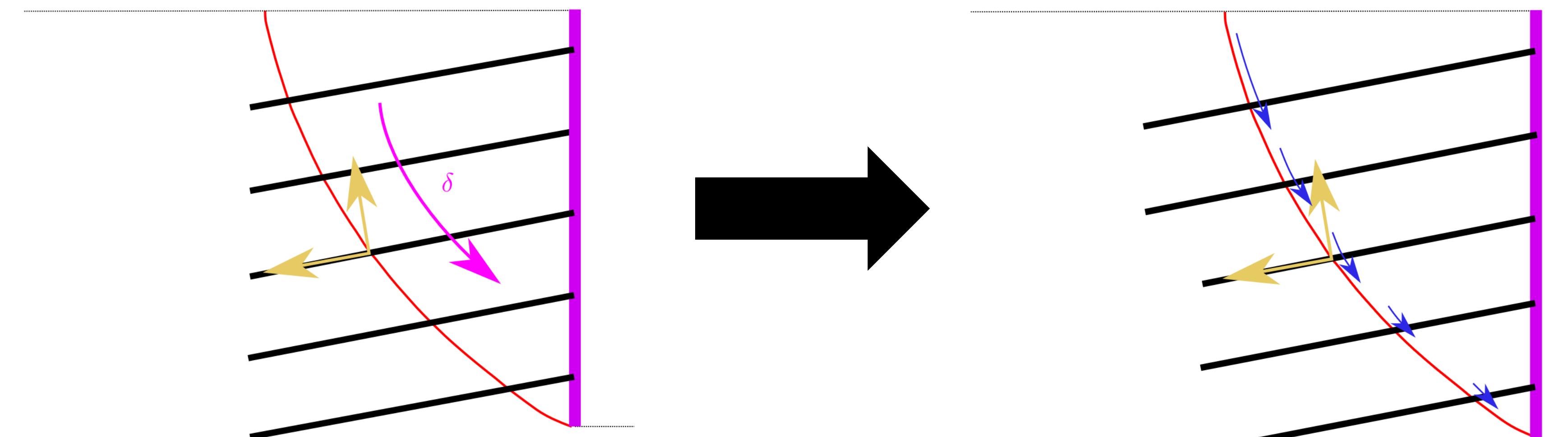
**In order to improve the PROSPER Method, one need to introduce a non homogenous mobilisation of nails**



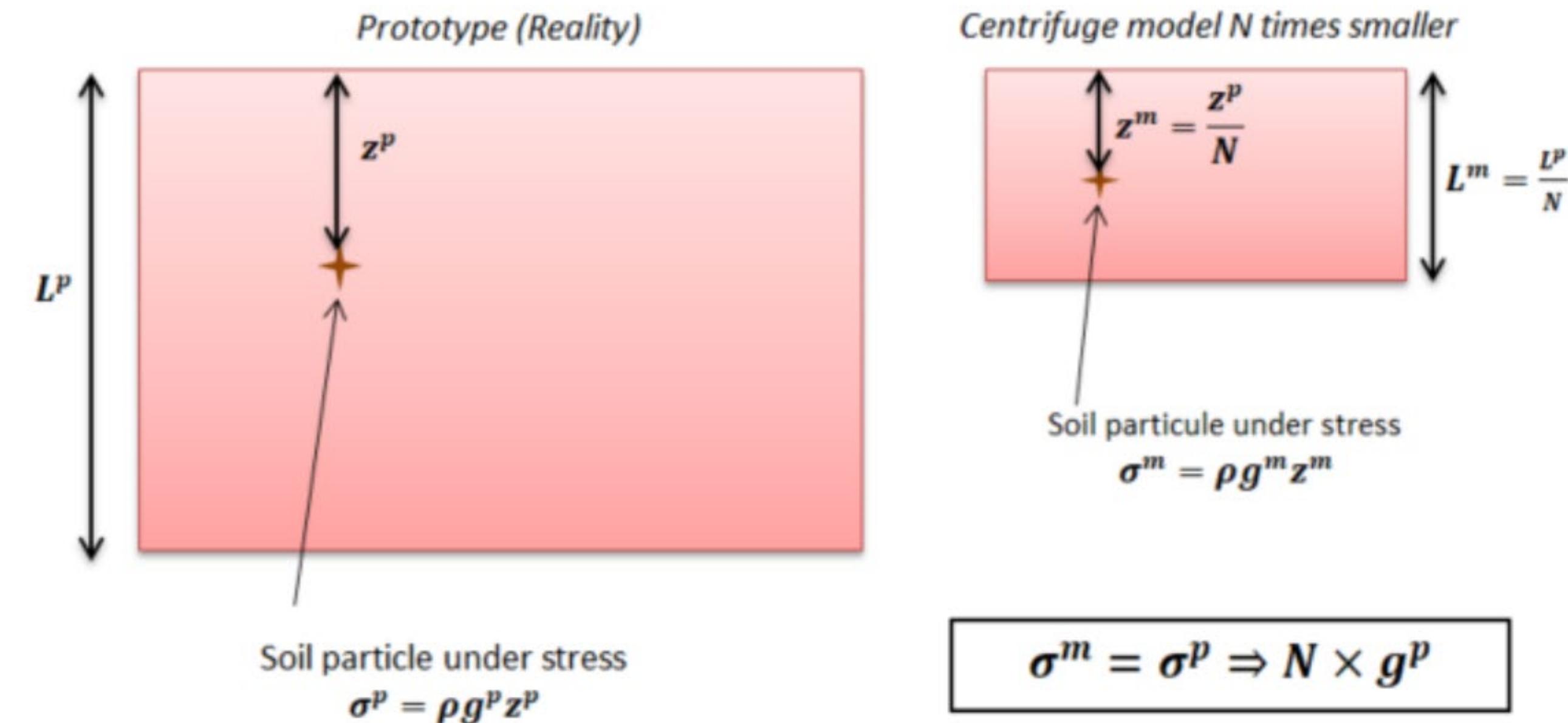
## Which shape for the function $\delta$ ?

Need for a better understanding of nails mobilisation

→ Use of centrifuge modeling



## 1869 : *De L'Equilibre Des Solides Elastiques Semblables*, E. Phillips



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1982 : First soil-nailed wall (realised at 1g, Shen)

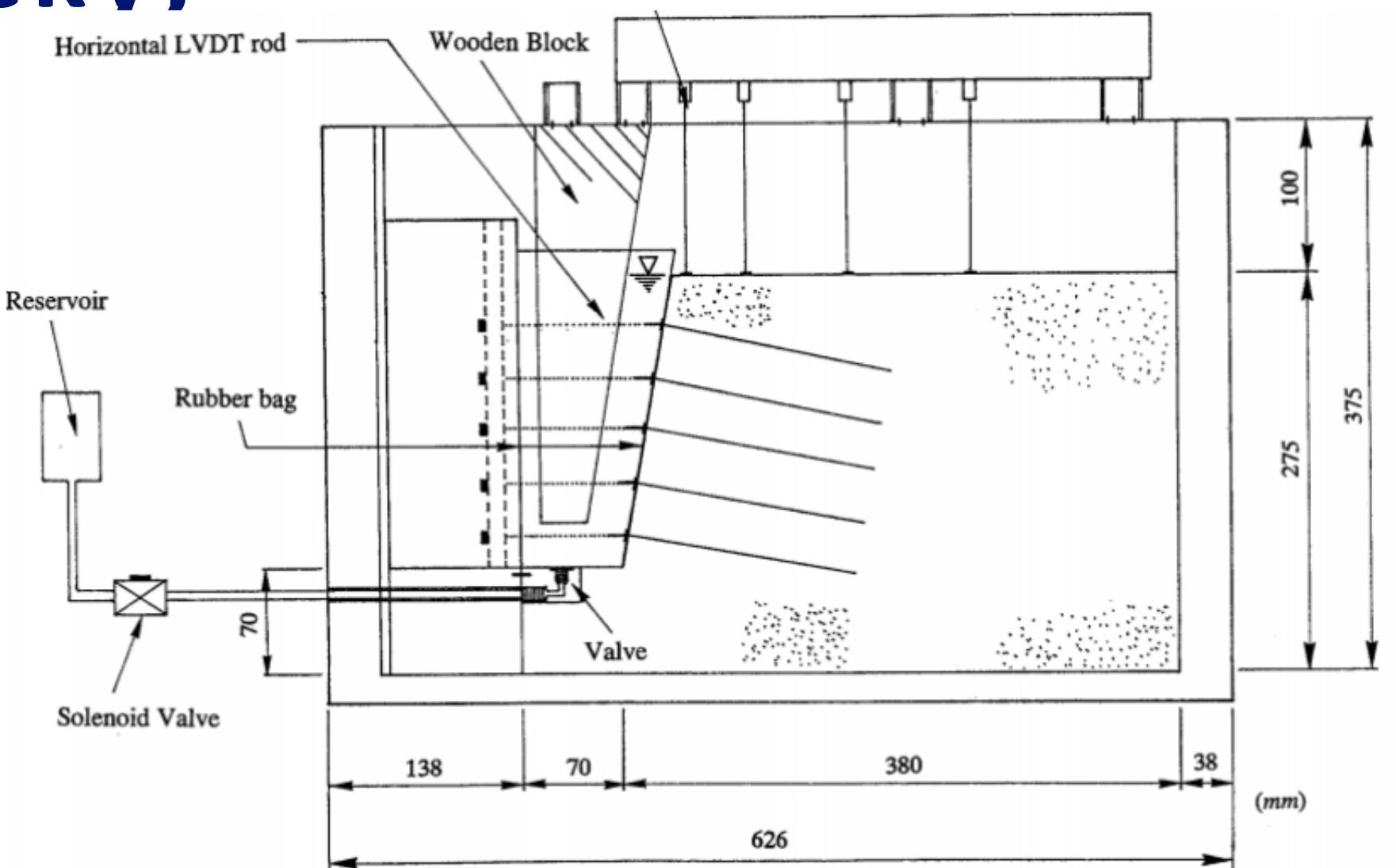


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1993 : Inflight excavation (fluid bags, Tei)



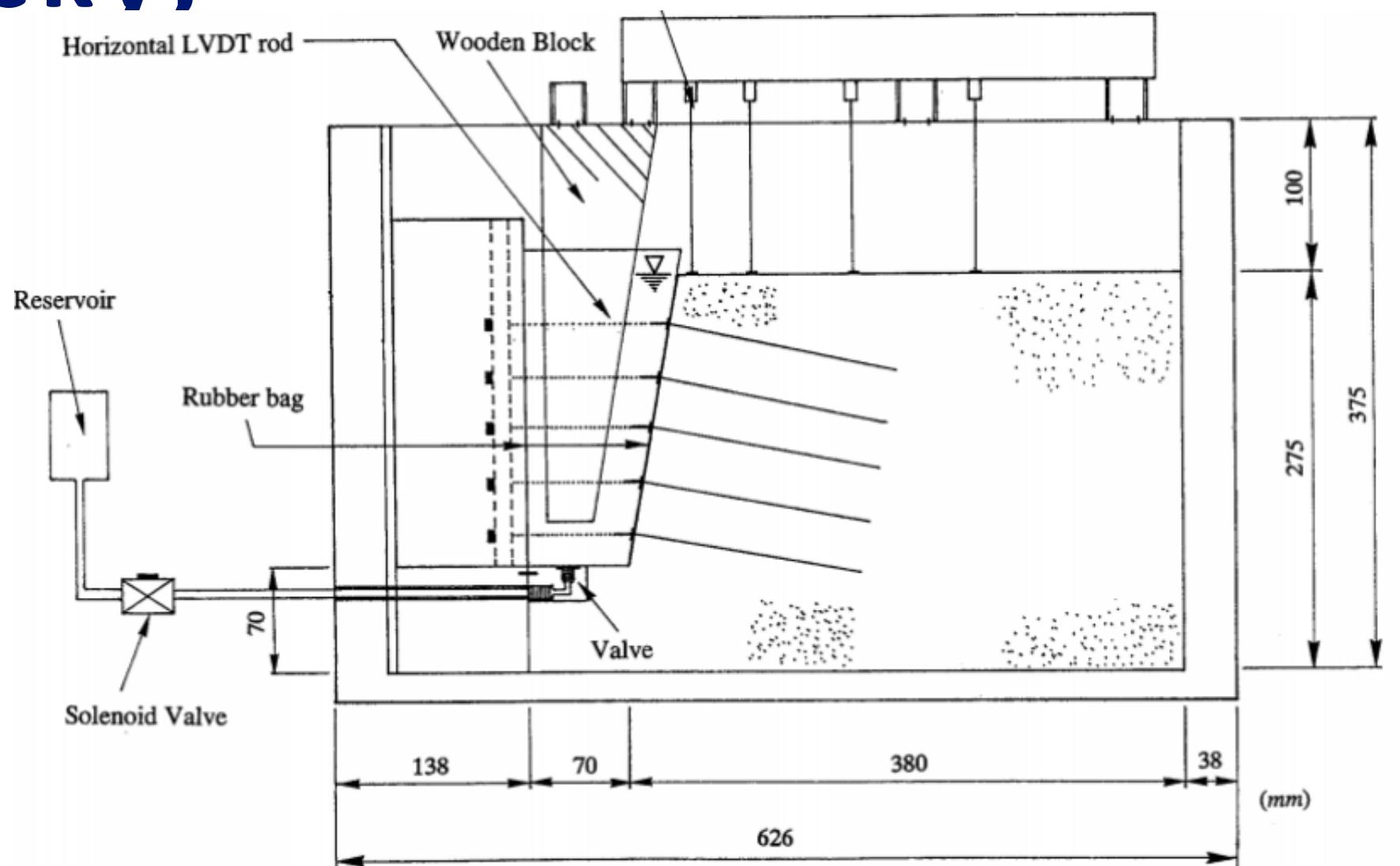
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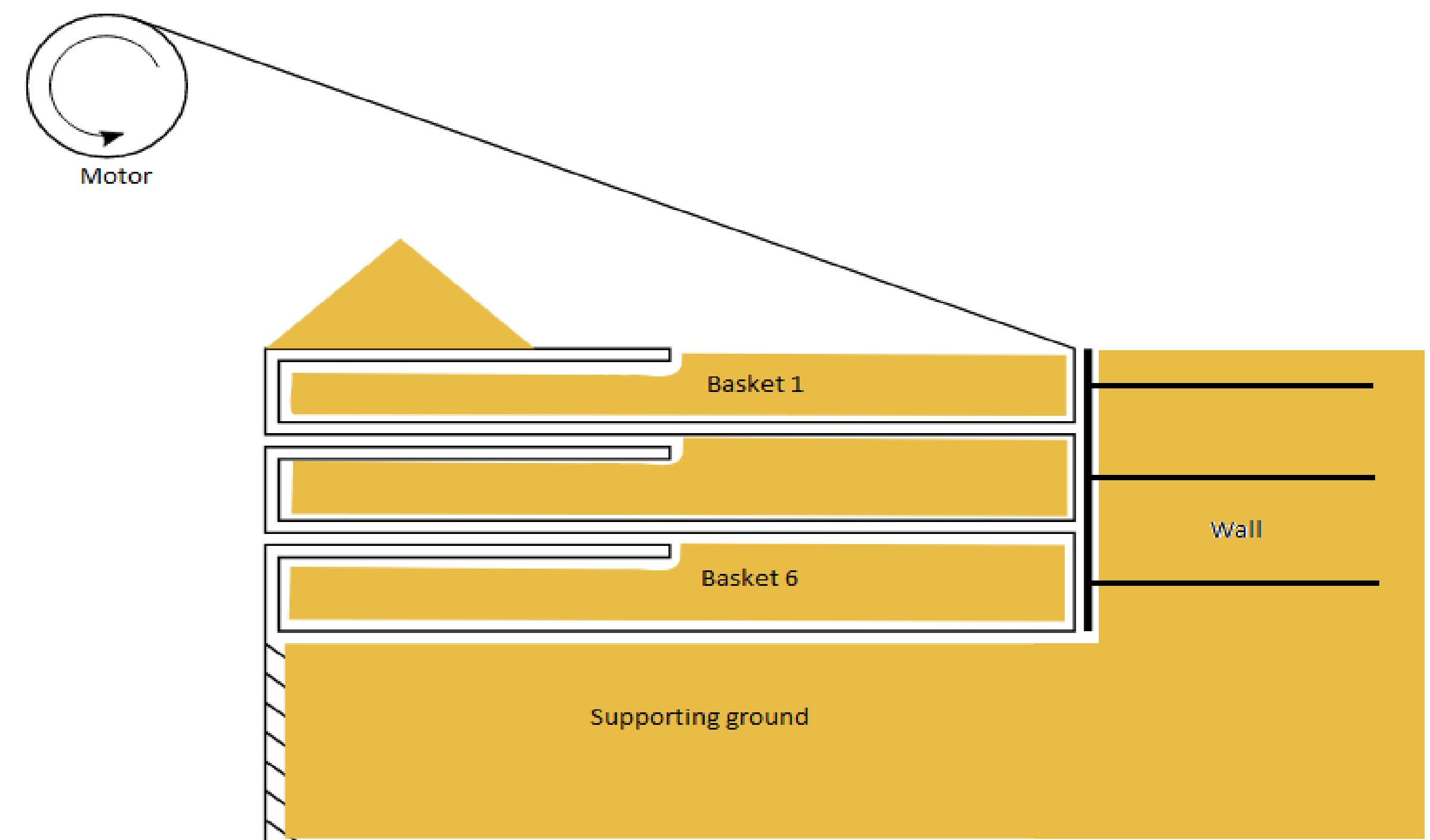
➤ Inflight excavation difficult but crucial to respect construction phasing



