KARAKAS
FRANÇAIS

ZSoil Day 2026

Challenges in modelling masonry structures with ZSoil

Rafal Obrzud   KARAKAS FRANÇAIS   GeoDev.

Robin Maye   KARAKAS FRANÇAIS

Outline

1. Motivation
2. Numerical Modelling of Masonry
3. Limitations
4. Case Study
5. Final Remarks

01 Motivation

Motivation

MOB & MVR RAILWAY COMPAGNIES

MOB and MVR operate more than 100 km of railway lines

MOB - 75 km
Montreux – Zweisimmen - Lenk

MVR - 27 km
Montreux – Rochers-de-Naye
Vevey – Les Pléiades

MVR – Funiculaires – 3 km
Territet – Glion
Vevey – Mont-Pèlerin
Les Avants – Sonloup

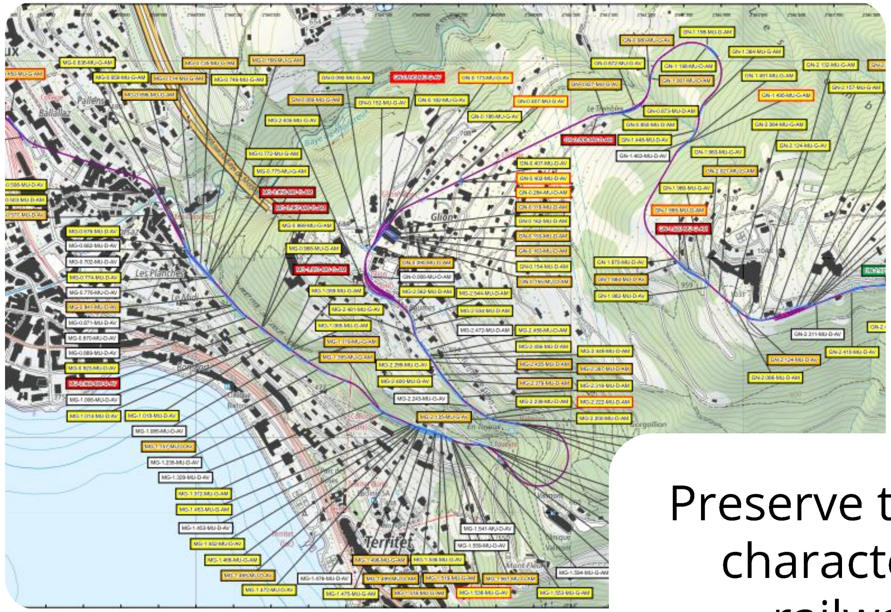
Motivation

Montreux–Rochers-de-Naye Railway Line

As the existing rolling stock is reaching the end of its service life, a **comprehensive modernization program for the railway line** has been launched in preparation for the introduction of new trains.

Motivation

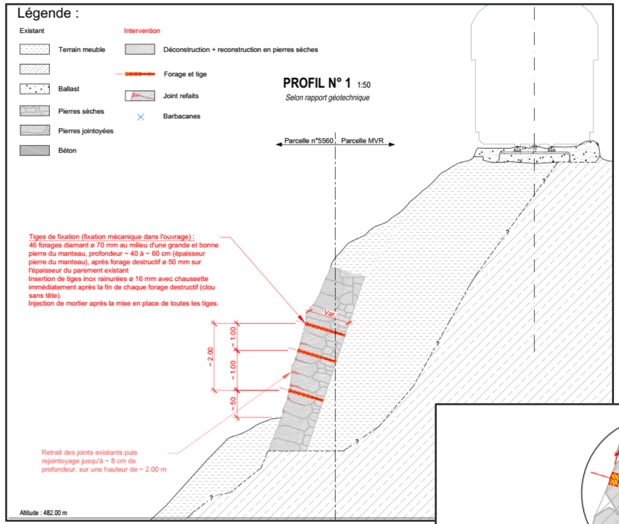
Montreux–Rochers-de-Naye Railway Line



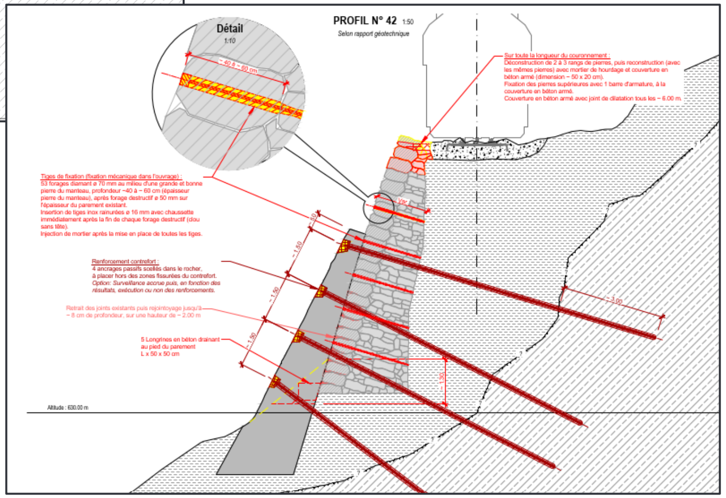
Preserve the historic character of the railway line

Motivation

REINFORCEMENT METHODS



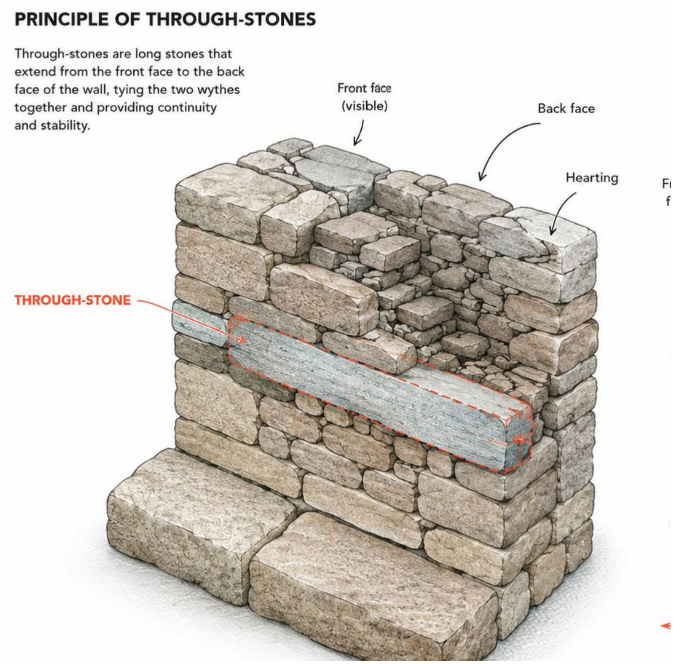
Grouted anchor rods



Classical anchors

Motivation

Reinforcement methods



Local stone replacement or introduction of through-stones

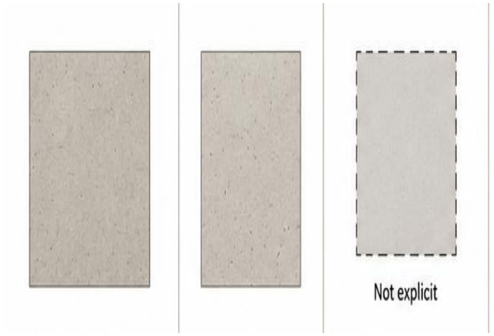
02 Numerical Modelling of Masonry

Numerical Modelling of Masonry

Approaches

1. MACRO

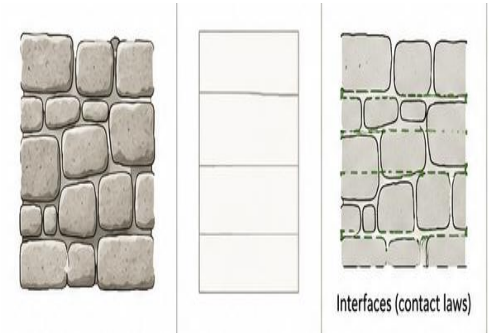
Homogenized continuum



Low cost
Global response

2. MESO

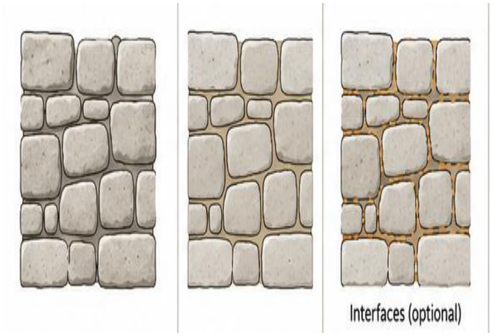
Units explicit,
joints as interfaces



Good compromise
Cracking & sliding

3. MICRO

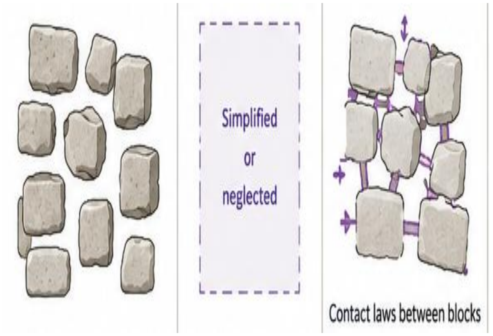
Units & mortar
modelled explicitly



High detail
Local failure

4. DISCRETE

Assembly of interacting blocks

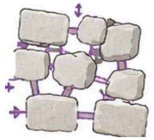


Large displacement
Rocking & collapse

Increasing level of detail and ability to capture local failure mechanisms

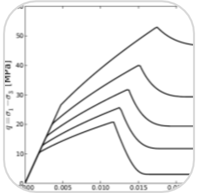
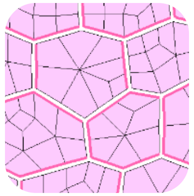
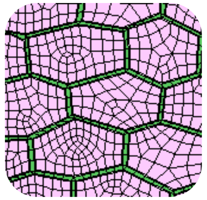
Numerical Modelling of Masonry

Approaches

APPROACH	DESCRIPTION	UNITS	MORTAR	JOINTS / INTERFACES	KEY FEATURES	TYPICAL APPLICATIONS
MACRO 	Equivalent homogeneous continuum with effective properties	Homogenized 	Homogenized 	Not explicit 	Smeared cracking Damage / plasticity Orthotropic behaviour	• Large structures • **Global structural analysis**
MESO 	Units explicit; mortar joints represented by interface/contact laws	Explicit 	Simplified 	Contact / interface laws 	**Tensile cracking** **Shear sliding** Cohesion & friction Residual strength	• Pushover non-linear analysis • Assessment and strengthening studies
MICRO 	Units and mortar represented explicitly; interfaces may also be included	Explicit 	Explicit 	Explicit / optional 	**Cracking in units** **Cracking in mortar** Interface debonding	• Detailed assessment of historic masonry • Parametric studies • Macro model calibration
DISCRETE 	Assembly of individual blocks (rigid or deformable) interacting through contact laws	Individual blocks 	Simplified or neglected 	Contact laws 	Large displacements Opening / sliding **Rocking** **Block separation** Contact calibration needed	• Collapse and landslide analysis • Structural failure and robustness • **Excavation and retaining walls**

Numerical Modelling of Masonry

ZSOIL CAPABILITIES

APPROACH	DESCRIPTION		
MACRO 	Equivalent homogeneous continuum with effective properties	Advanced constitutive plasticity models including softening and plastic damage	
MESO 	Units explicit; mortar joints represented by interface/contact laws	Simple or complex geometries Contact law Computational efficiency	 
MICRO 	Units and mortar represented explicitly; interfaces may also be included	All above features	 
DISCRETE 	Assembly of individual blocks (rigid or deformable) interacting through contact laws	Dislocation possible to simulate	

Numerical Modelling of Masonry

Definition of Parameters

Estimation of compressive strength resistance of the masonry

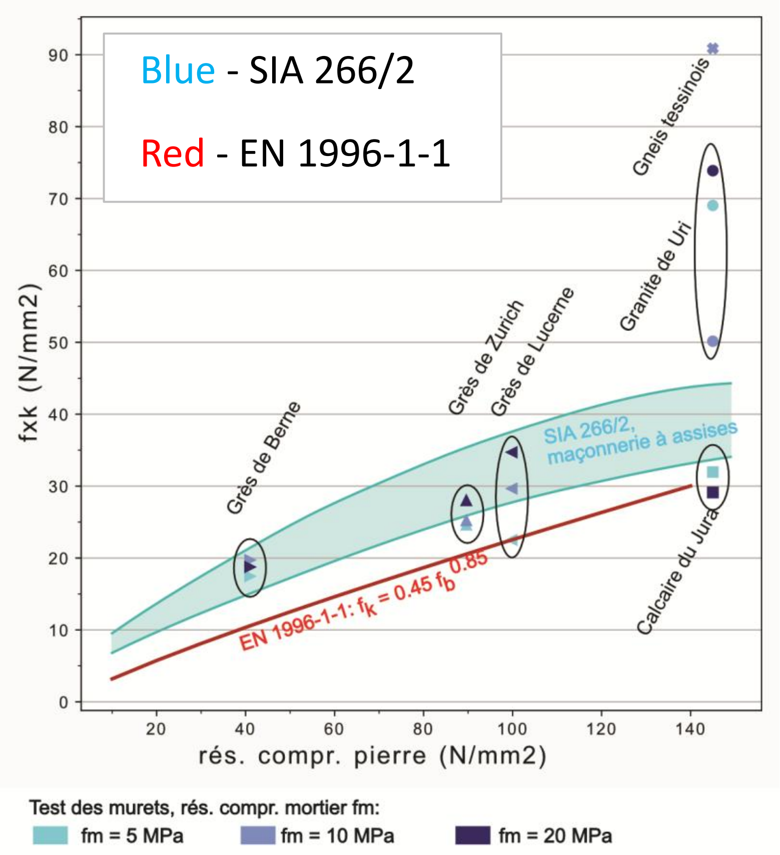
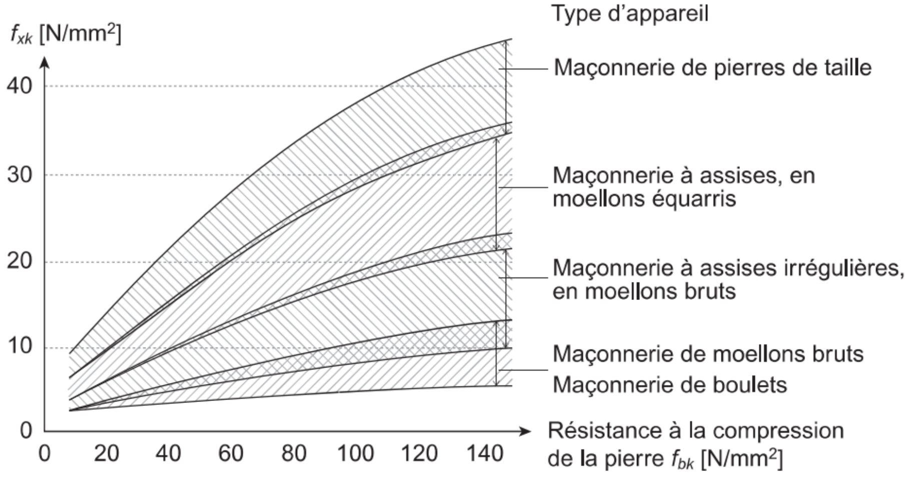


Figure courtesy of Dr. Fabio Donadini
(Materialtechnik Am Bau)

SIA 266/2

Compressive strength as a function of masonry type



Compressive strength of stone

	Masonry type
E	Ashlar masonry
D	Coursed masonry with squared rubble stone
C	Irregularly coursed rubble masonry
A+B	Uncoursed rubble / boulder masonry

Numerical Modelling of Masonry

Definition of Parameters

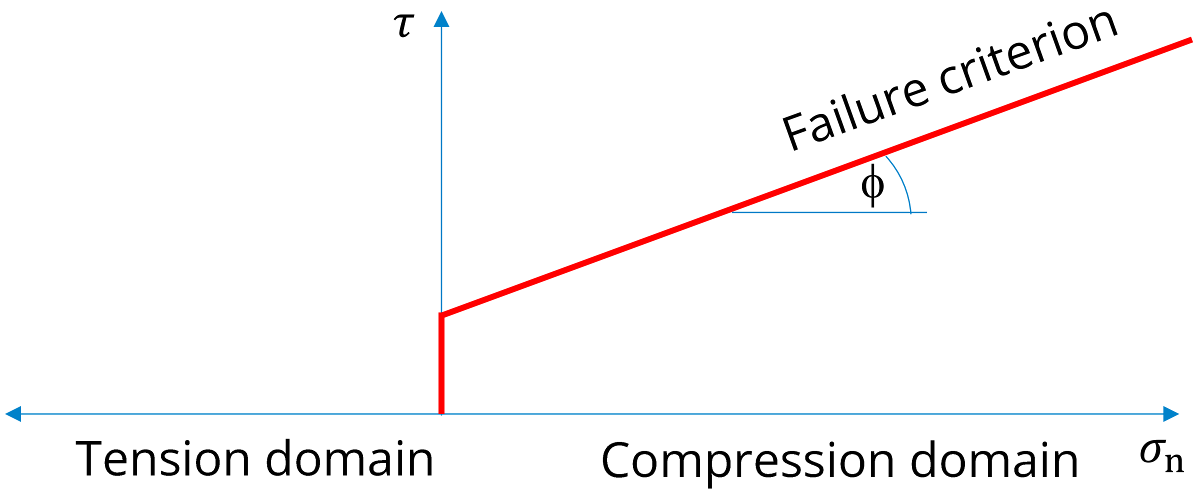
Estimation of tensile strength resistance of the masonry

03 Limitations

Limitations

STANDARD COULOMB FRICTION

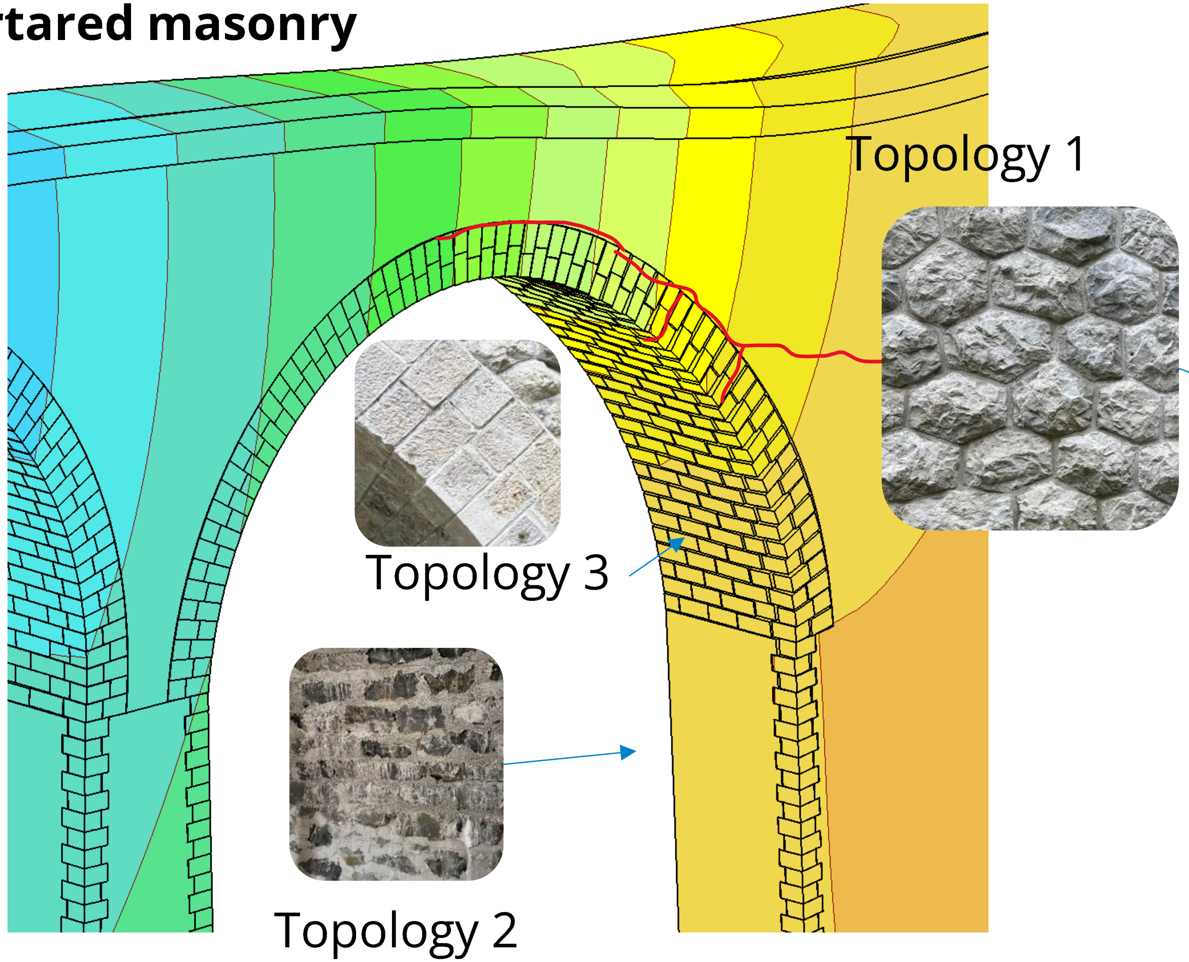
The standard Coulomb friction and contact law which rely on compressive normal stress ($\sigma_n < 0$) to scale frictional shear stress ($\tau = \sigma_n \tan(\phi) + c$), is not applicable in pure tension domains if needed.