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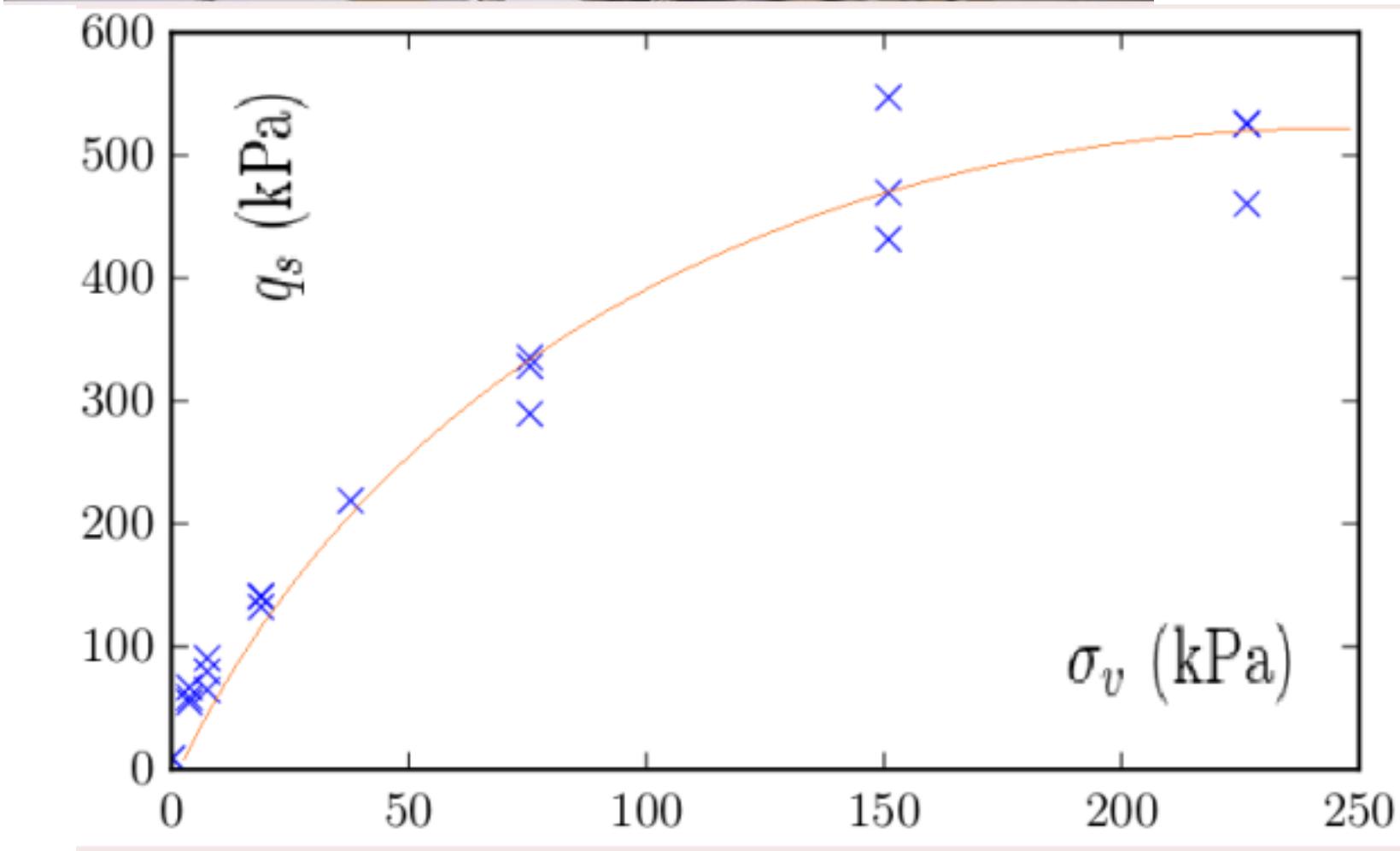
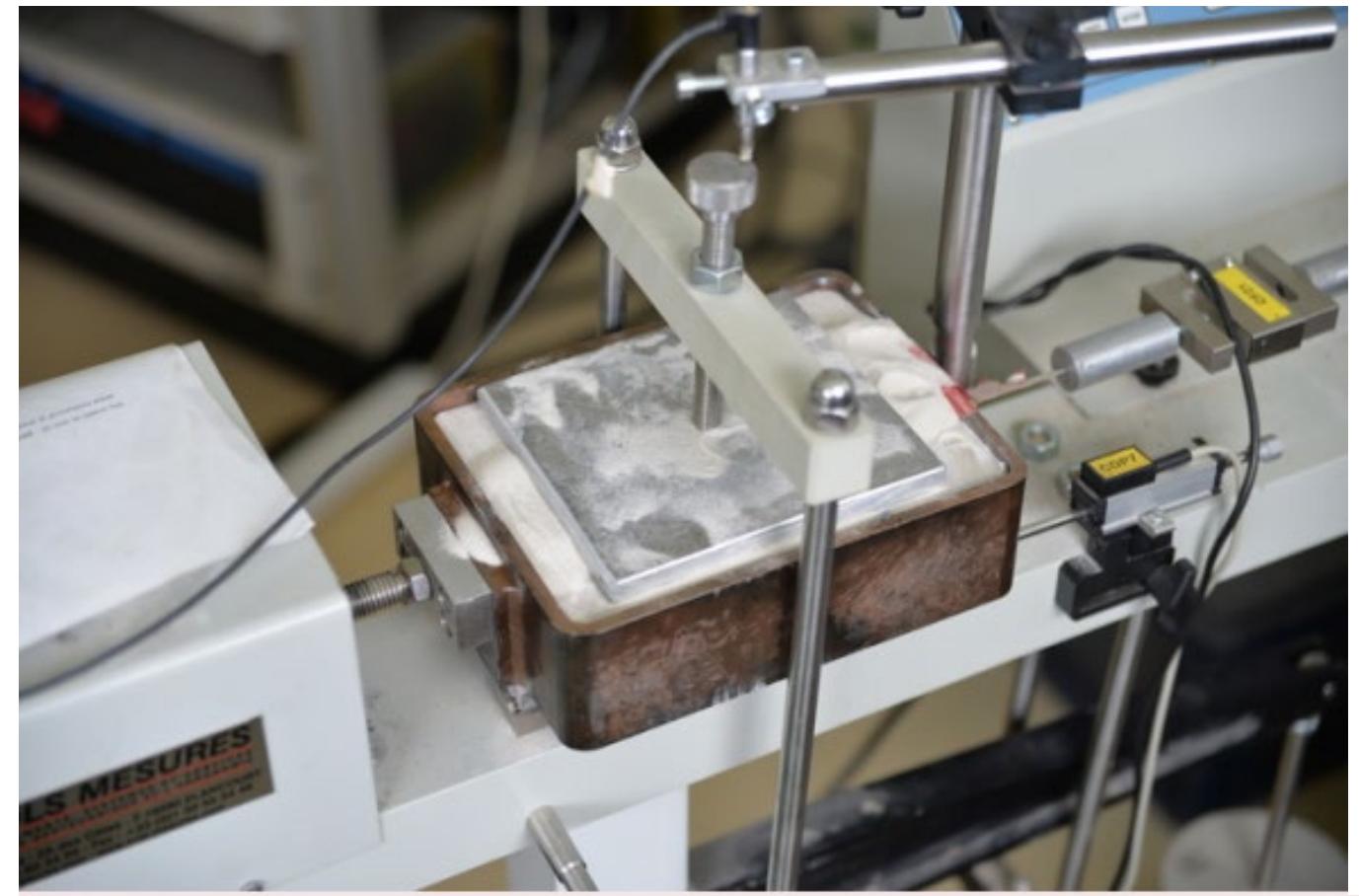
Wrapping of geotextile around  
the axis of a motor

(soil = dense Hostun sand HN38)



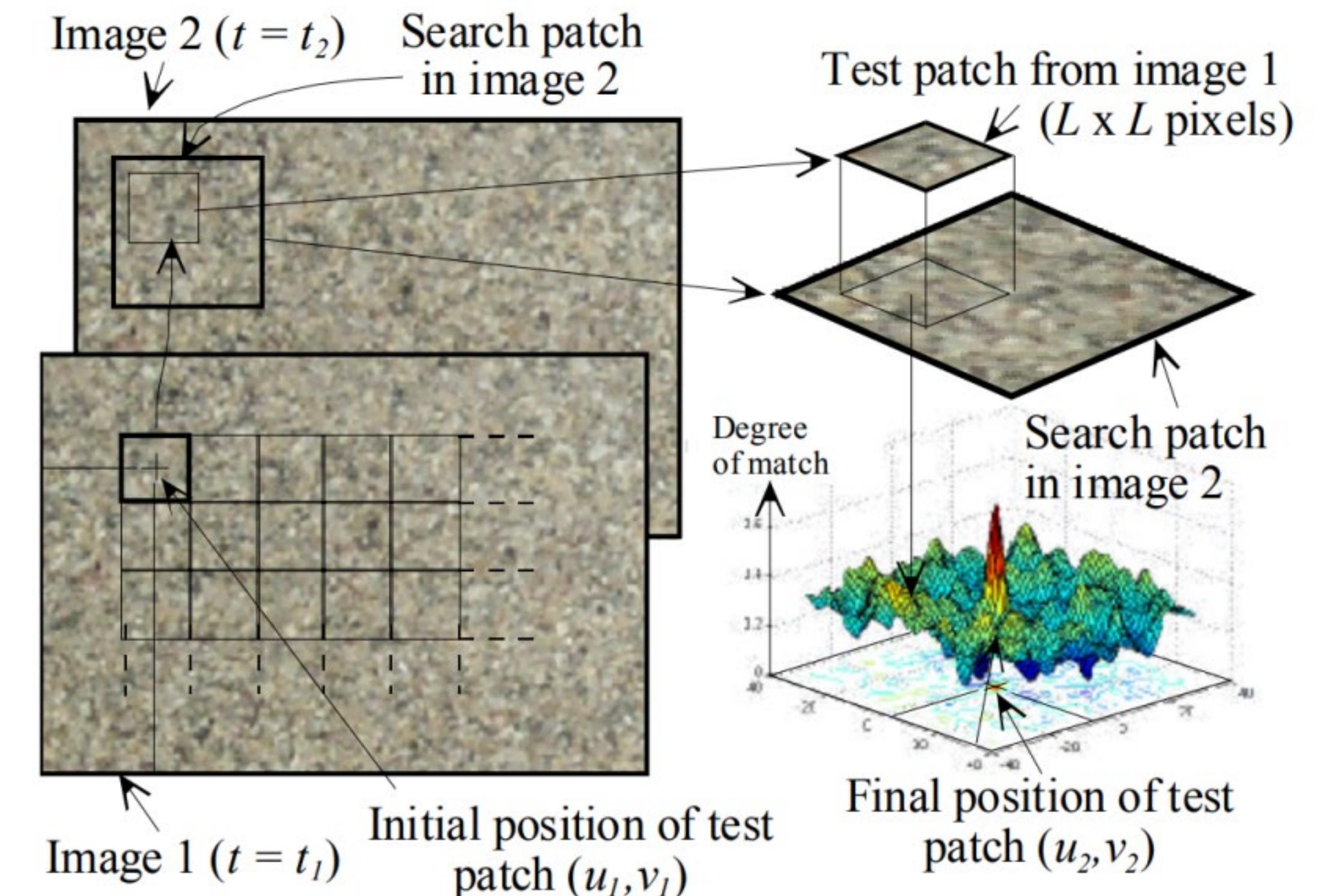
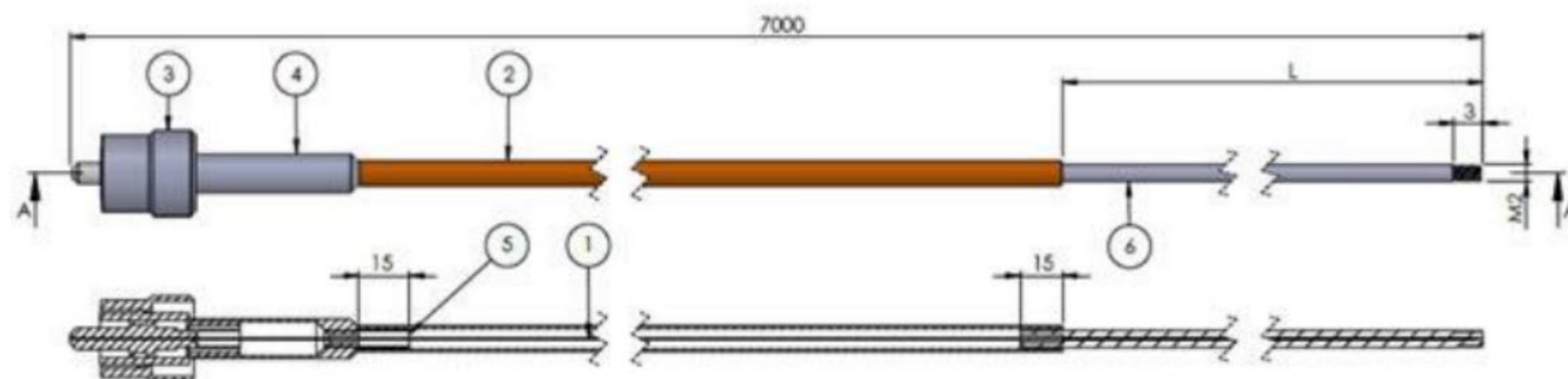
### Relevance of physical model ?