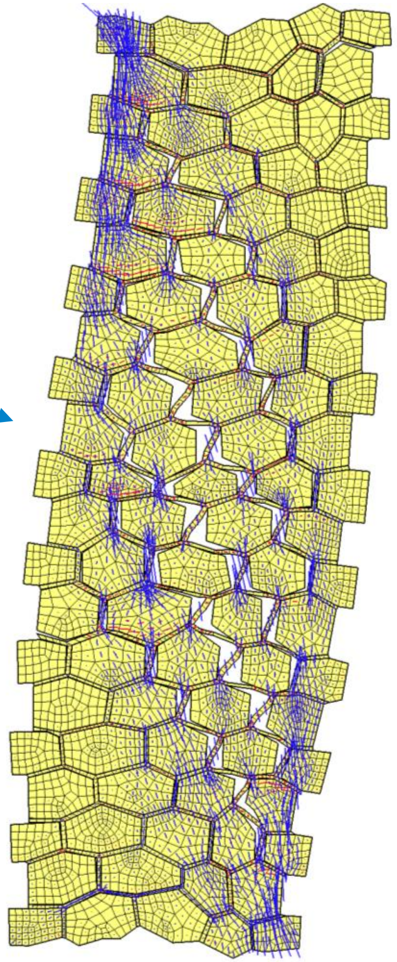


Limitations

Standard Coulomb Friction

Issue when modelling mortared masonry

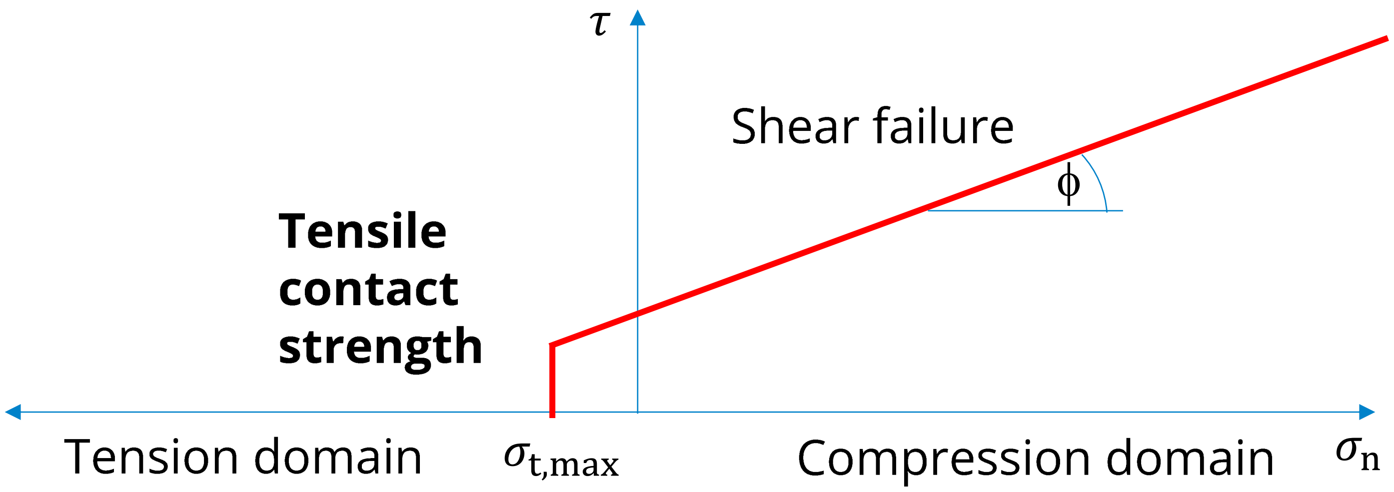




Limitations

Standard Coulomb Friction

Tensile Failure Criterion: Under tensile normal stress ($\sigma_n > 0$), failure occurs when the tensile strength of the interface is reached. The normal contact stiffness then drops to zero or to a small residual value to account for possible adhesive or fiber-bridging effects.



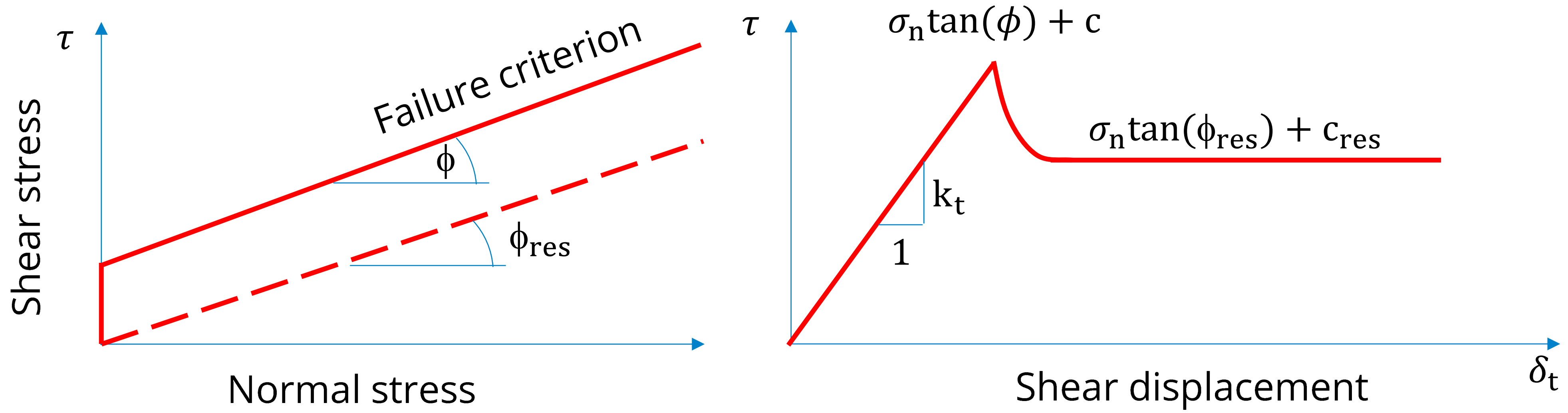
In **masonry**, this is particularly relevant for:
- brick–mortar or stone–mortar interfaces
- masonry joints subjected to bending
- crack initiation and subsequent joint opening
- masonry–concrete interfaces or repaired/strengthened masonry

In **rock mechanics**:
- cemented joints
- healed fractures
- bedding planes with some tensile bonding
- rock–grout interfaces

Limitations

Standard Coulomb Friction

The standard Coulomb friction law defines a single strength envelope and therefore cannot reproduce the post-peak transition to a residual state.



In **masonry**, the analogy is very useful: a mortar joint can initially have cohesion/interlocking and relatively high frictional resistance. After cracking and significant sliding, cohesion may be lost and the joint behaves more like a frictional contact.

In **rock mechanics** fundamental for joints and discontinuities. Rough, interlocked rock joints can develop substantial peak strength; with increasing shear displacement, asperities are damaged or overridden and the resistance decreases toward a residual value.
This matters for rock slopes, tunnels, foundations on rock, and block stability, anchor pull-out tests.

In **geotechnics**, peak-to-residual behaviour matters for progressive failure and large-displacement problems:

- pre-existing shear surfaces
- landslides
- clay interfaces
- anchor pull-out

Limitations

However, these limitations should not significantly affect the case study that I will present next. The retaining wall can essentially be considered as a dry-stone masonry structure, since the existing mortar is of very poor quality and its contribution can reasonably be neglected.

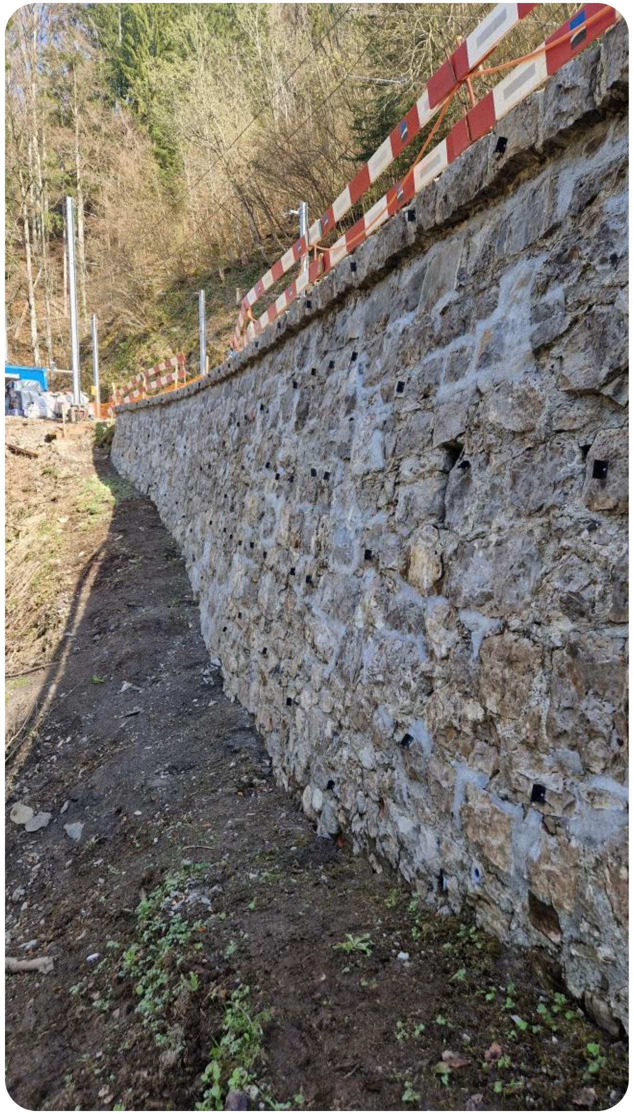
04

Case Study

Case Study

Static load on the retaining wall

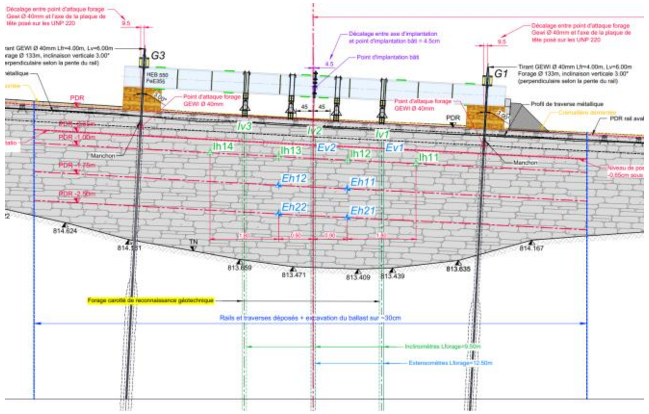
Composite wall consisting of mortared rubble masonry with an Alpine stone infill; the wall is considered as dry-stone masonry.



Case Study

Static load on the retaining wall

Preparation of the static load test setup



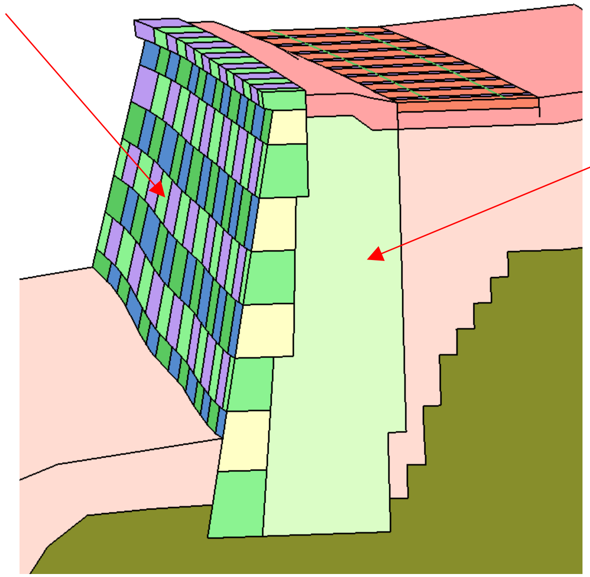
Case Study

STATIC LOAD ON THE RETAINING WALL

Preparatory desk studies – what approach to model the masonry wall?

Outer masonry facing

Meso scale model of dressed rubble stones with frictional interfaces representing the mortar



Infill

The discrete model of small blocks should be replaced by a **continuum model**

?