- In the soil mass, similitude of phenomena observed is warranted by the respect of scaling laws.
- Around nails, very limited number of grains → scaling laws not warranted
- Mini pull out tests



## Monitoring of the model

- Optic fiber nails
- GeoPIV

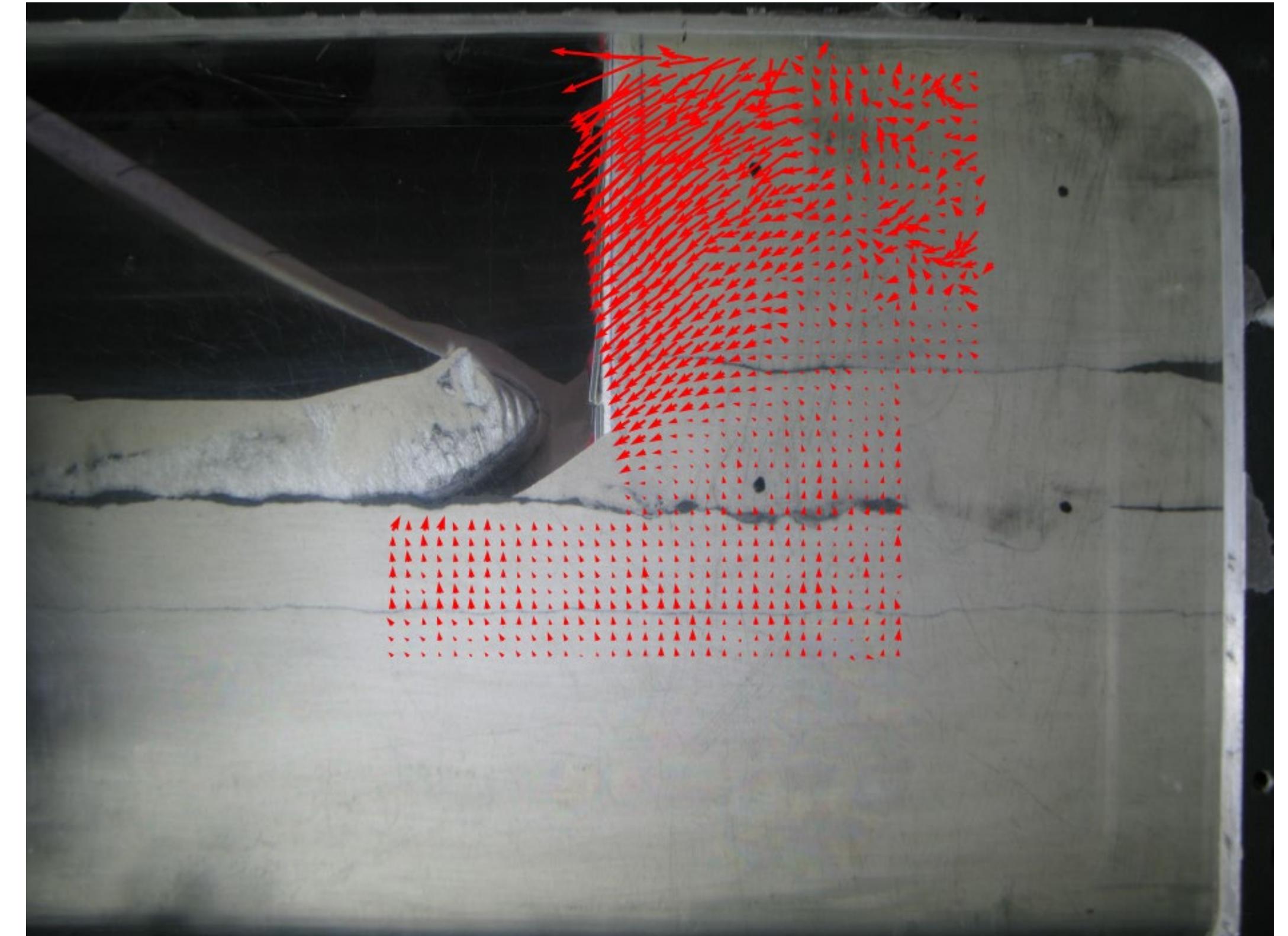
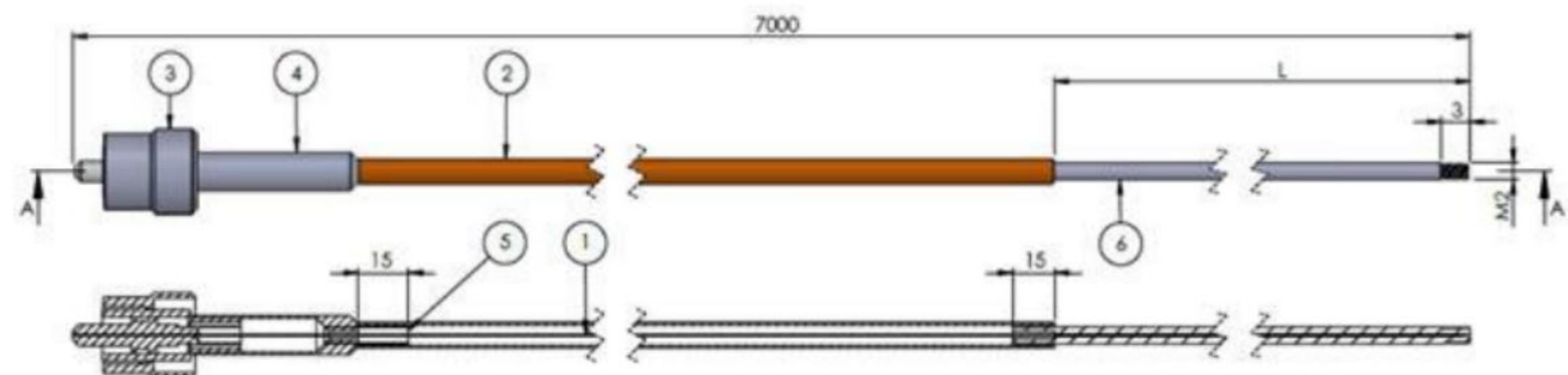


Stanier et al., 2015



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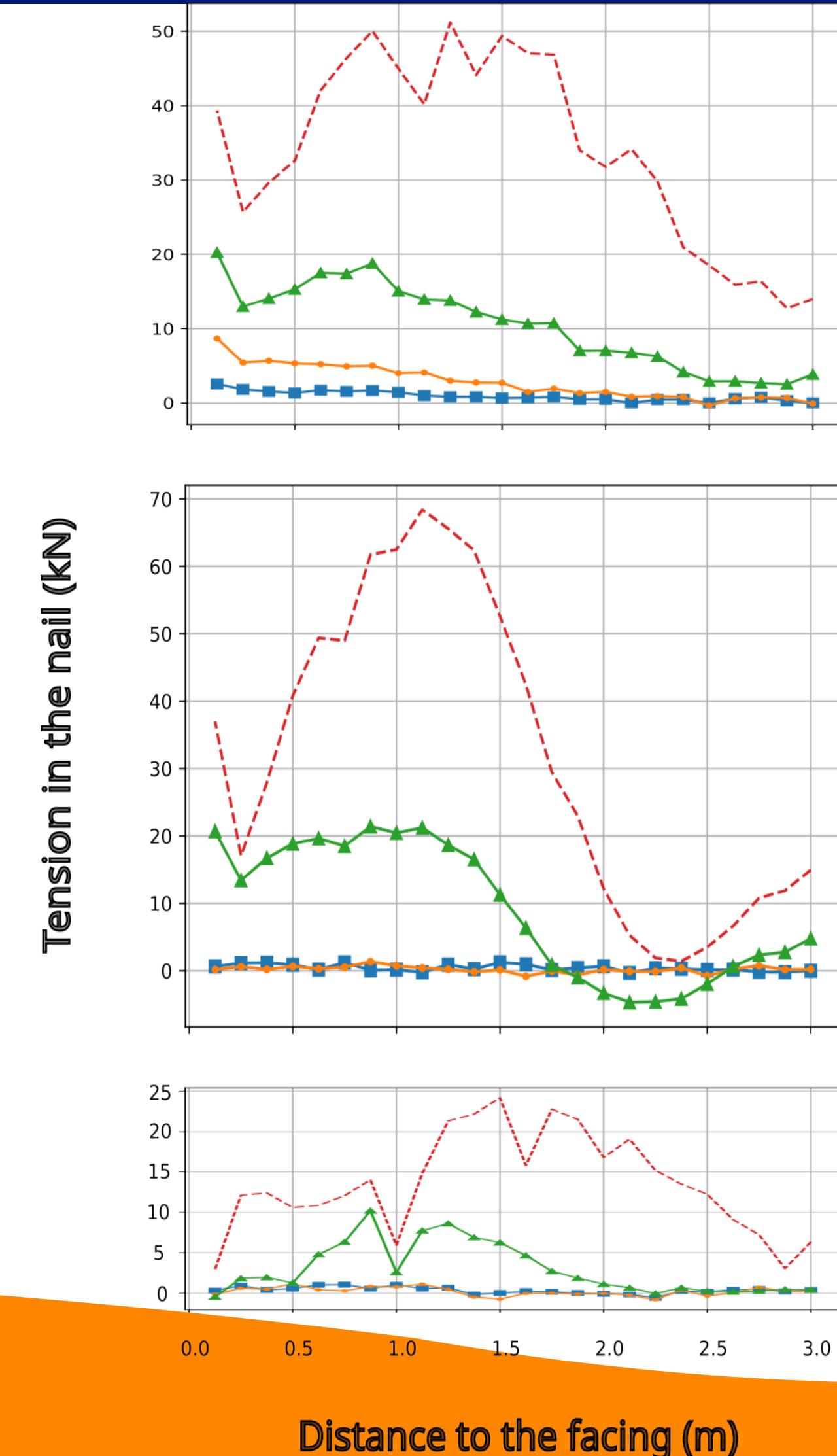