Type **Plastic damage model**

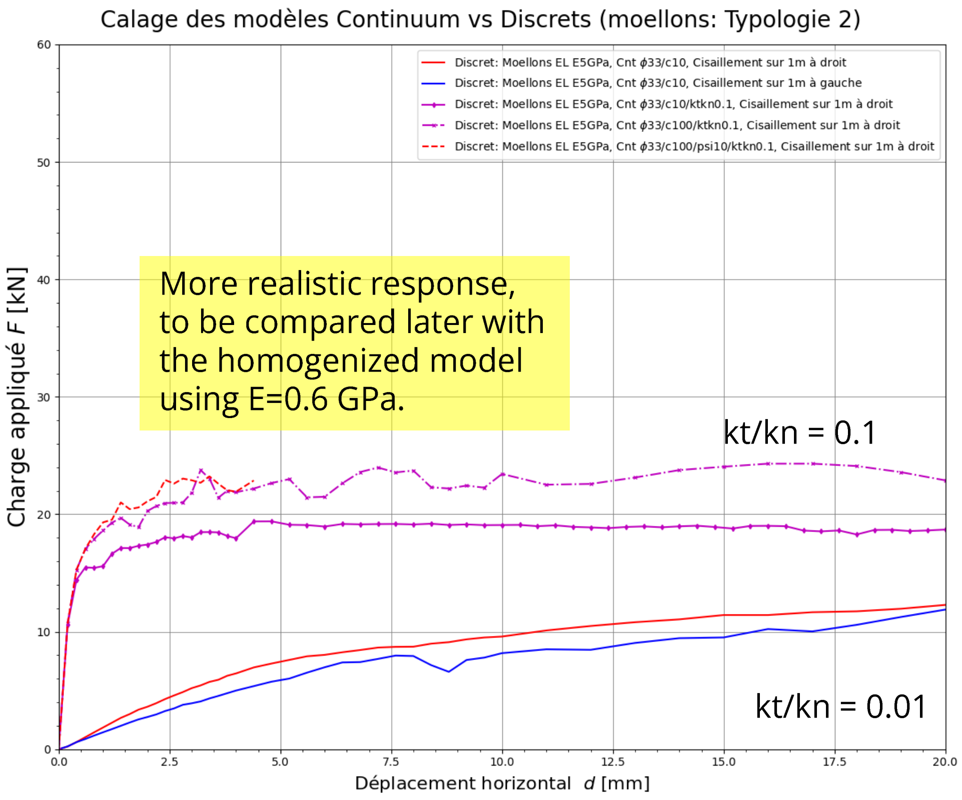
Höek-Brown with softening

Determining the parameters of the homogenized masonry remains a challenge.

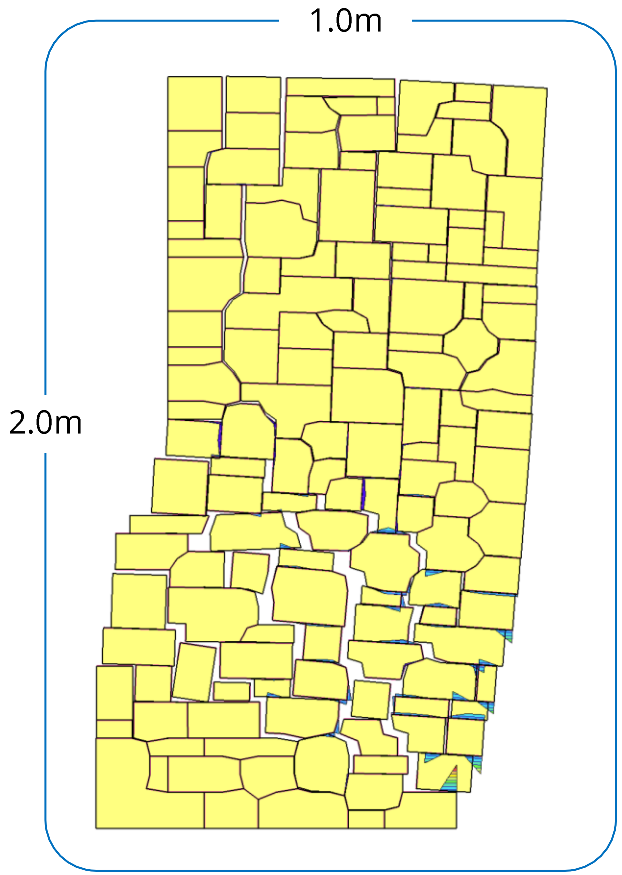
Case Study

STATIC LOAD ON THE RETAINING WALL

Preparatory desk studies – calibration of the continuum macro model



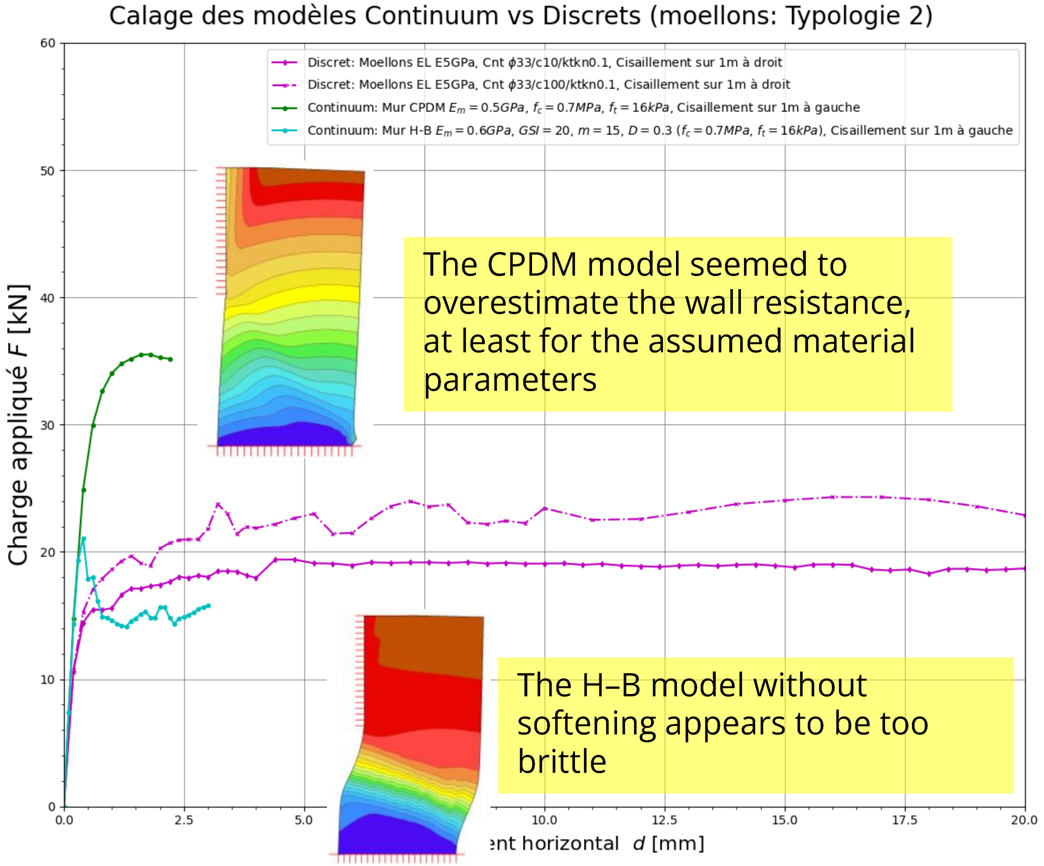
Discrete model



Case Study

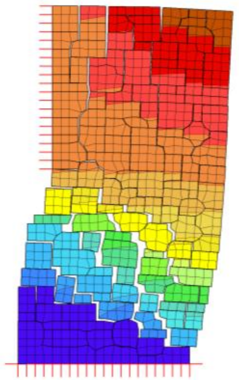
Static load on the retaining wall

Preparatory desk studies – calibration of the continuum macro model



The CPDM model seemed to overestimate the wall resistance, at least for the assumed material parameters

The H–B model without softening appears to be too brittle



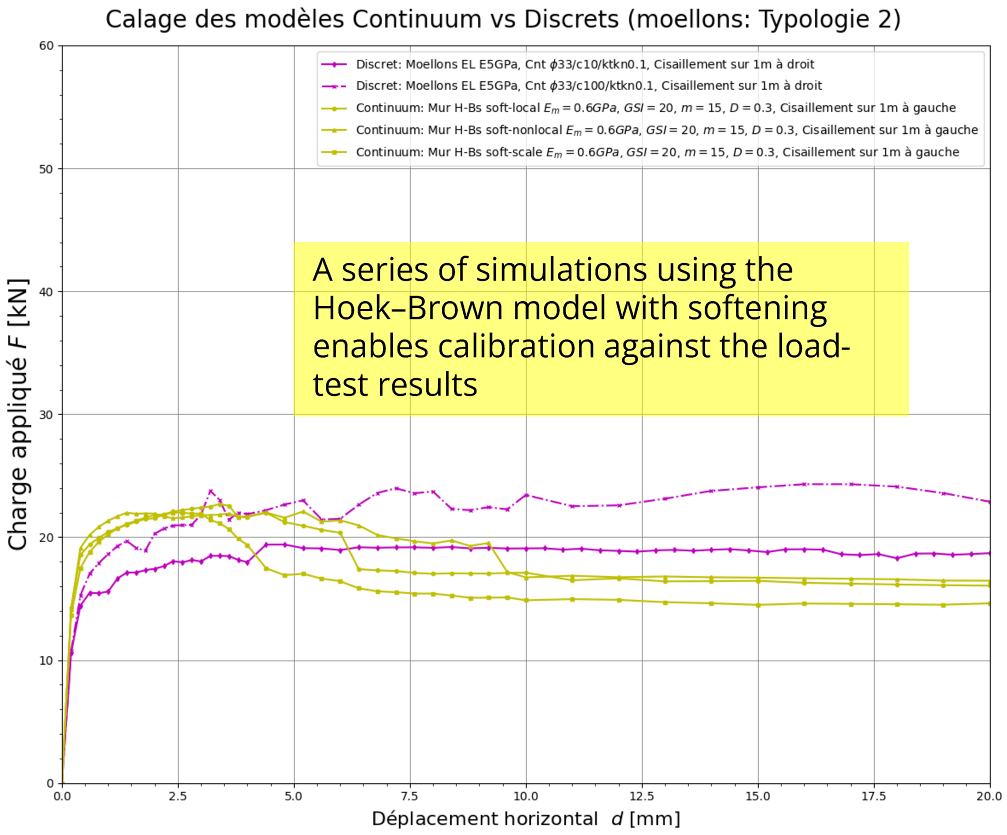
Discrete model kinematics

H-B without softening

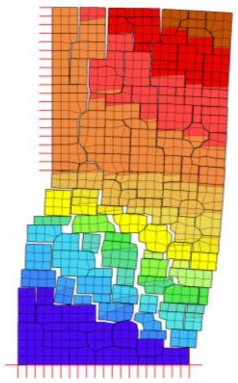
Case Study

STATIC LOAD ON THE RETAINING WALL

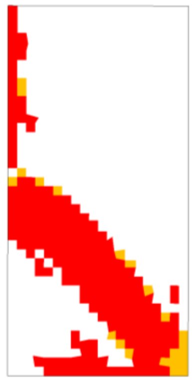
Preparatory desk studies – calibration of the continuum macro model



A series of simulations using the Hoek–Brown model with softening enables calibration against the load-test results