Also allows to compute strains



- Tensions in the nails
- Strains in the soil

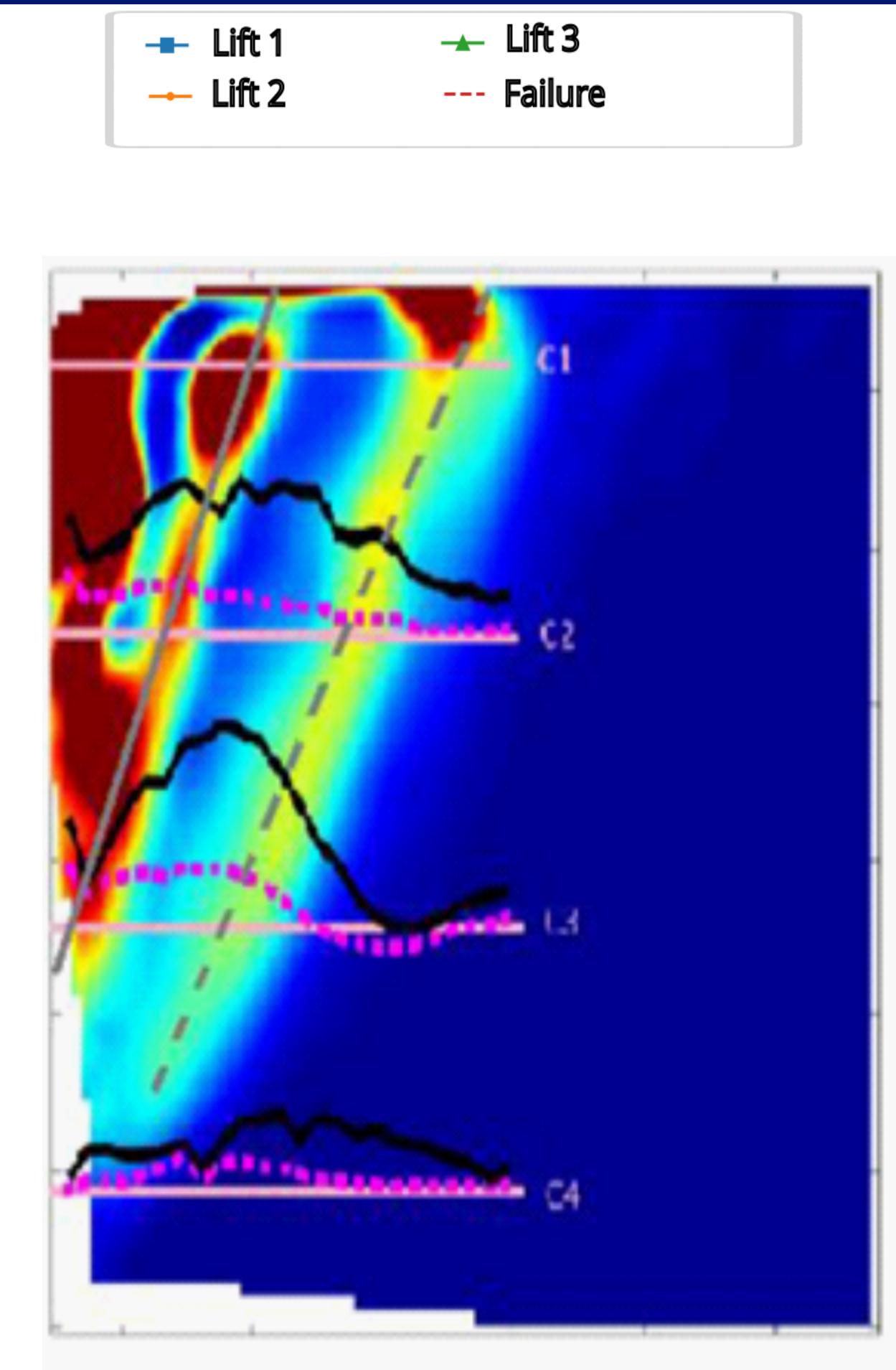
A complex kinematic



C2

C3

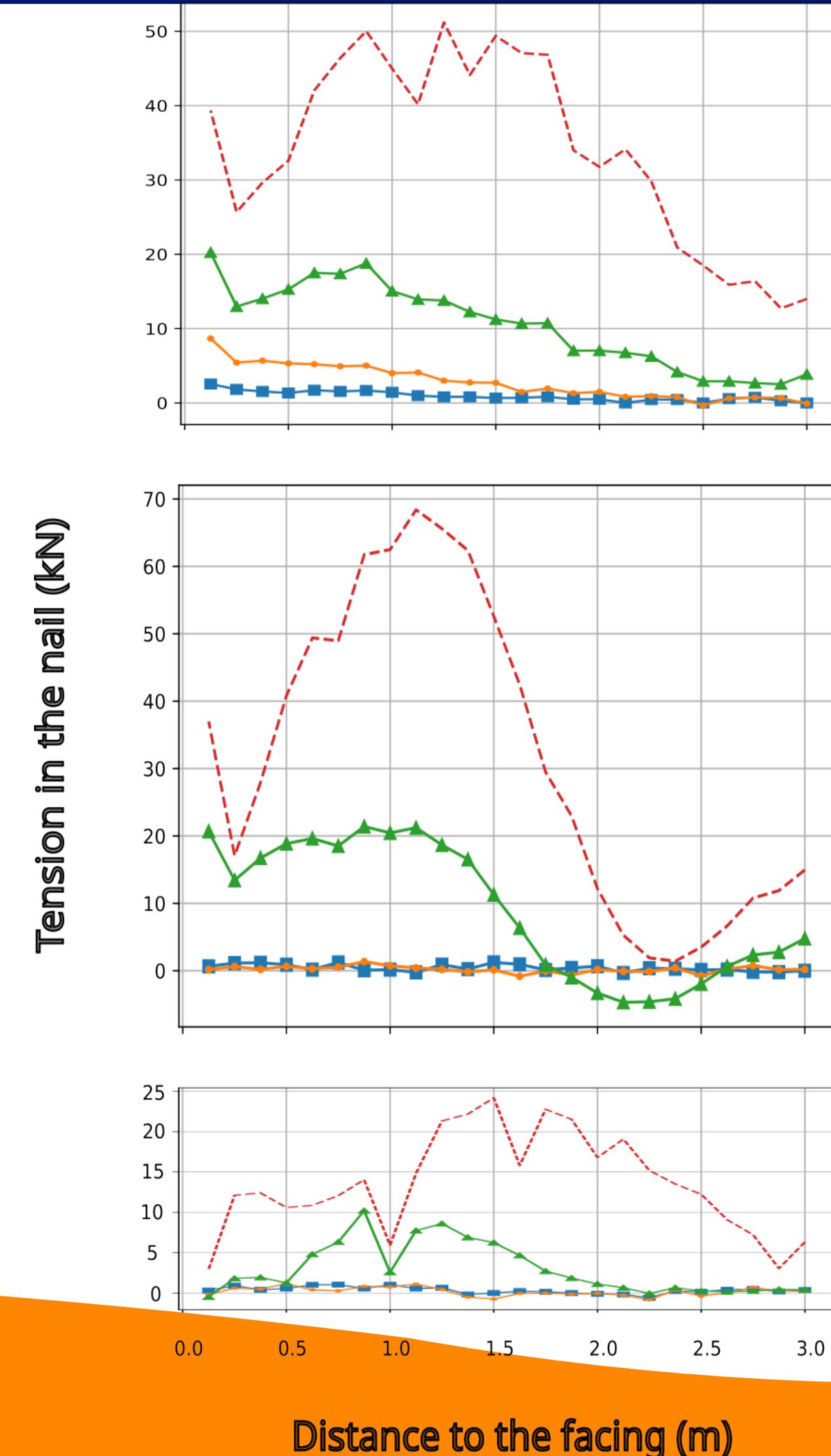
C4



- Tensions in the nails
- Strains in the soil

## A complex kinematic

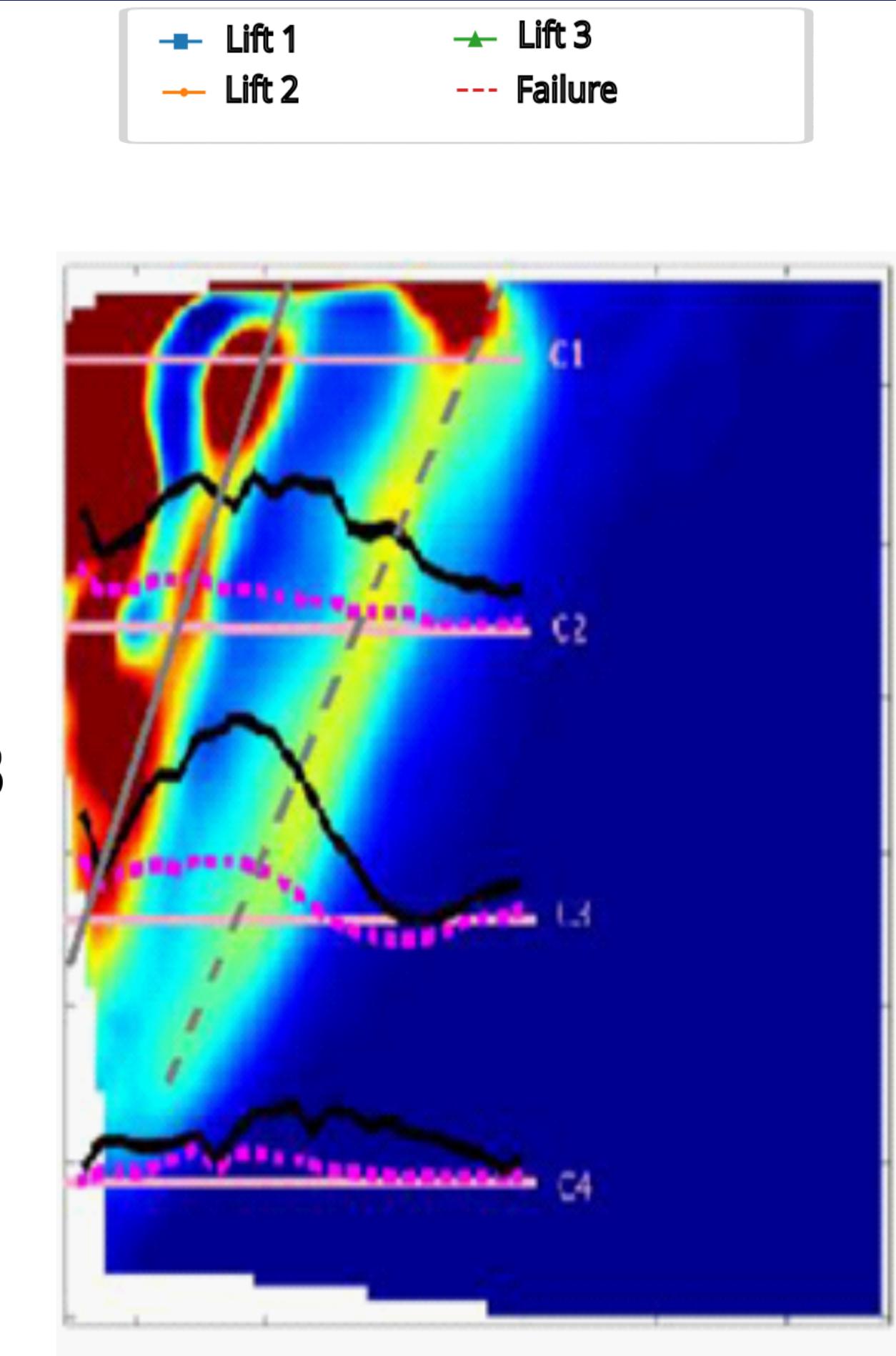
- Phasing is a crucial parameter
- Observed displacements do not reflect the mobilisation of the nail



C2

C3

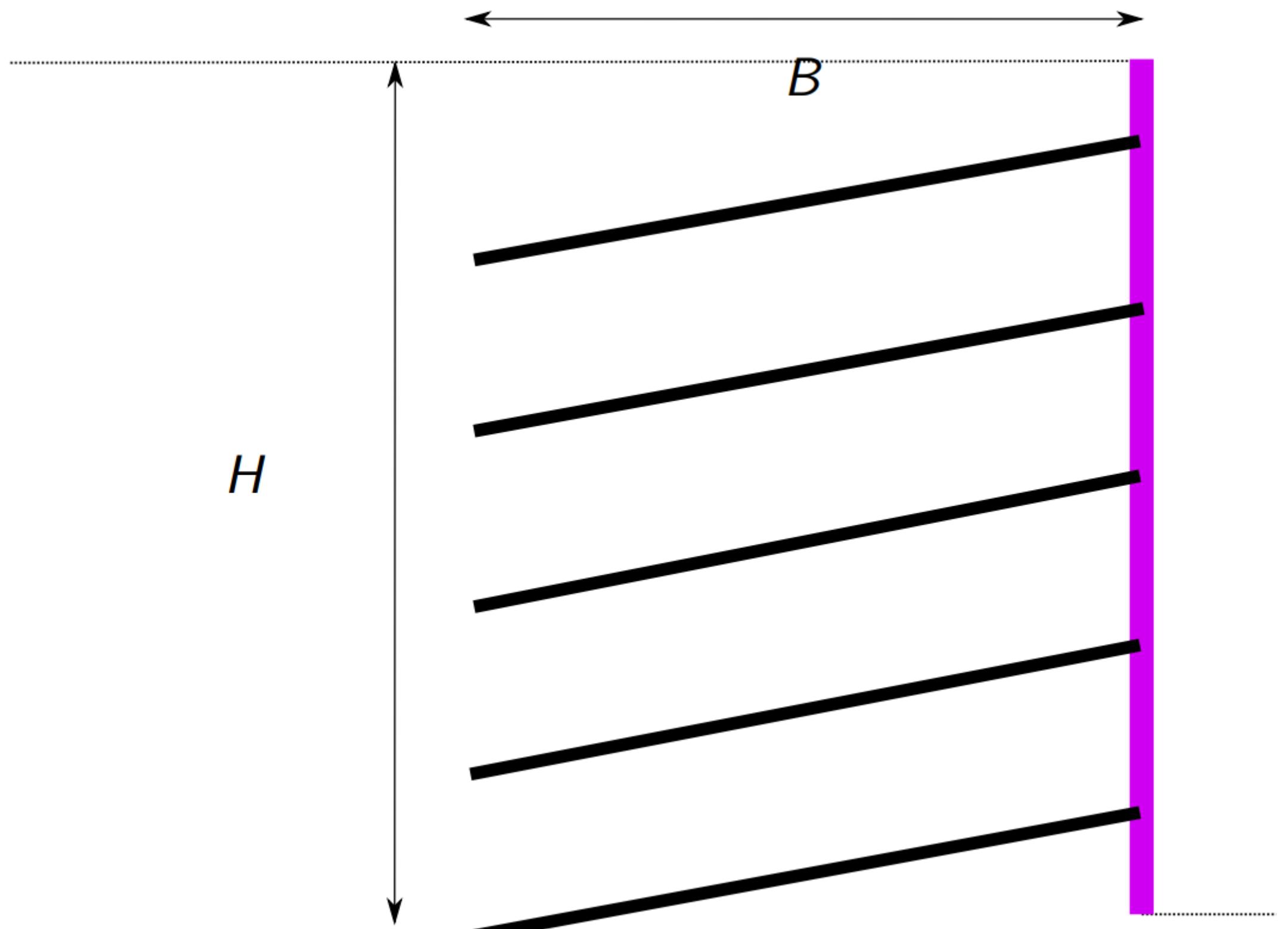
C4



### A complex kinematic

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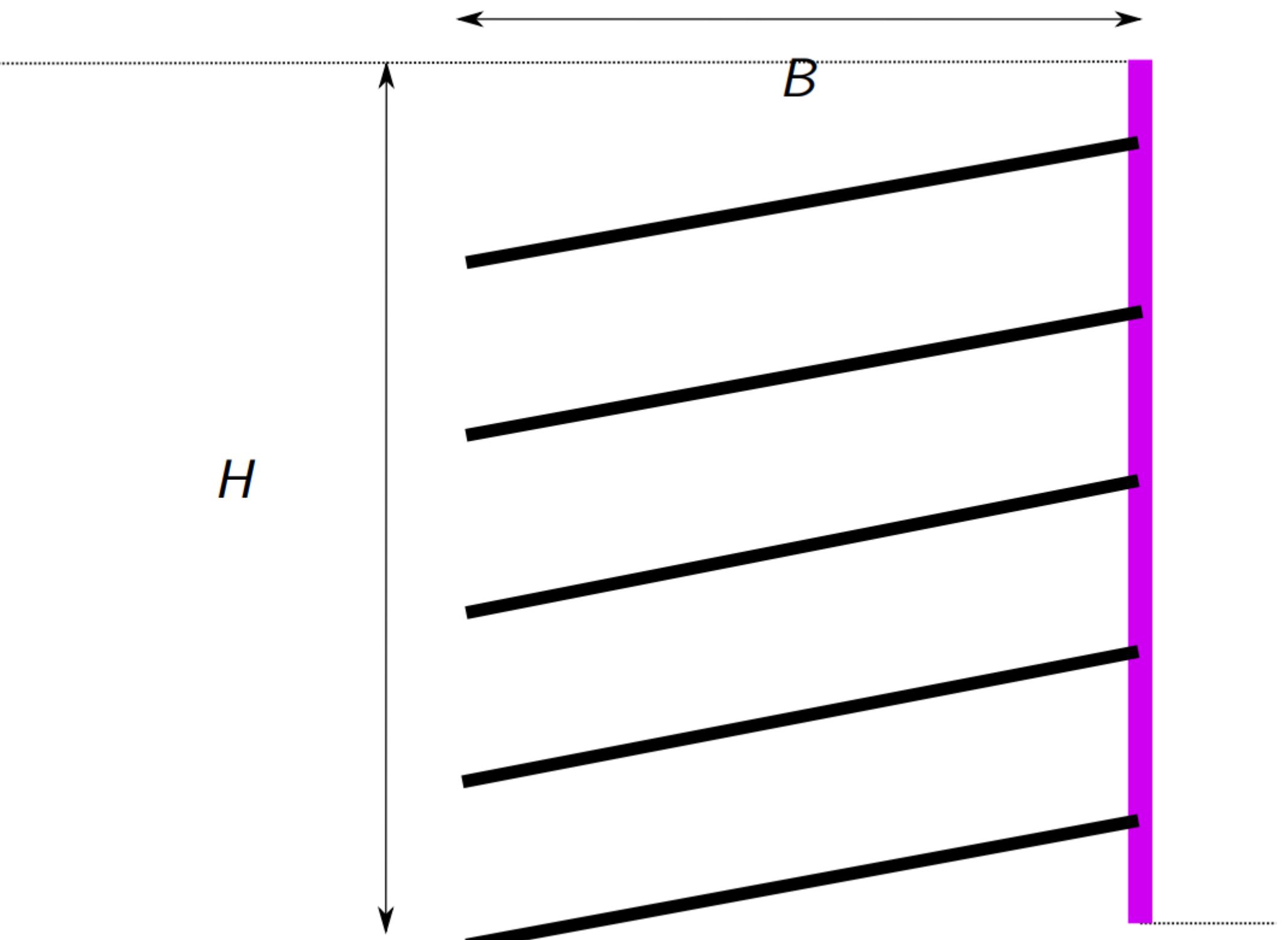
Results published in RFG21 highlight the influence of slenderness ratio  $B/H$

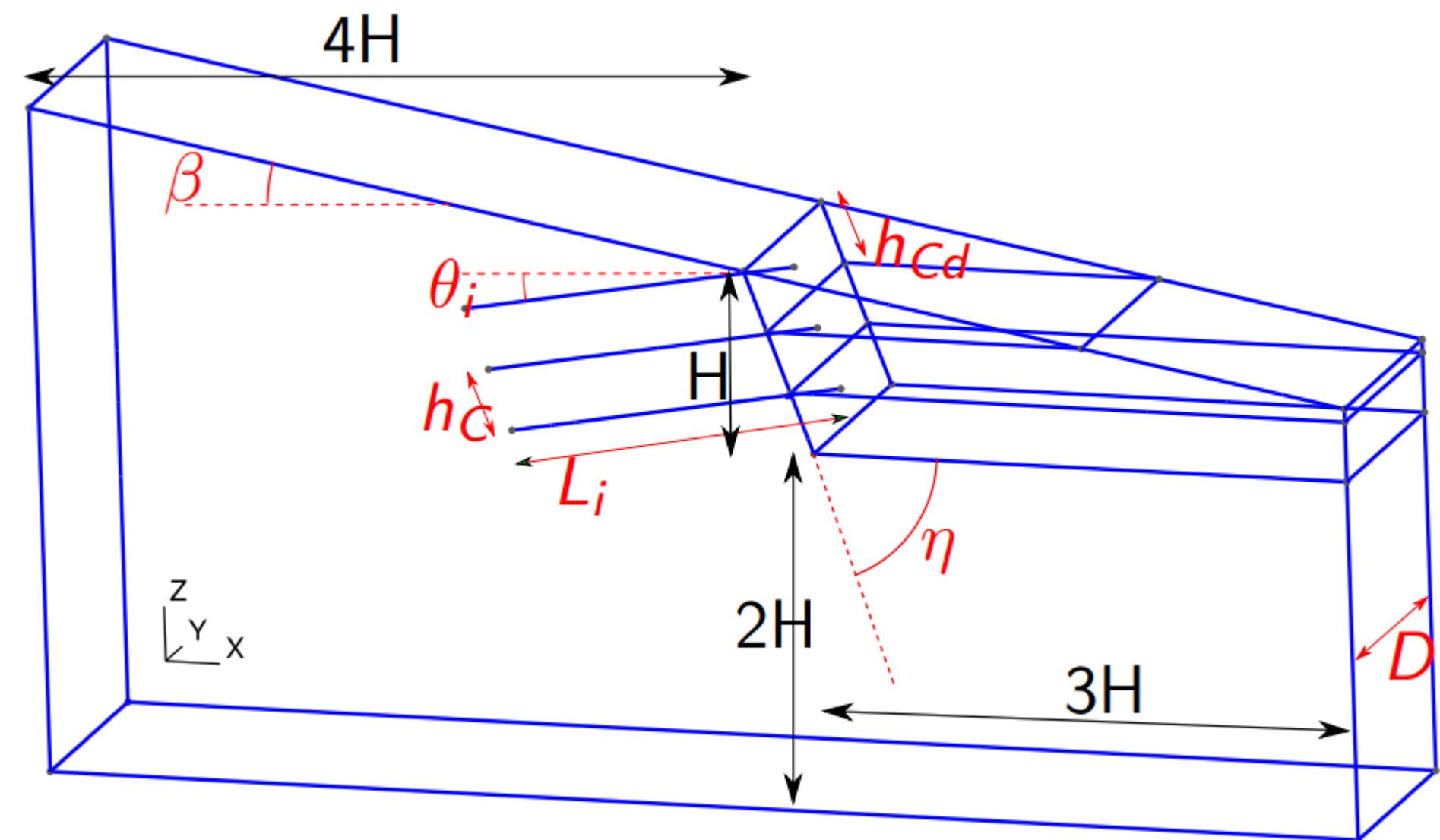


### A complex kinematic

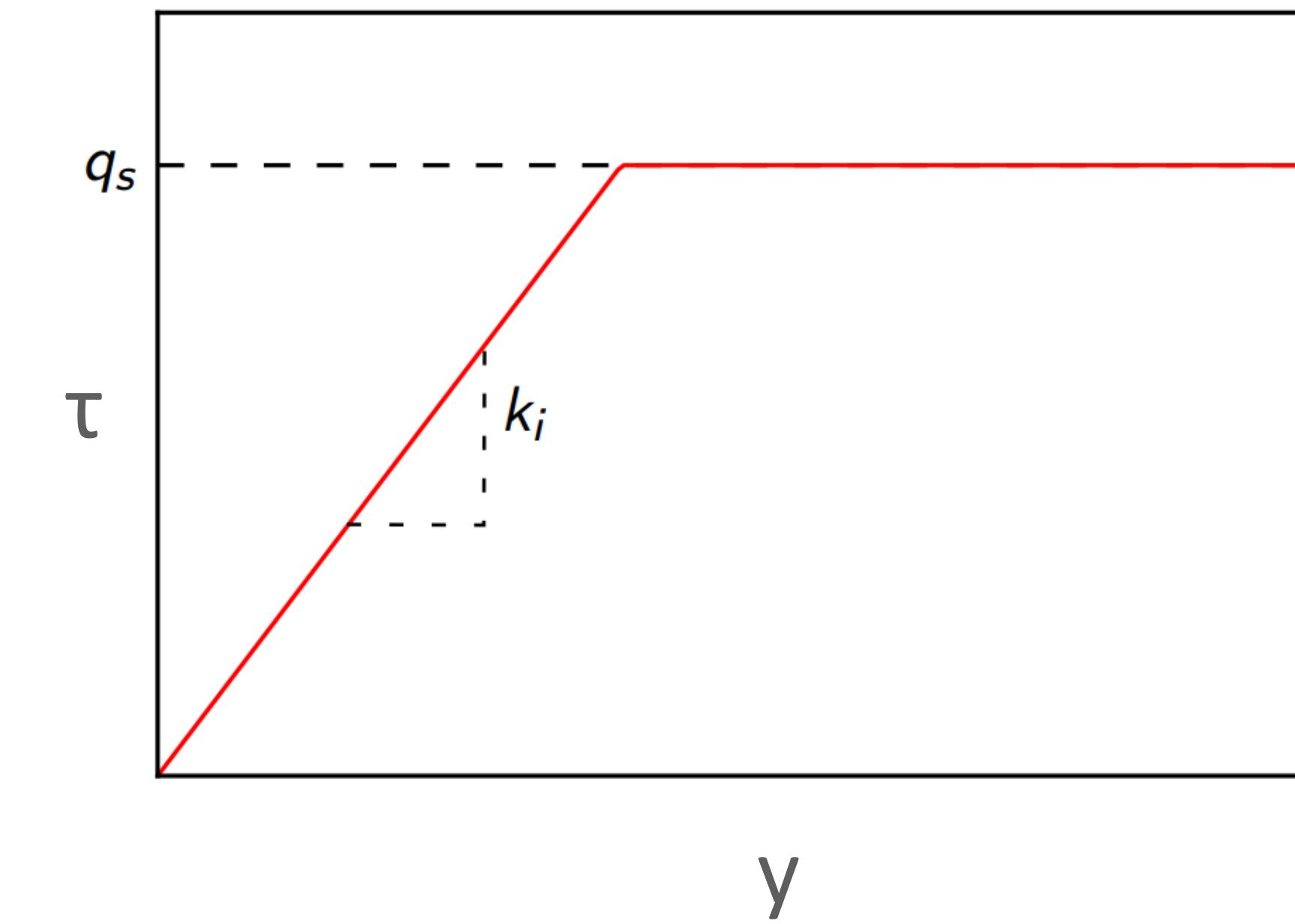
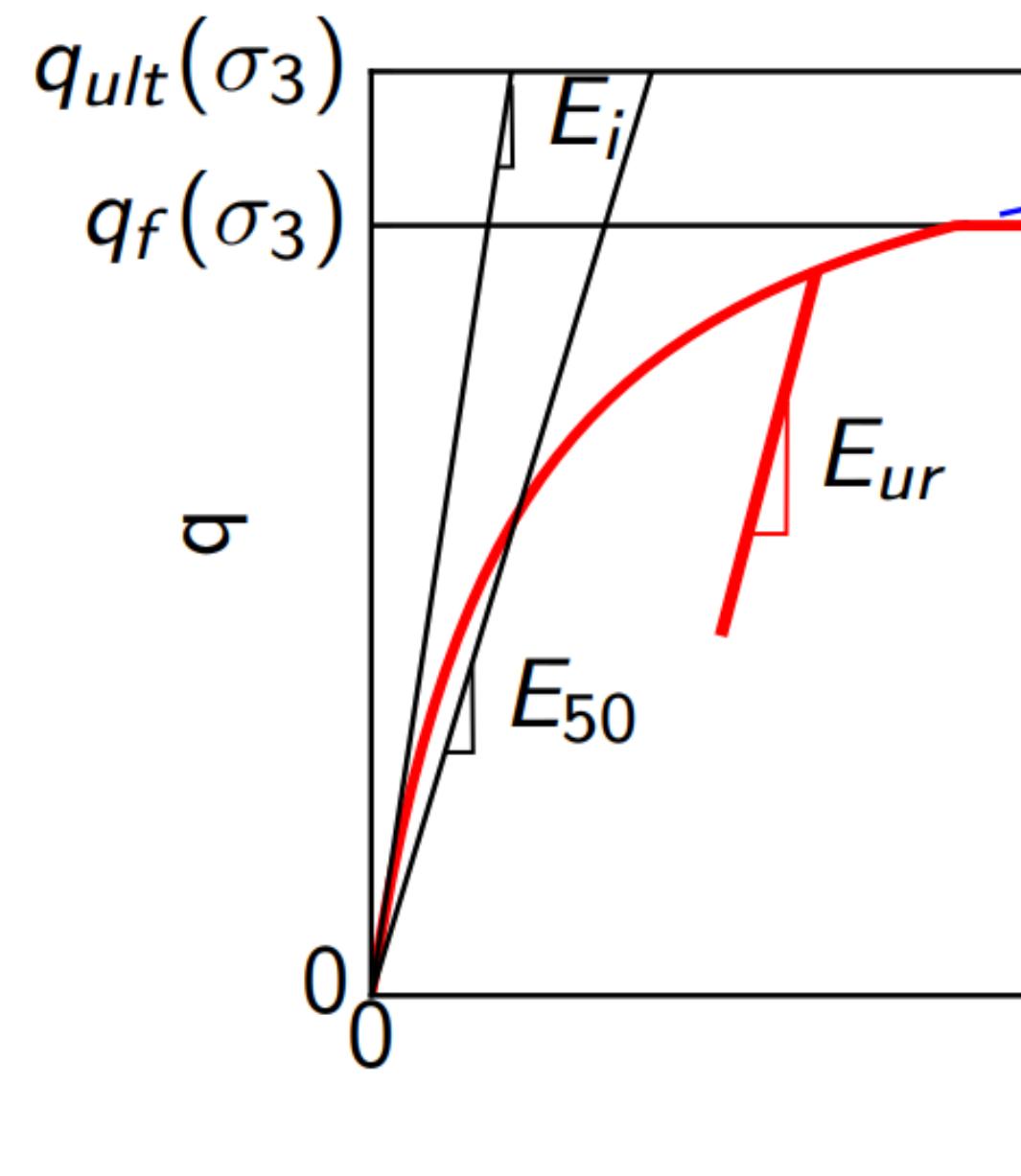
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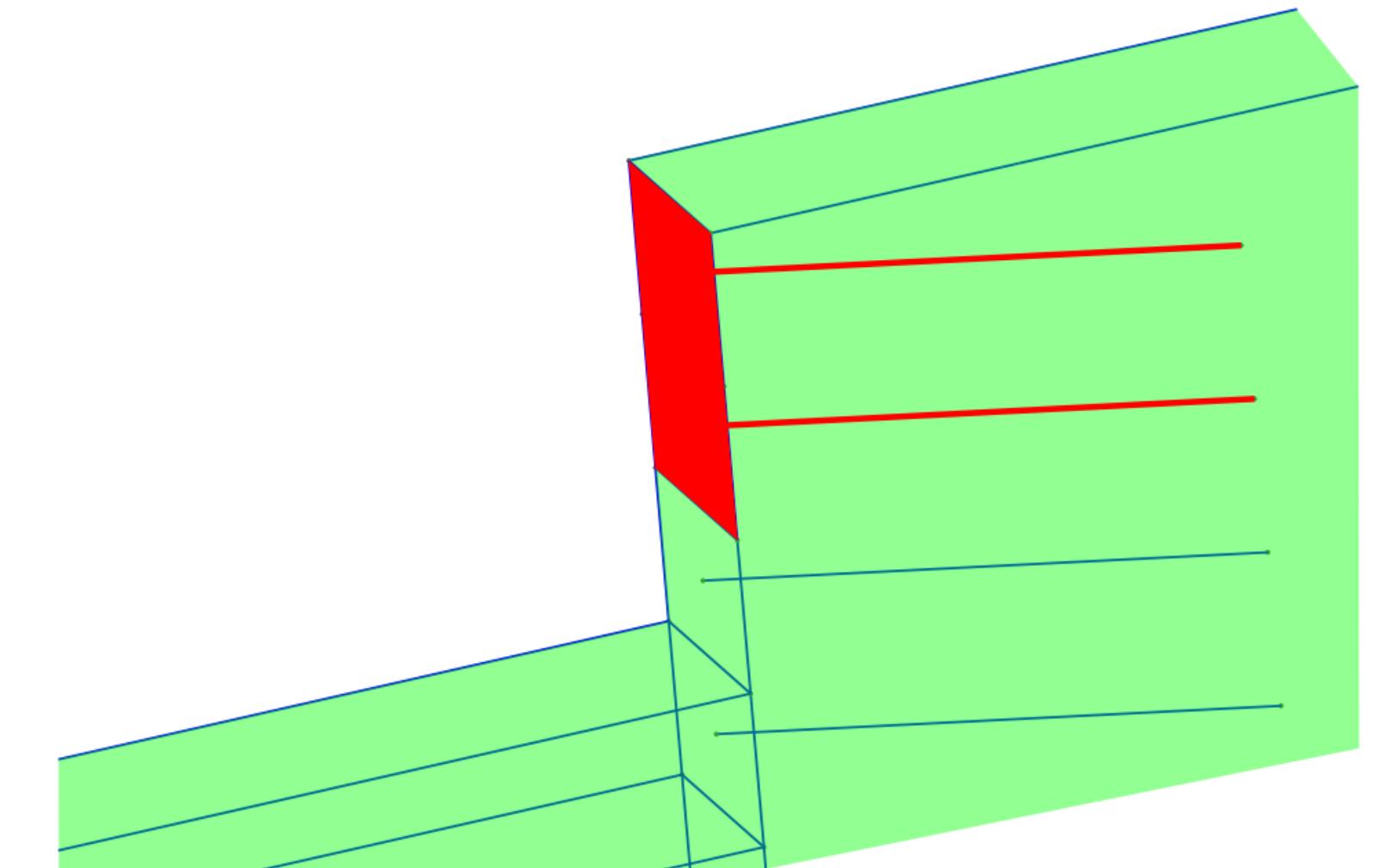
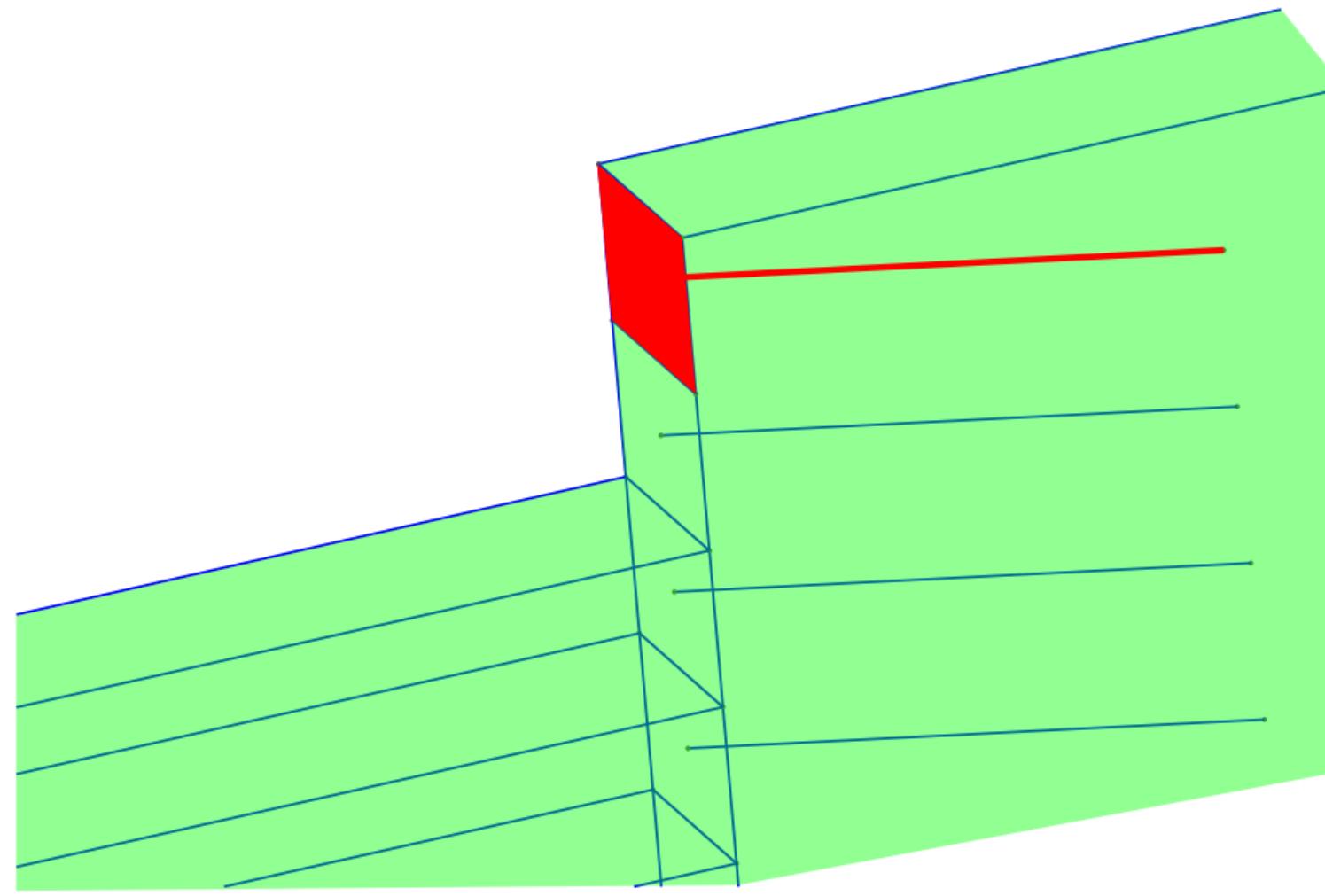
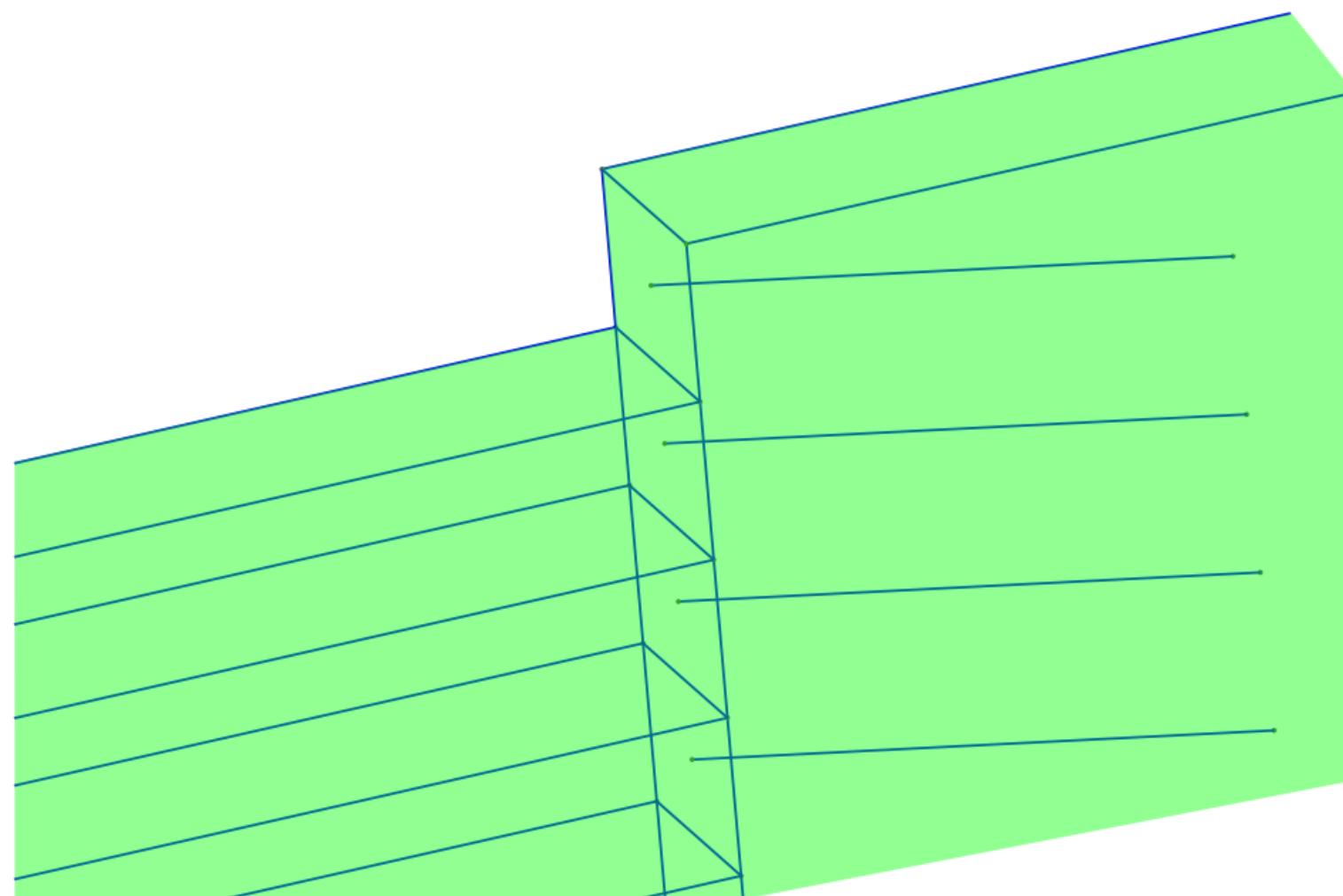