Discrete model kinematics

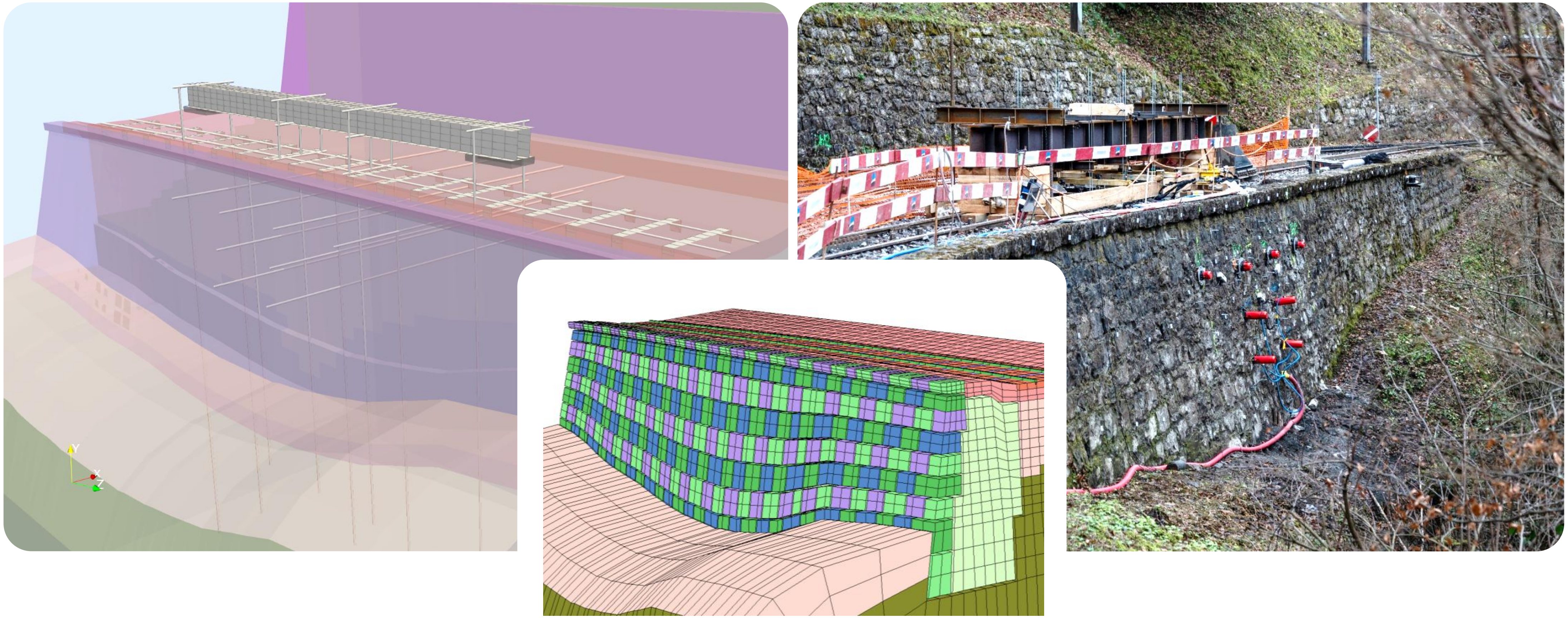


Failure mode: predominantly tensile

Case Study

STATIC LOAD ON THE RETAINING WALL

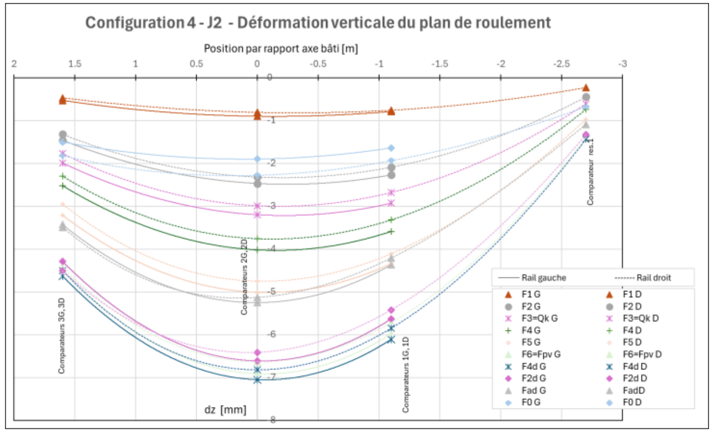
Creation of a digital twin representing real setup

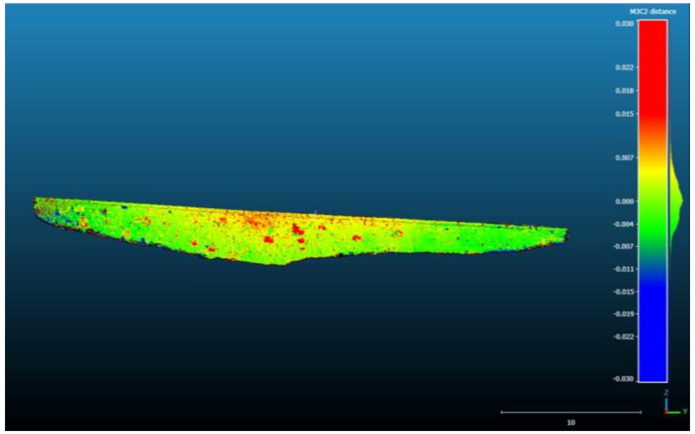


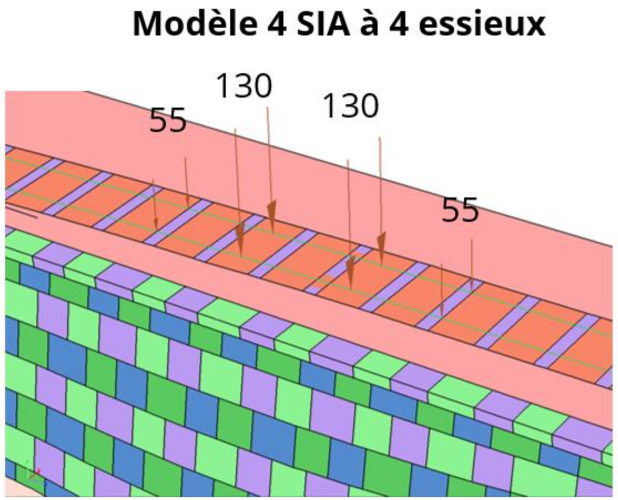
Case Study

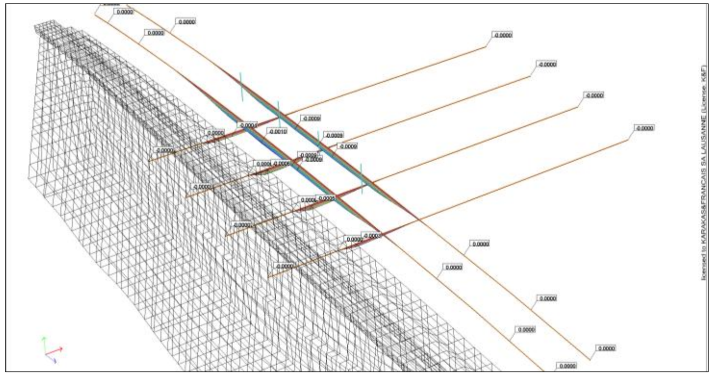
STATIC LOAD ON THE RETAINING WALL

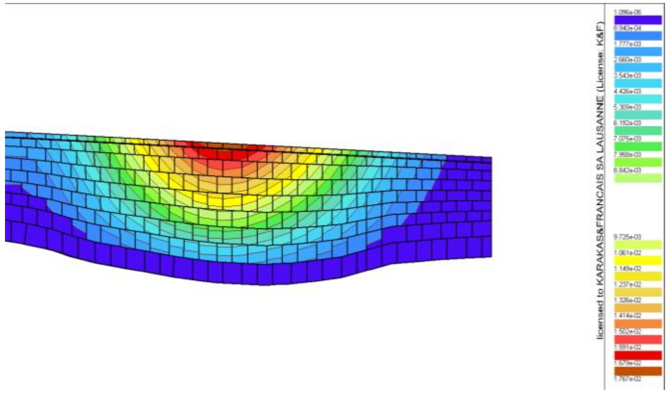
Reproduction of measurements → Comparison → Model calibration