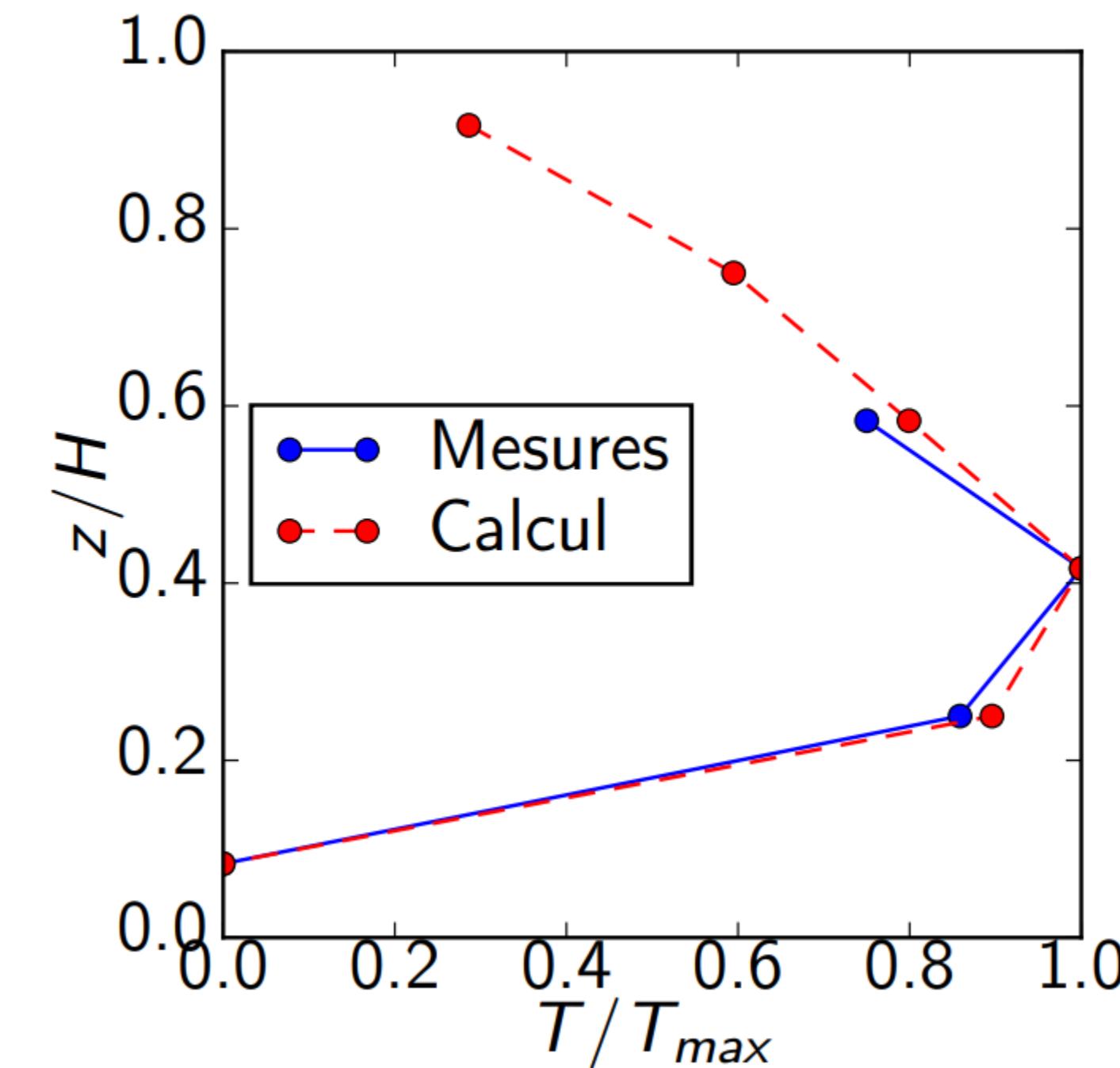
## Hardening Soil Model + Frictional beam elements



## Simulation of construction phasing



# Comparison of normalised head nail tensions between FE model and centrifuge model



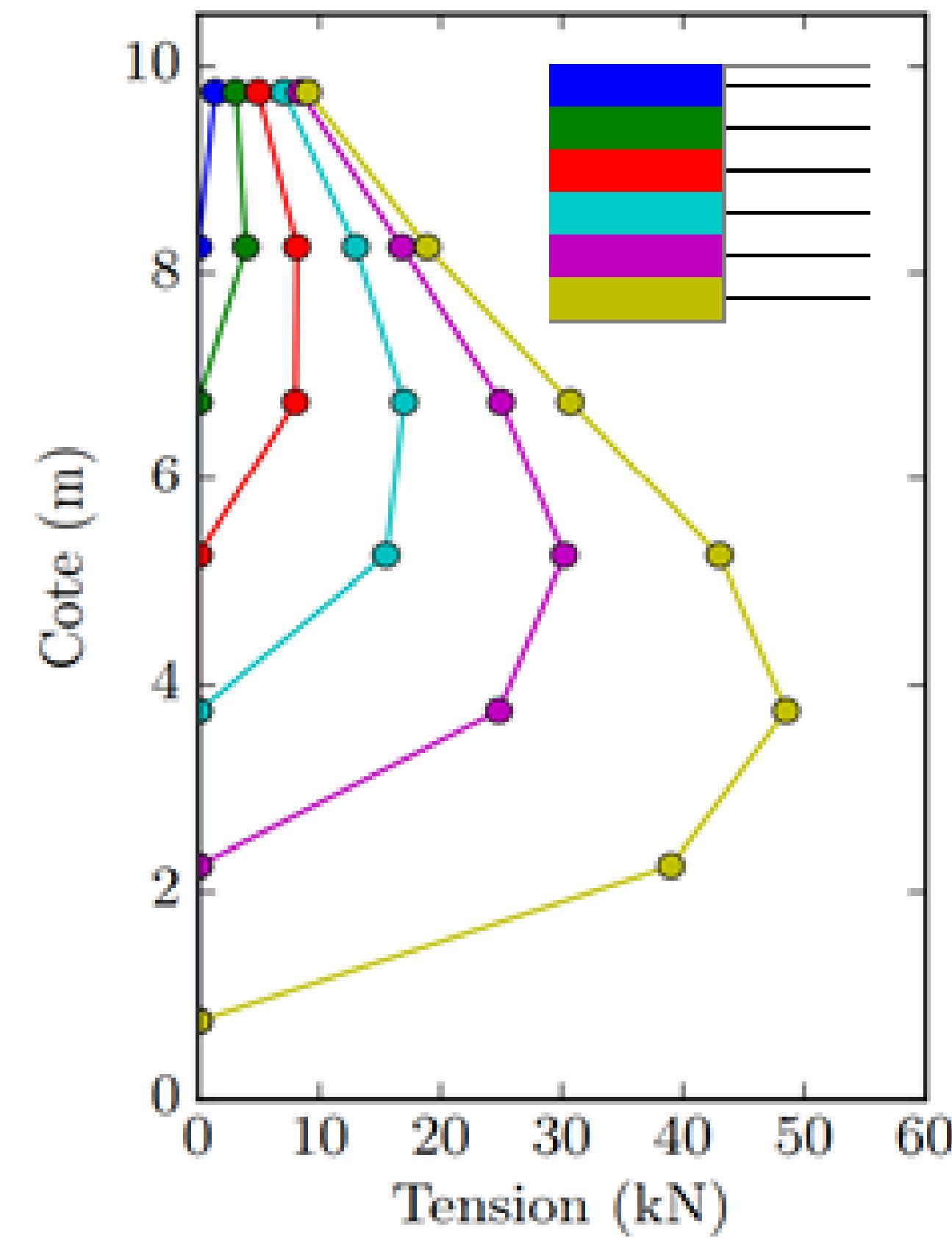
## Parametric study on the slenderness ratio B/H

	Length of nails (m)												
Height (m)	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10.5
6	0.66		0.83		1								
7.5		0.6		0.73		0.86		1					
9			0.56		0.66		0.78		0.89		1		
10.5						0.62		0.71		0.81		0.9	1



### Parametric study on the slenderness ratio B/H

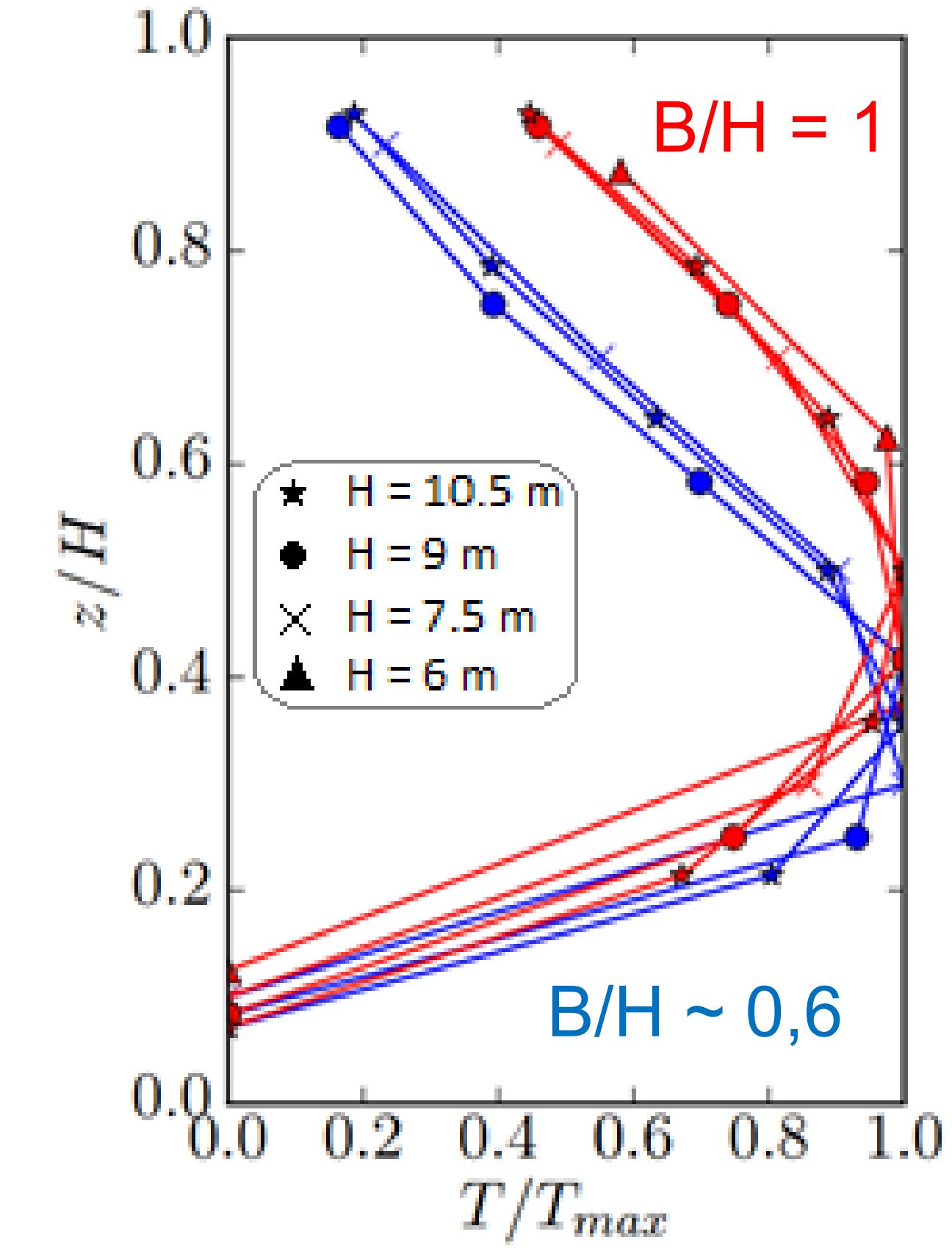
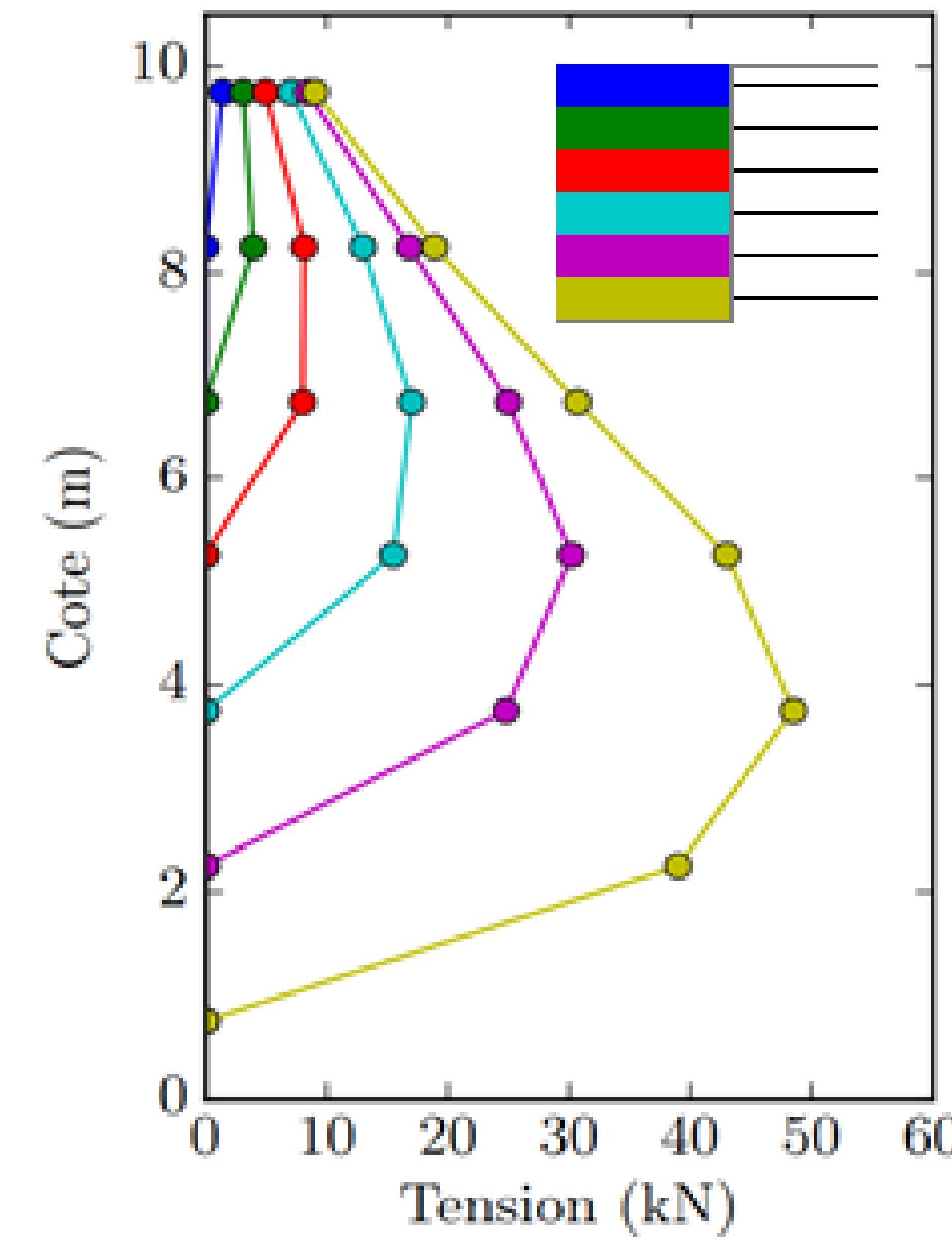
→ Transition from round shape to pear shape