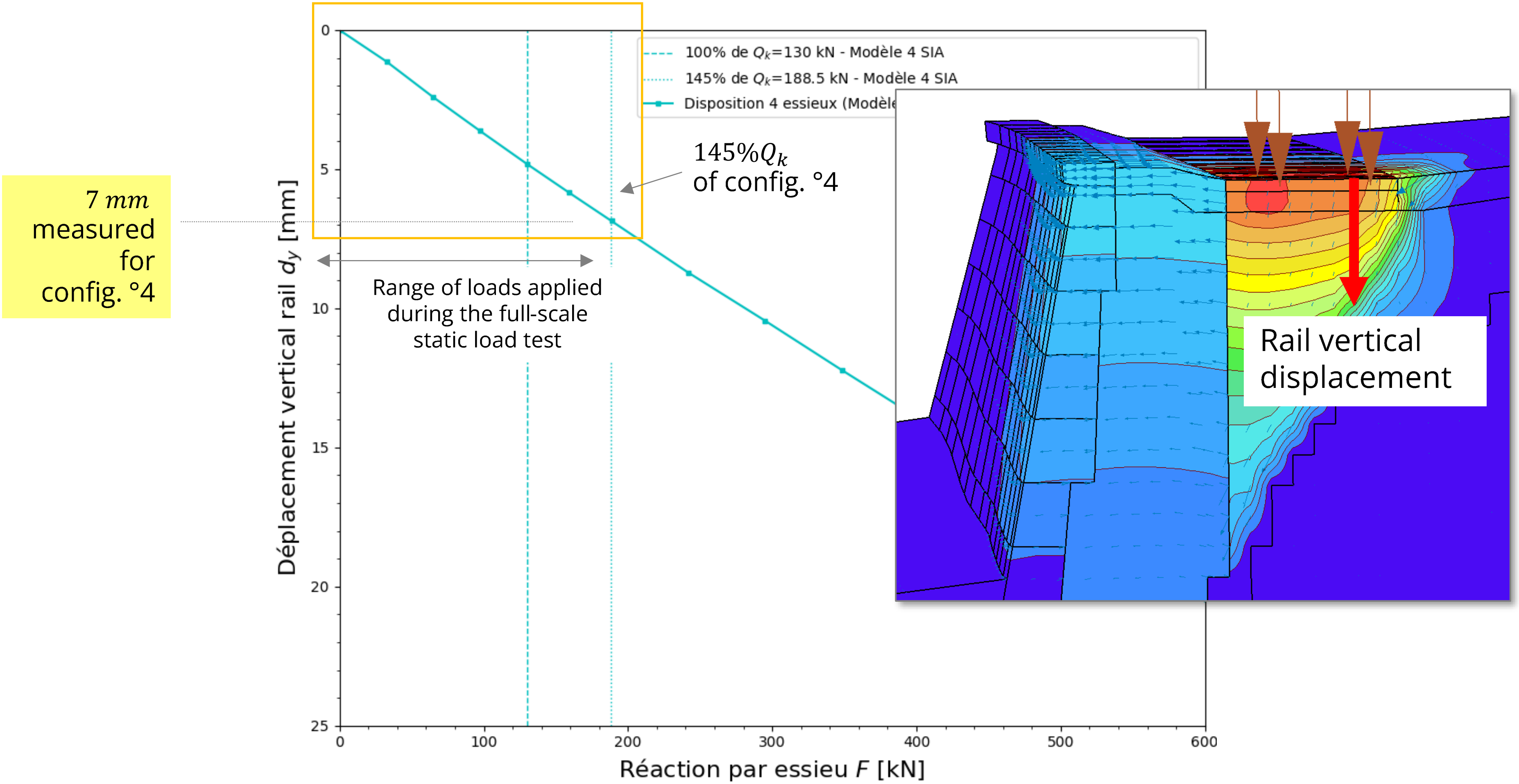




Case Study

Static load on the retaining wall

Validation of the 3D model in the elastic range

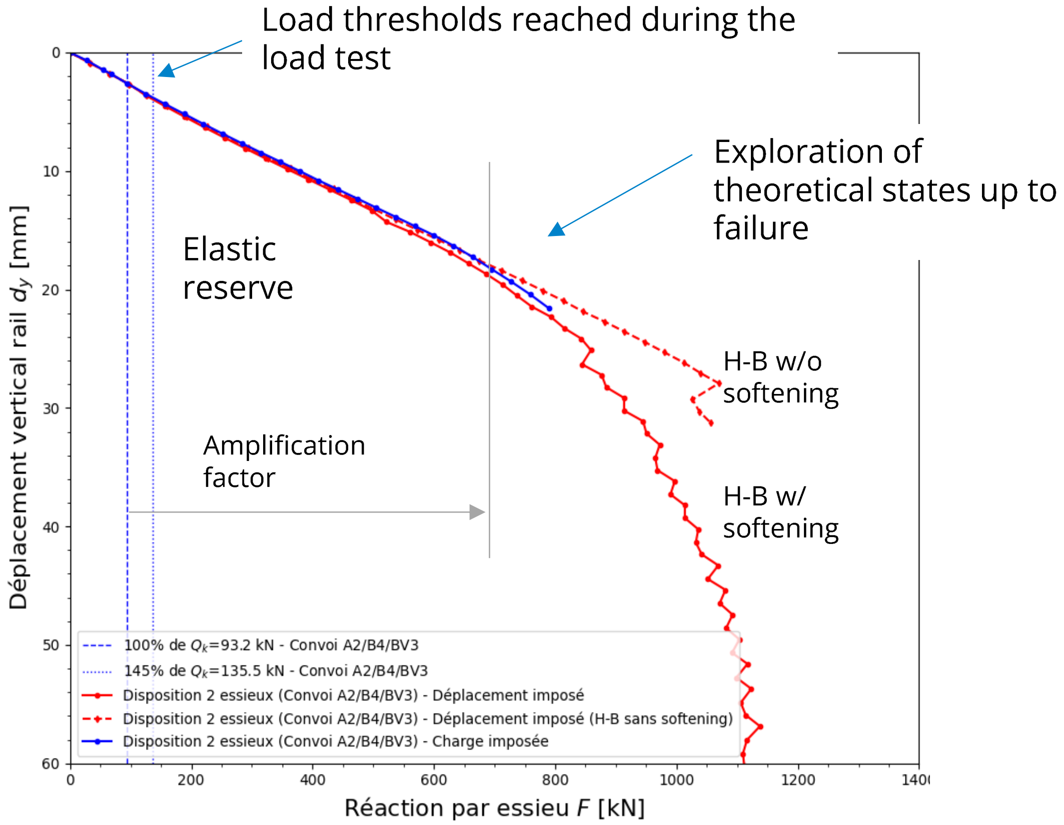


Case Study

Static load on the retaining wall

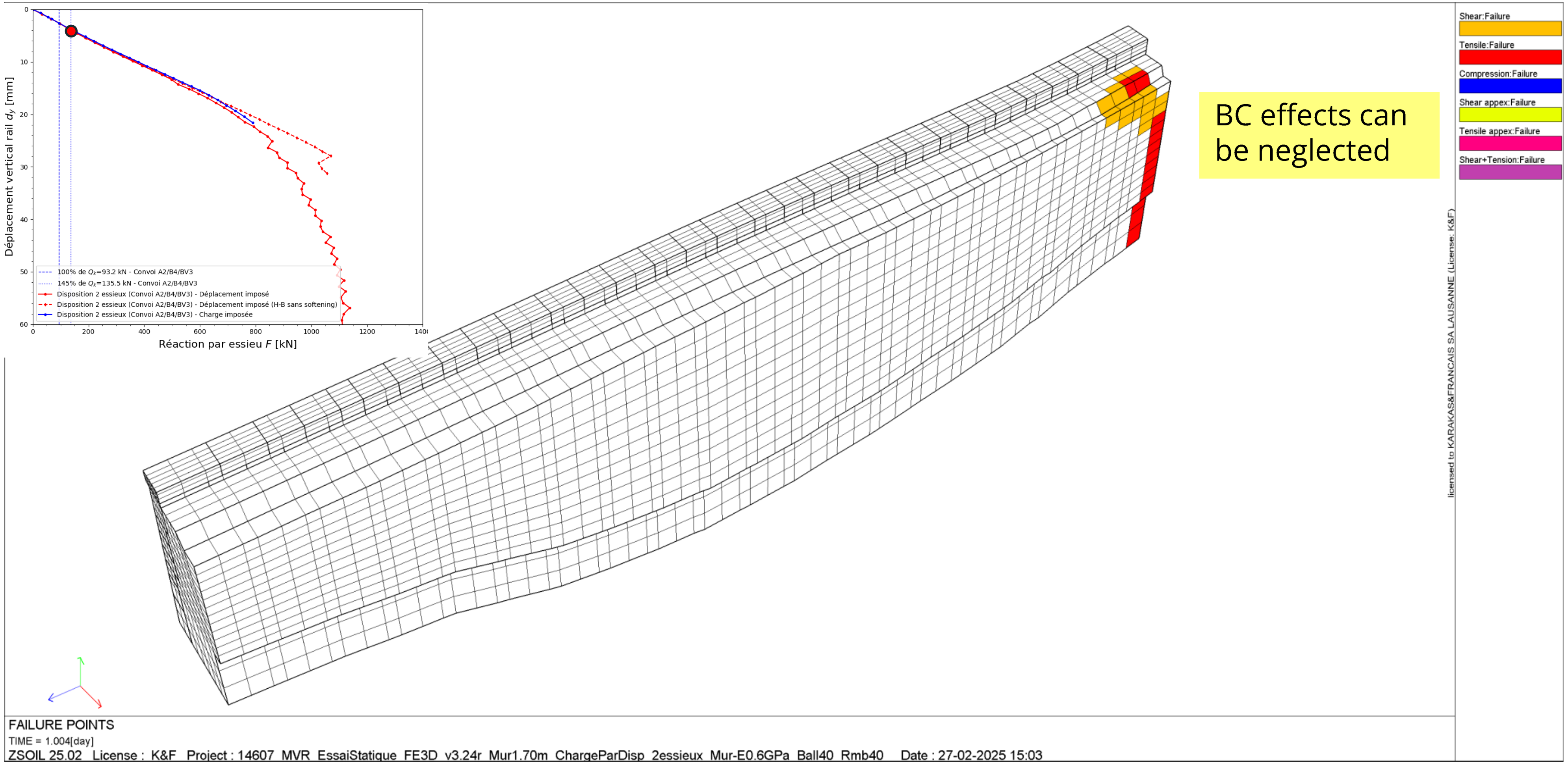
Assessment of capacity limits of the wall

Continuation of the load test: approaching the global resistance limit of the structure and estimating its reserve capacity with respect to railway loads



Case Study

Inspection of the wall for localized plastic zones



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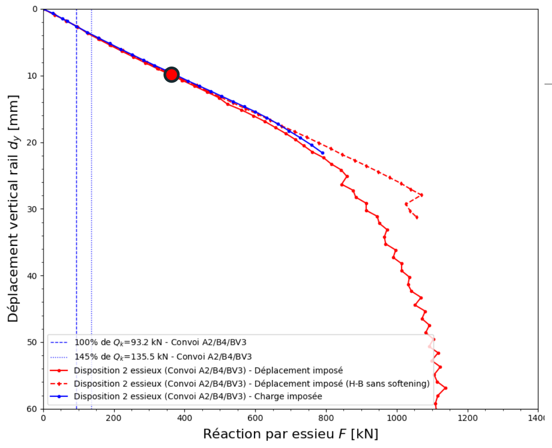
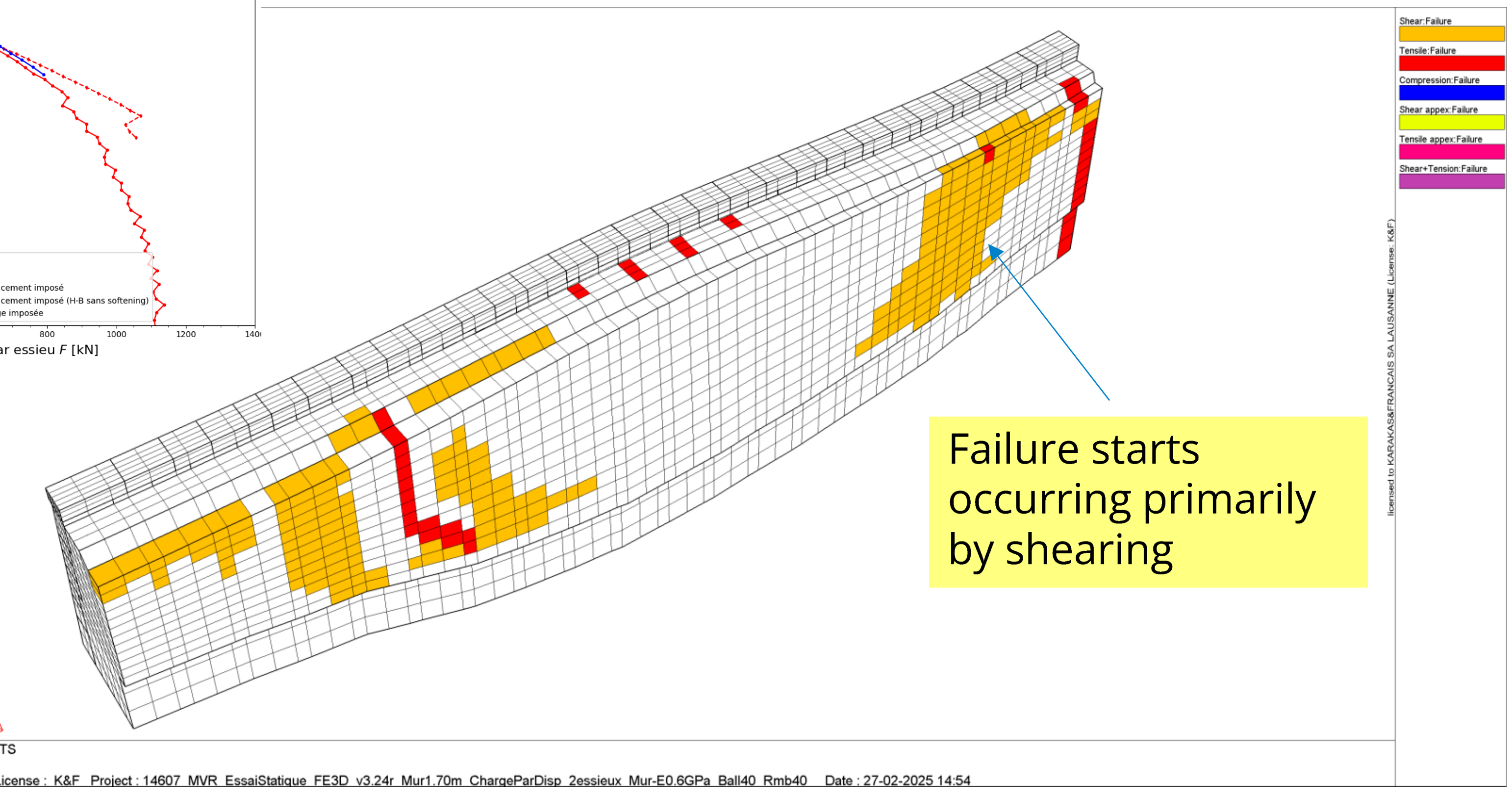
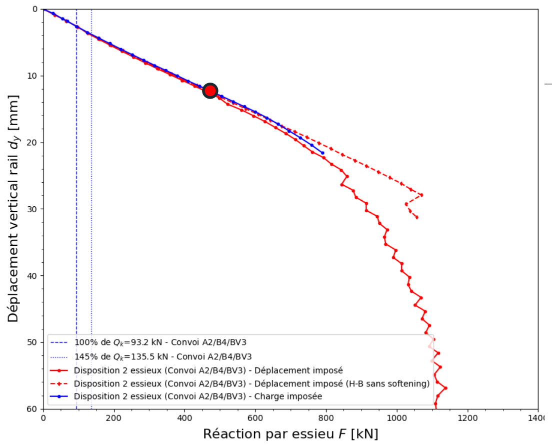