### Parametric study on the slenderness ratio $B/H$

→ Transition from round shape to pear shape

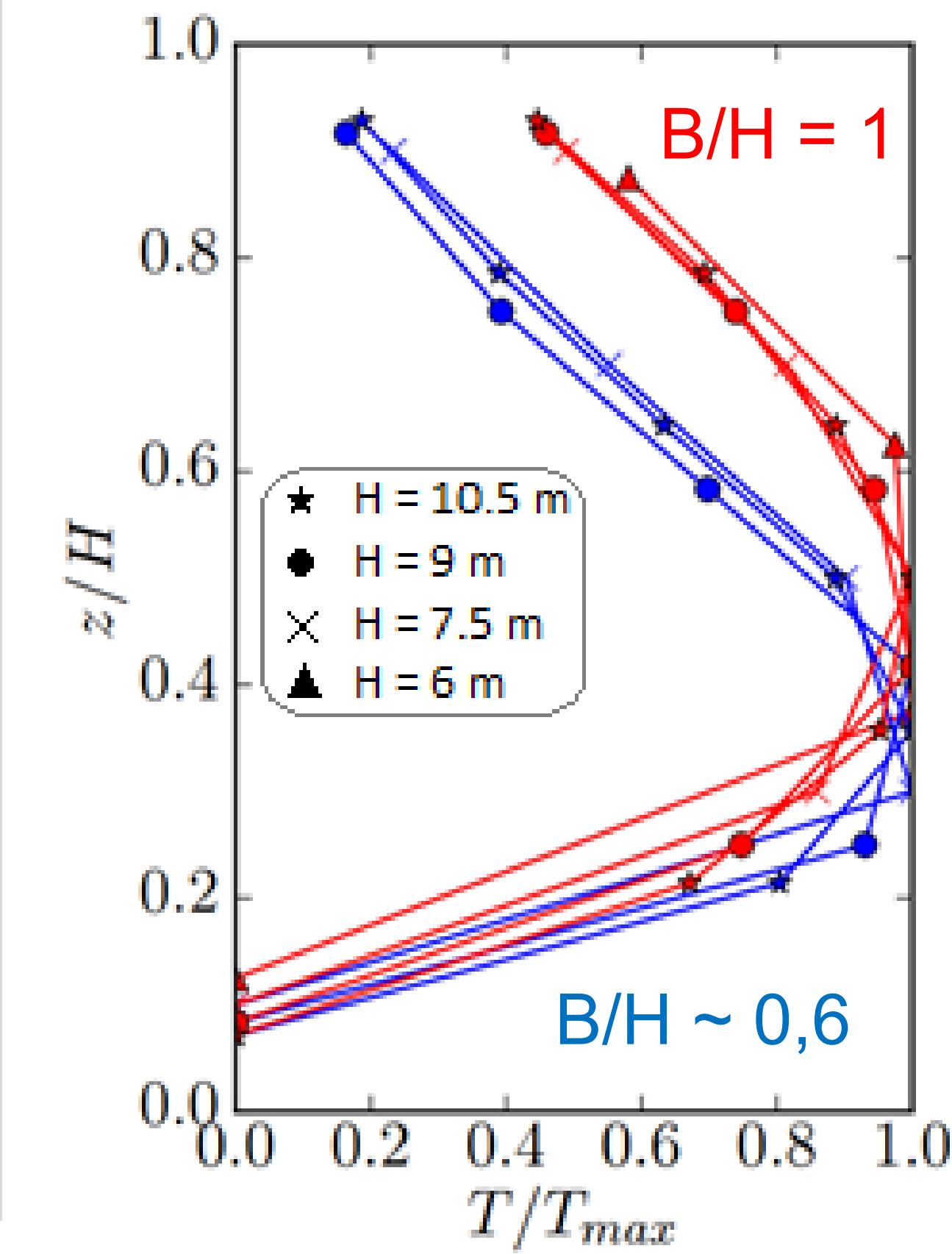
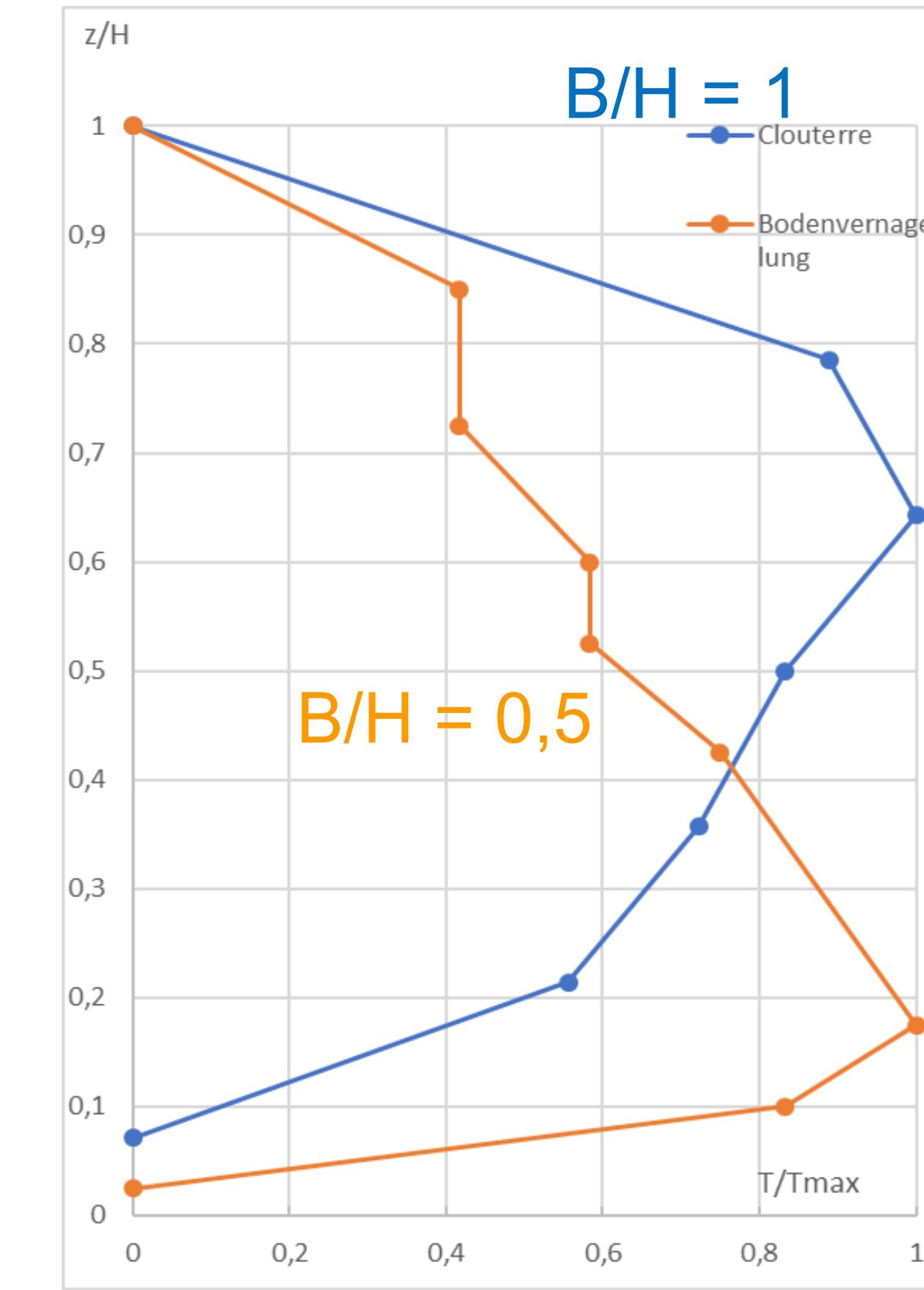
→ Whatever  $H$  is



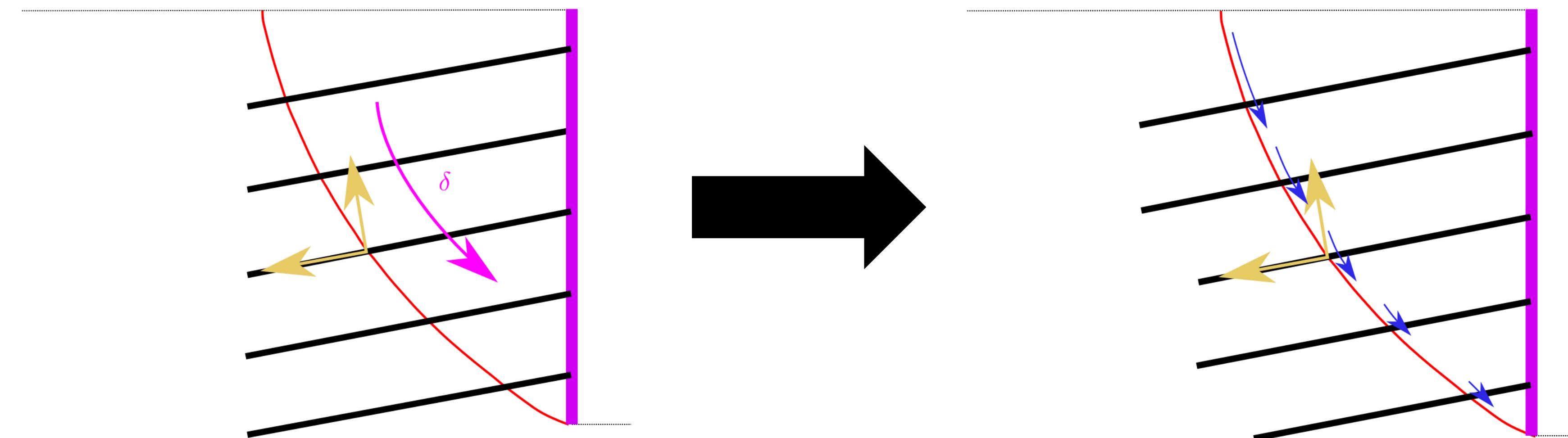
## Parametric study on the slenderness ratio $B/H$

→ Transition from round shape to pear shape

→ Consistent with literature



Back to the initial question : what is the shape of  $\delta$  ?



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**For bulky walls ( $B/H = 1$ ) : facing load shape is round**

**For slender walls ( $B/H \ll 1$ ) : facing load shape is pear-shaped**

**For  $B=0$  (no nails) : facing load shape is triangular (active thrust)**



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→ Idea : « the bulkier the wall, the further it gets from active earth pressure distribution »

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$$\delta \propto T_{red} = \frac{T_{head}}{K_a \gamma S_v S_h (H - z)} \propto \frac{T_{head}}{(H - z)}$$



→ Mobilisation of nails can be characterised by the « distance » to the active earth pressure distribution

$$\delta \propto T_{red} = \frac{T_{head}}{K_a \gamma S_v S_h (H - z)} \propto \frac{T_{head}}{(H - z)}$$

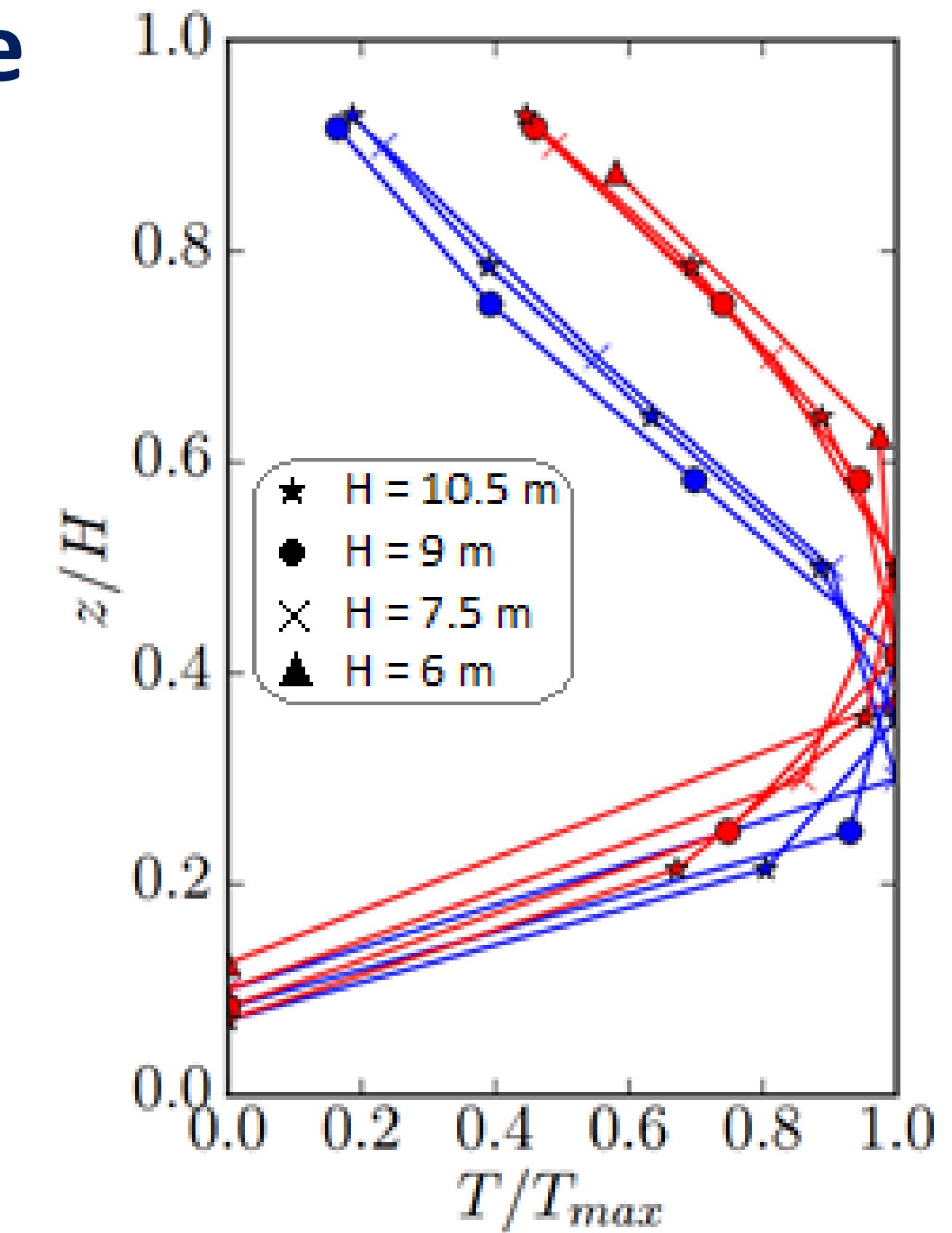
Shape known to be a function of B/H



## Third order polynom needed to capture the transition between round and pear shape

$$T_{head} \propto a \left( \frac{z}{H} \right)^3 + b \left( \frac{z}{H} \right)^2 + c \left( \frac{z}{H} \right) + d$$

$$\begin{cases} a = 18.5 - 13.8 B/H \\ b = 21.3 B/H - 32.9 \\ c = 15.6 - 7.8 B/H \\ d = -0.5 \end{cases}$$



→ The shape of  $\delta$  is given by :

$$\delta \propto \frac{T_{head}}{(H - z)}$$

$$T_{head} \propto a \left( \frac{z}{H} \right)^3 + b \left( \frac{z}{H} \right)^2 + c \left( \frac{z}{H} \right) + d, \quad \begin{cases} a = 18.5 - 13.8 B/H \\ b = 21.3 B/H - 32.9 \\ c = 15.6 - 7.8 B/H \\ d = -0.5 \end{cases}$$



The previous relation is based on a FE parametric study where soil parameters were fixed.