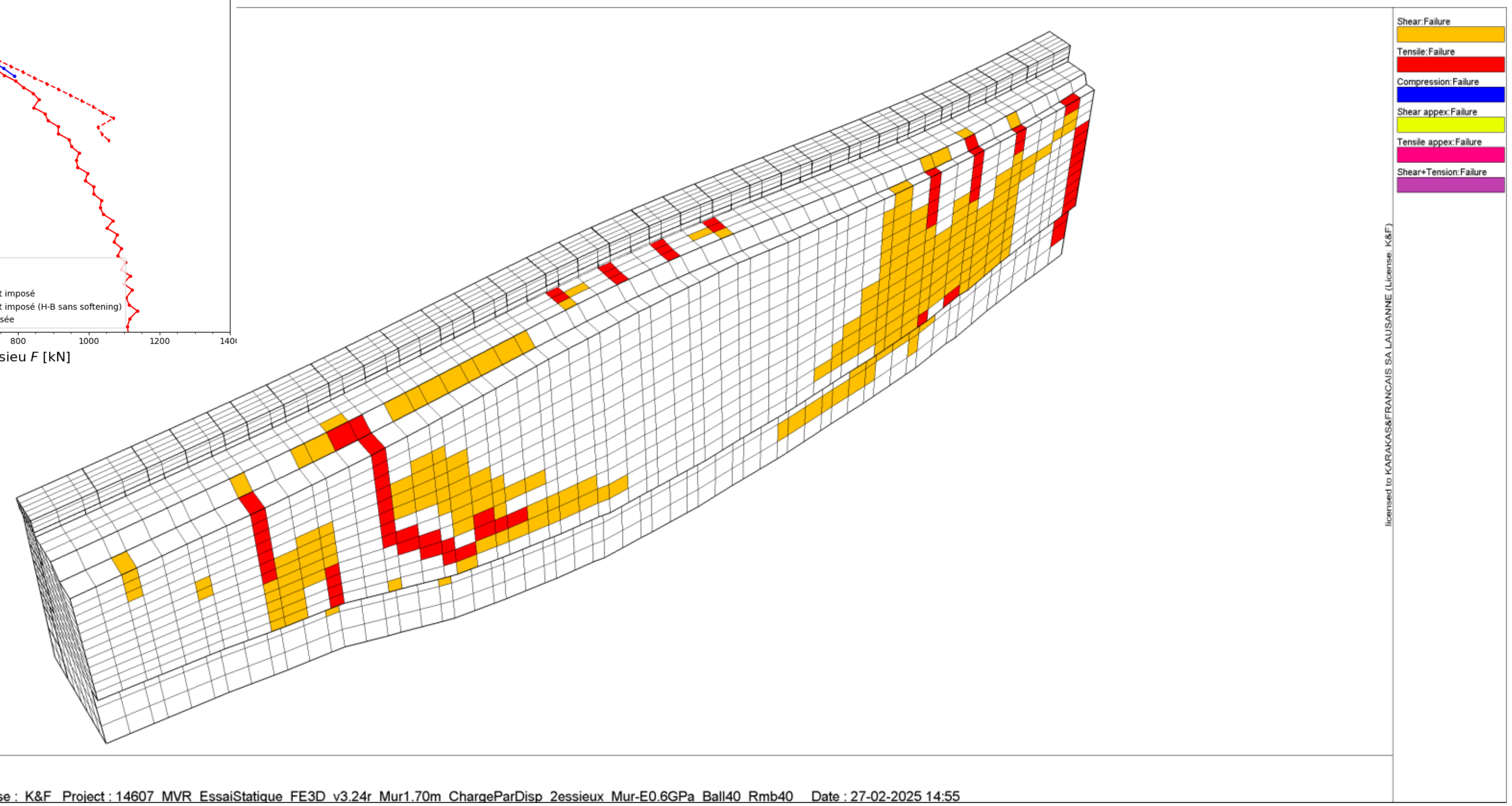


Failure starts occurring primarily by shearing

Case study

Inspection of the wall for localized plastic zones





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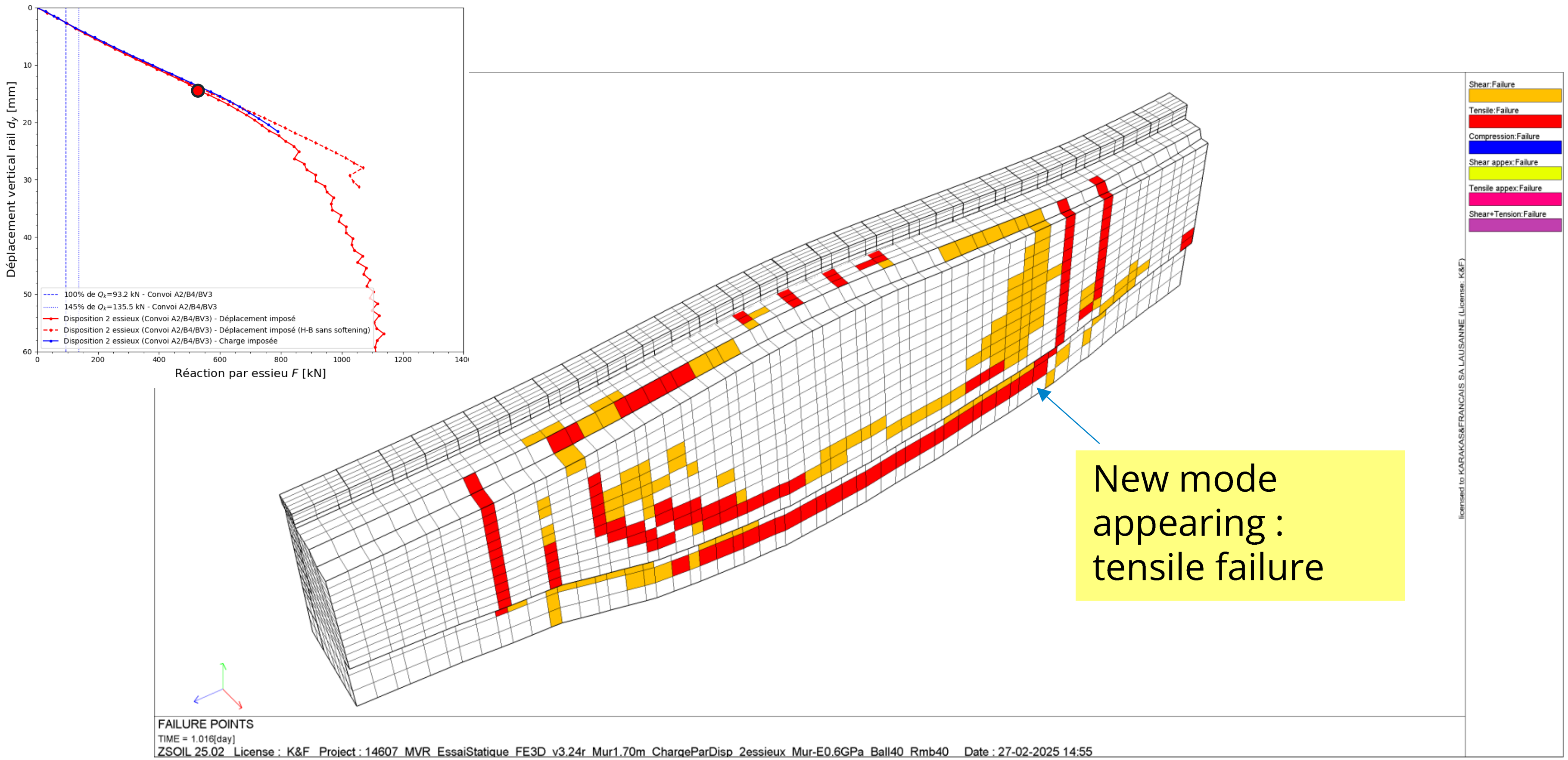

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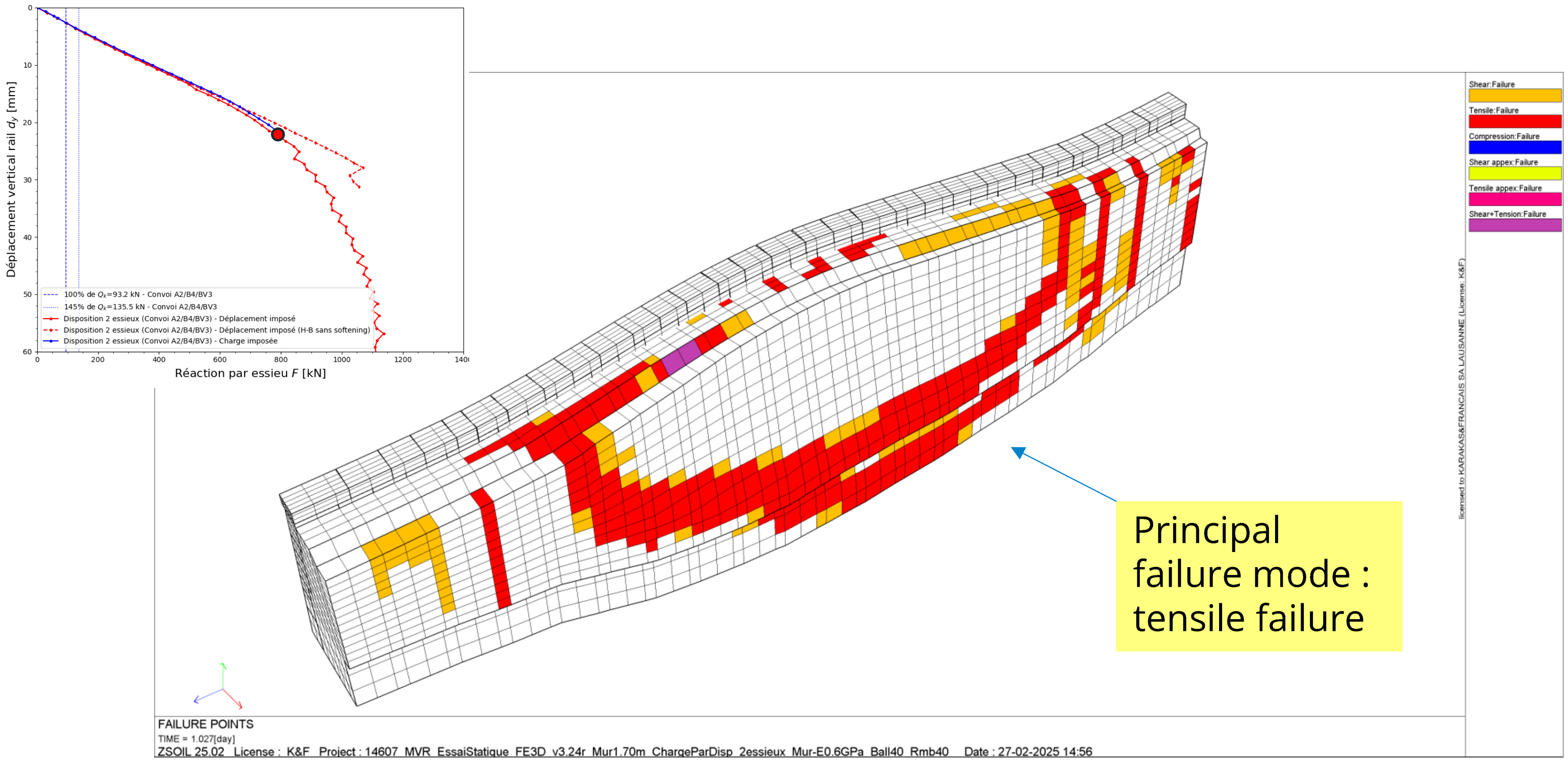