→ A new parametric study has been carried out by varying B/H as well as the relative stiffness of the soil defined as :

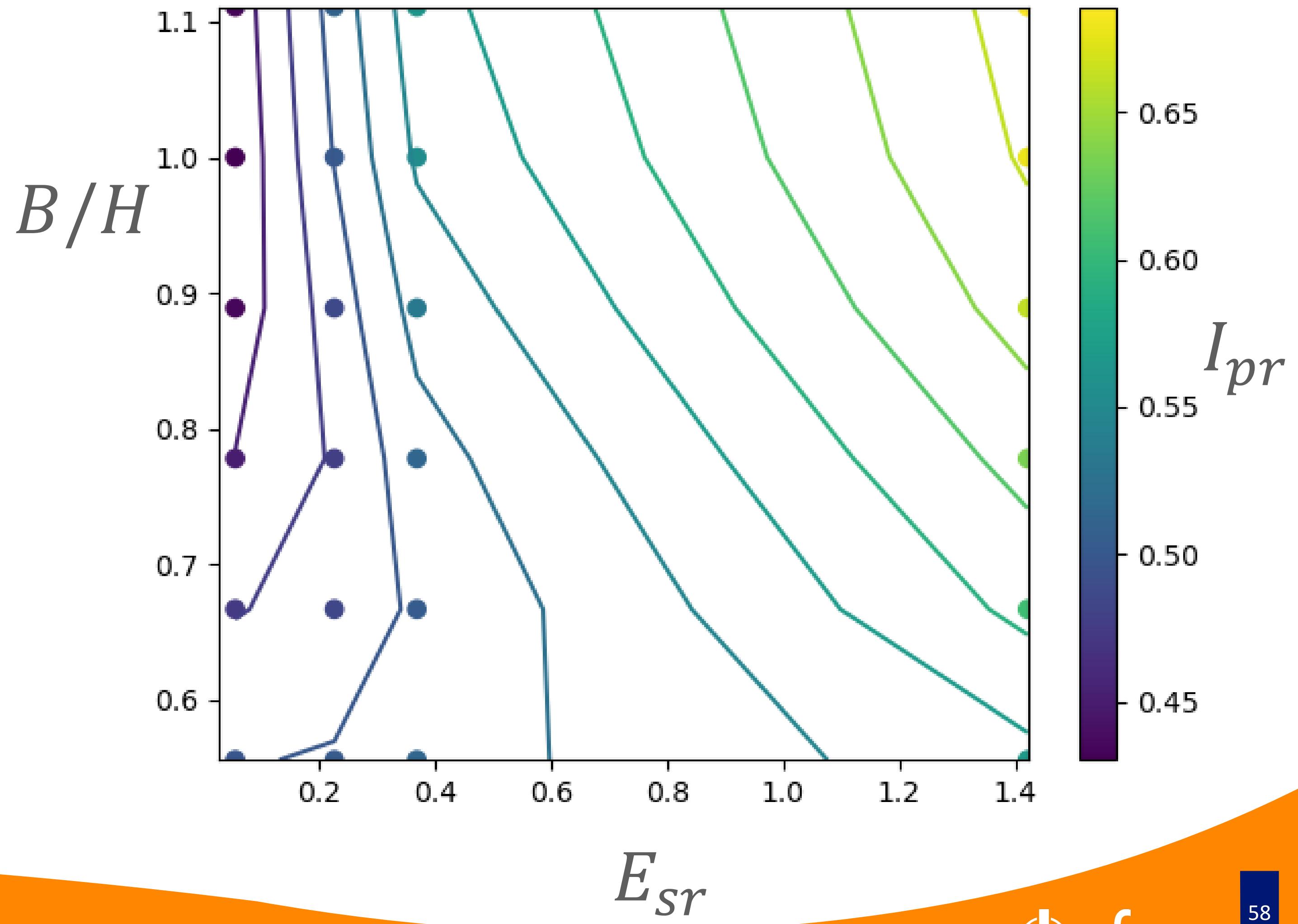
$$E_{sr} = \frac{S_h S_v}{A_a} \frac{E_{soil}}{E_a}$$

To characterize the shape of the facing loads, we introduce :

$$I_{pr} = \int_{z=0}^{z=H} \frac{T}{T_{max}} \frac{dz}{H} = \begin{cases} 0,5 \text{ if triangular} \\ 1 \text{ if all nail tensions equal} \end{cases}$$



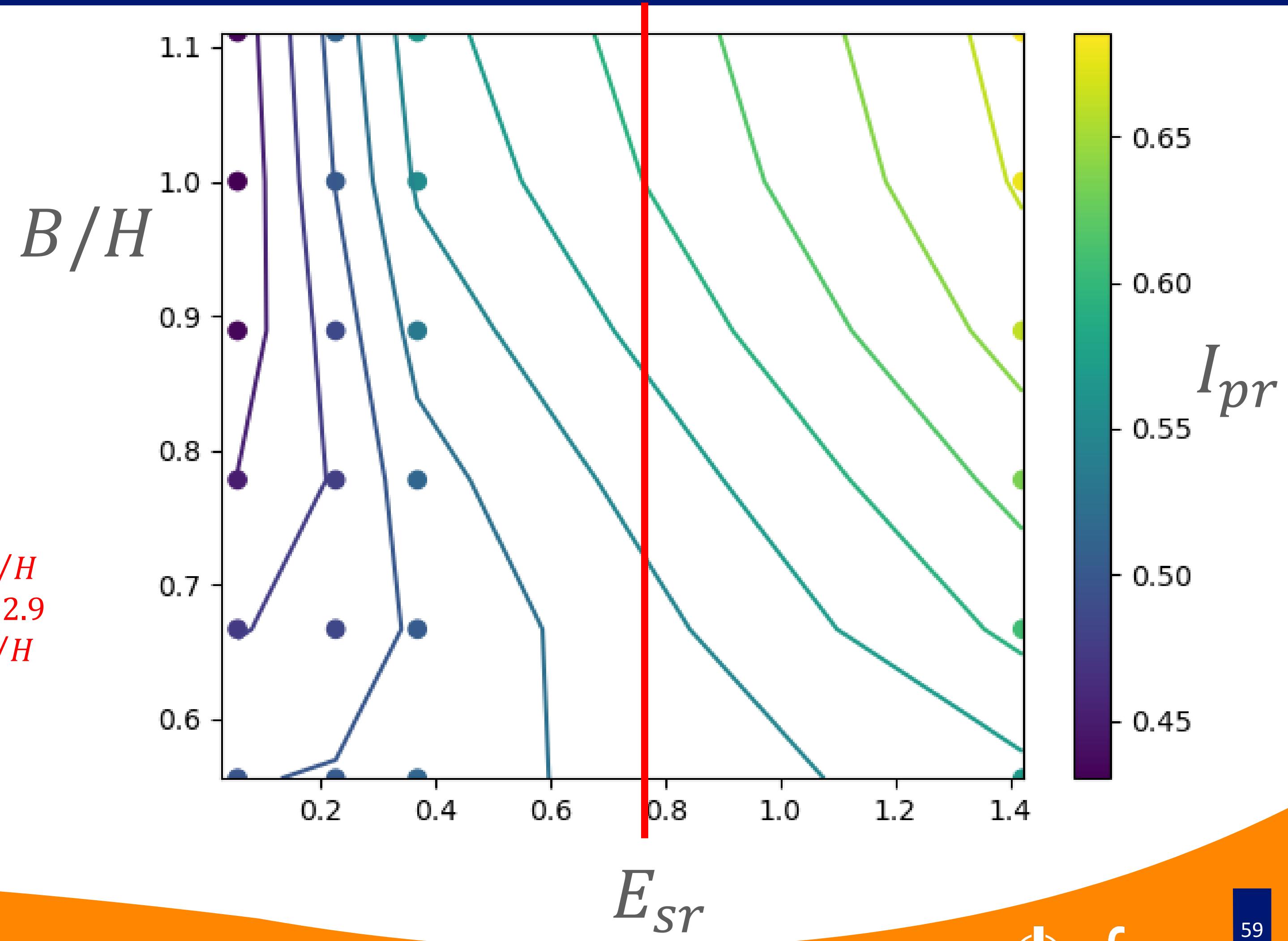
## Plot of iso- $I_{pr}$ lines in the $B/H - E_{sr}$ plane



## Plot of iso- $I_{pr}$ lines in the $B/H - E_{sr}$ plane + reference equation

$$\delta \propto \frac{T_{head}}{(H - z)}$$

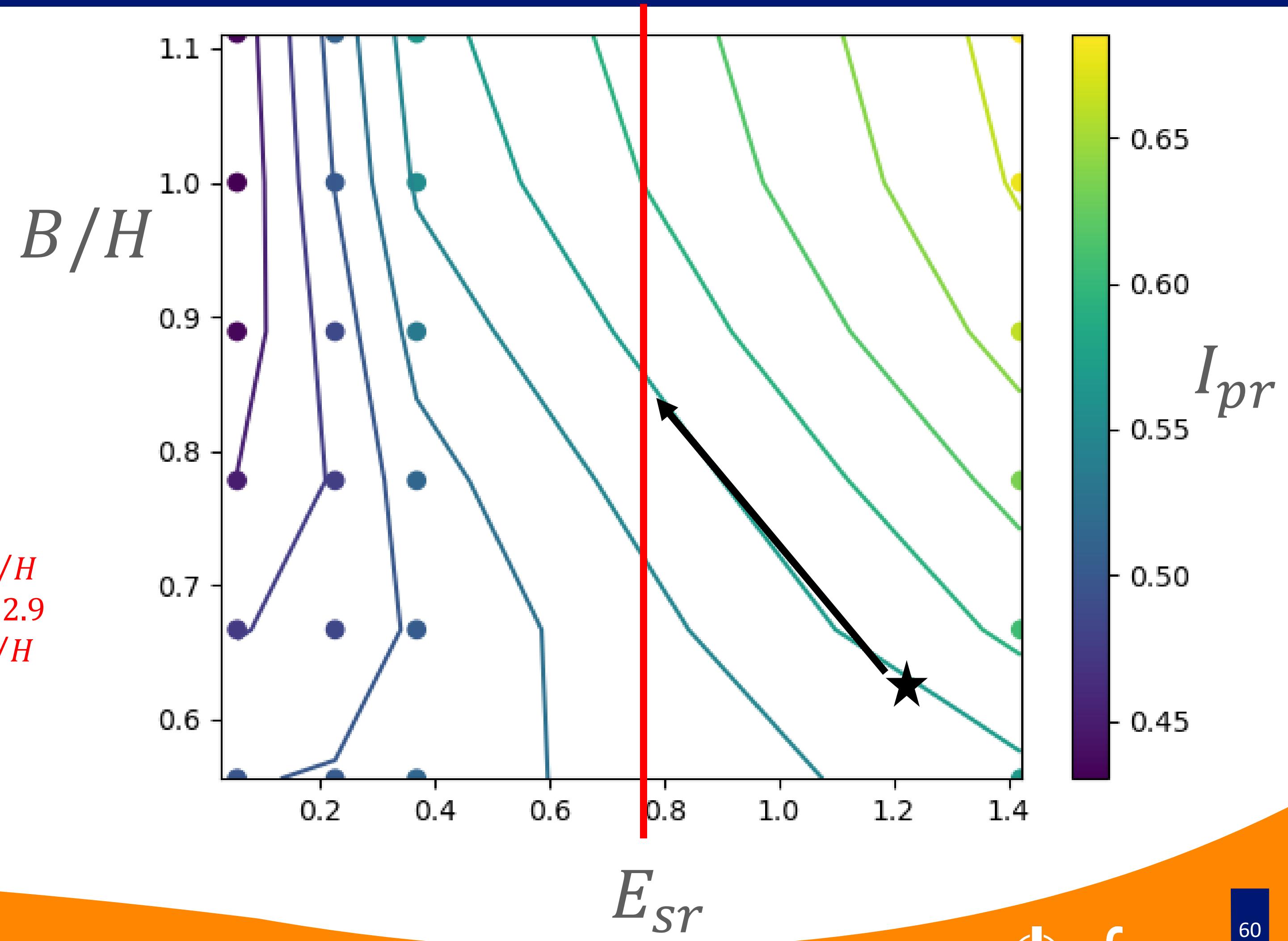
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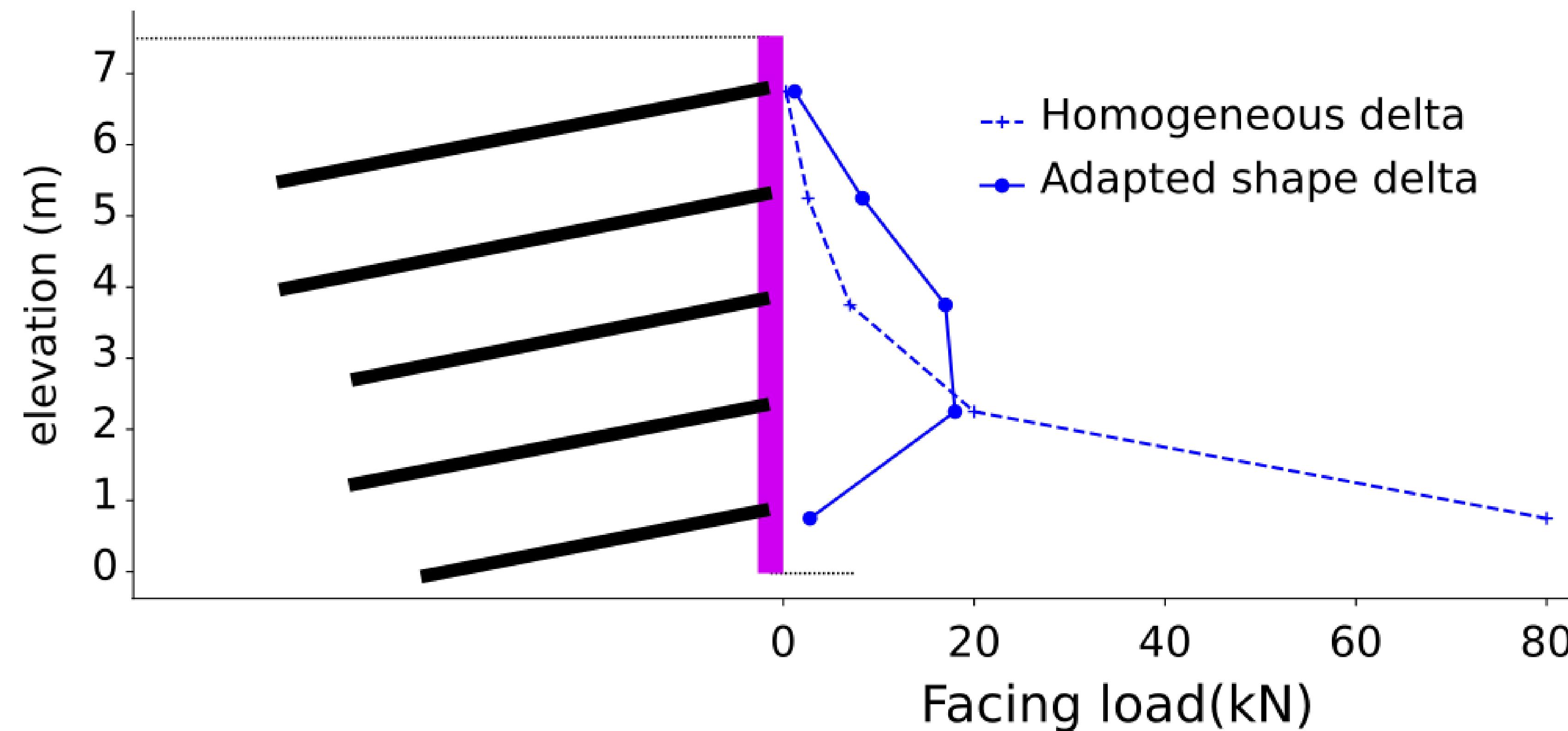
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## Application to a real wall



- Use of a method derived from limit equilibrium analysis
- Considerations on the relative mobilization of nails
- Improvement of the PROSPER Method regarding the design of facing
  
- Considering the construction phasing in the design of geotechnical structures is promising, especially when passive anchors are involved

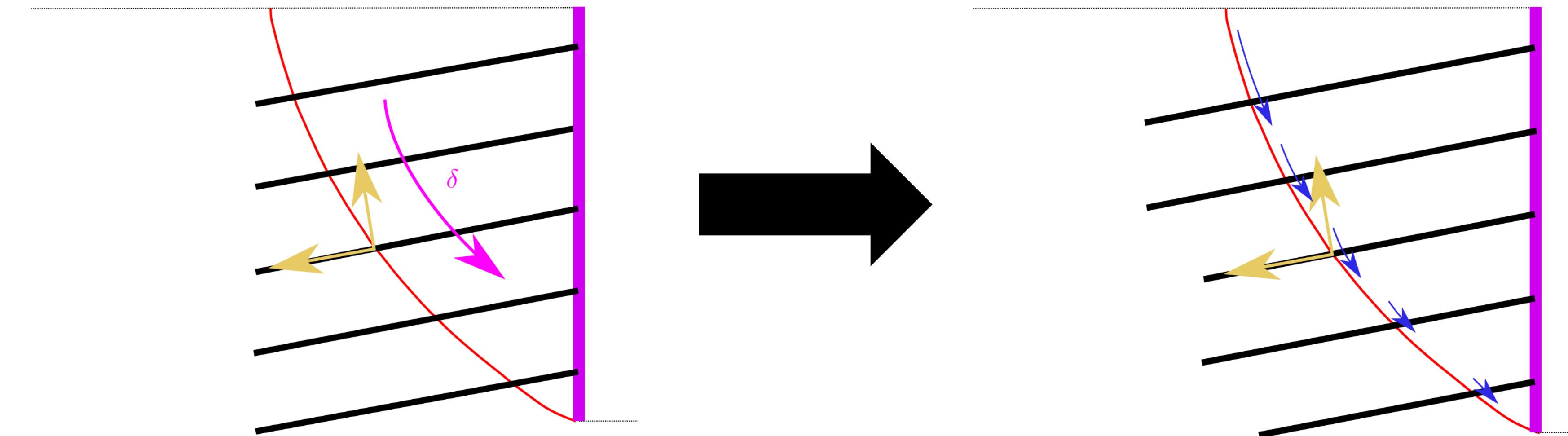


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Thank you for your attention !

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