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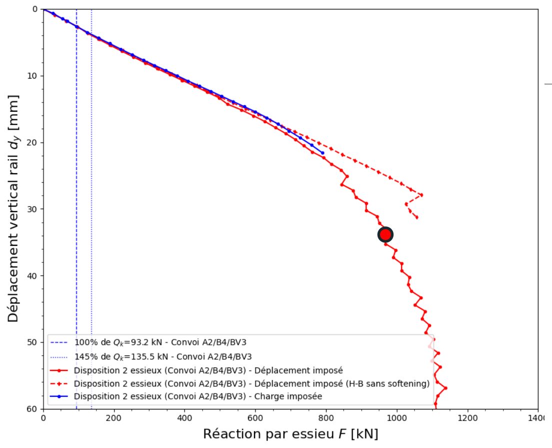
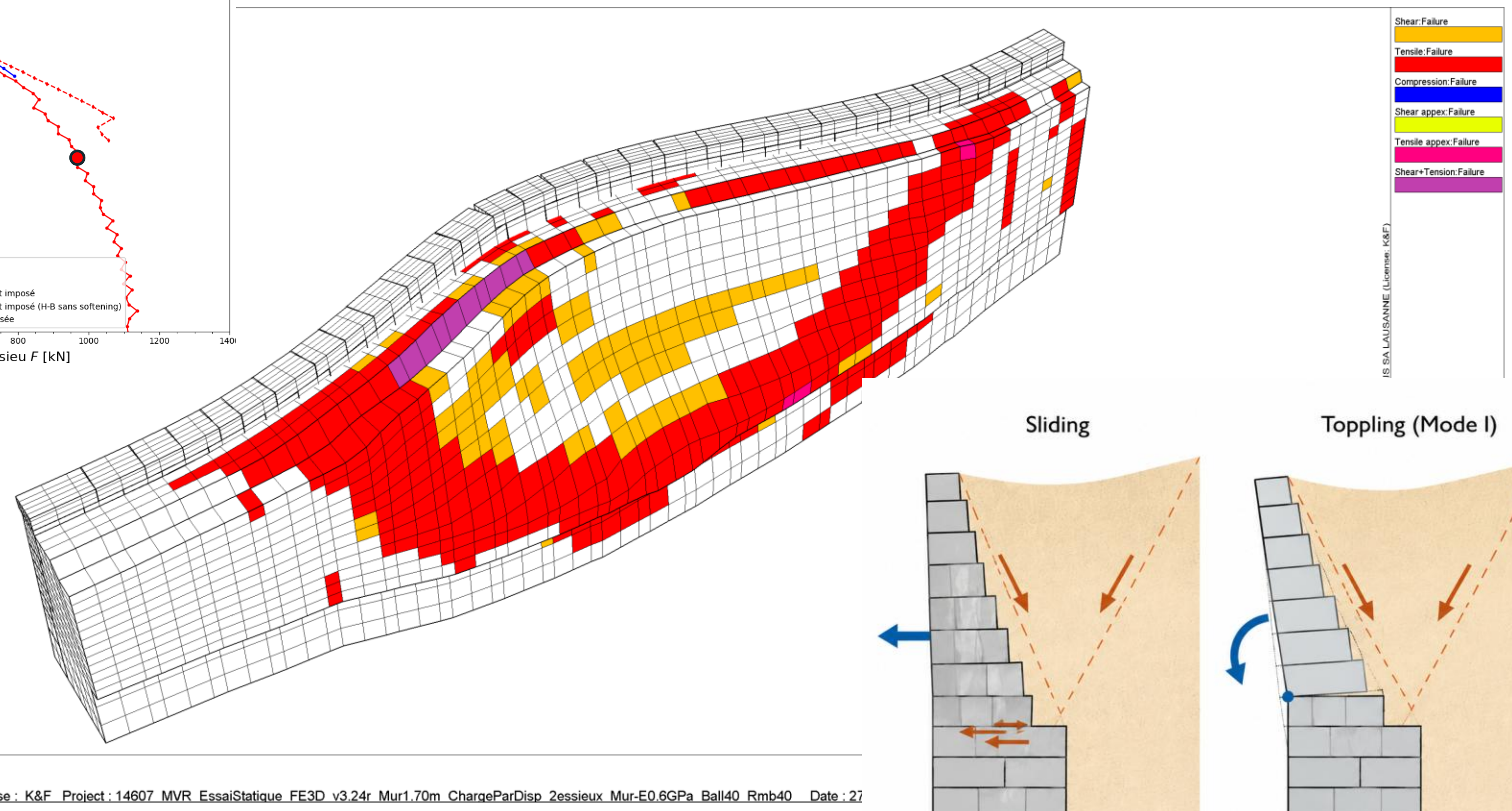
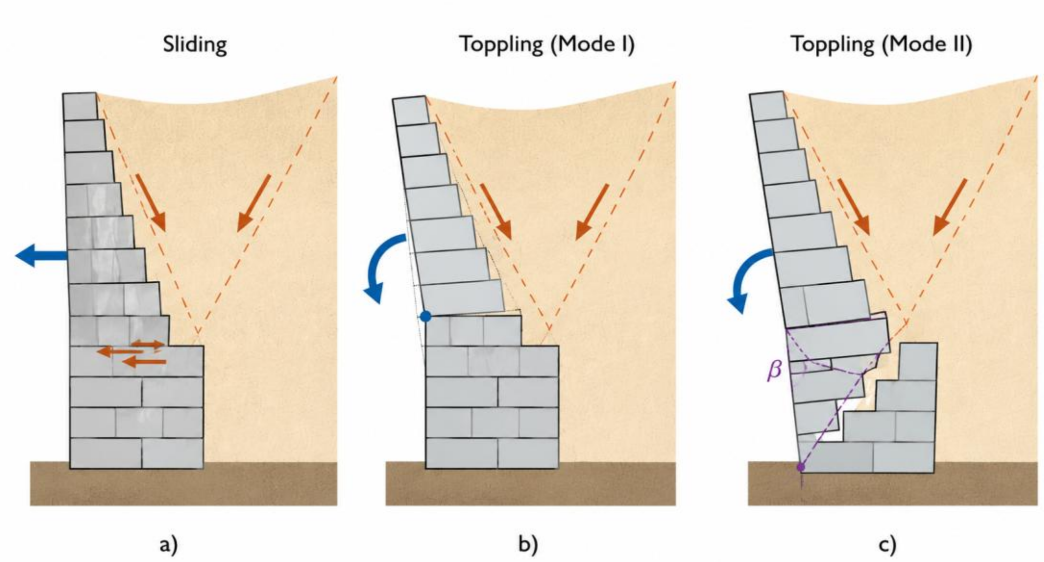


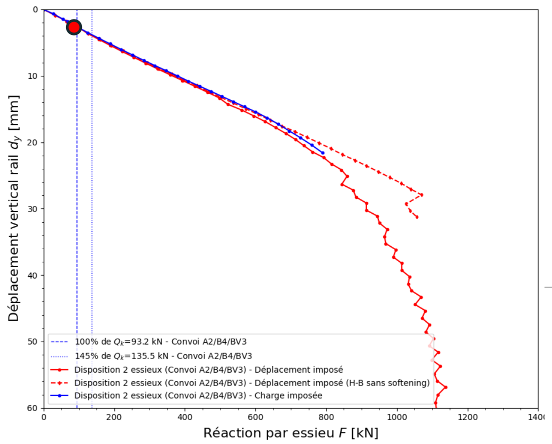


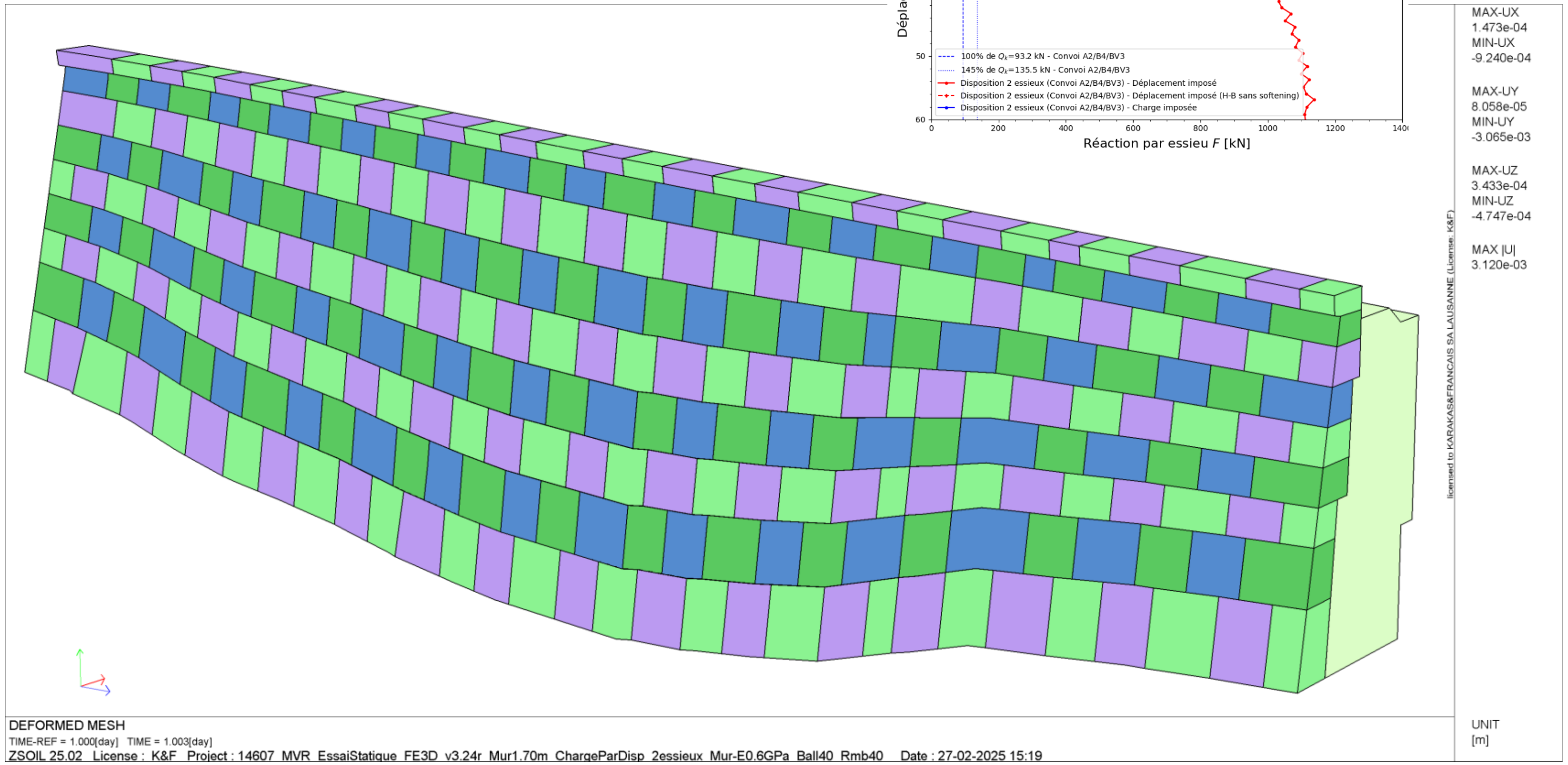


Based on Alejano et al. (2025)

Case study

Assessment of wall-facing kinematics





Case study

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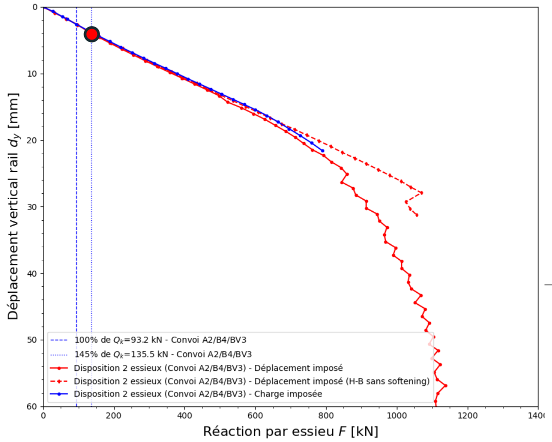
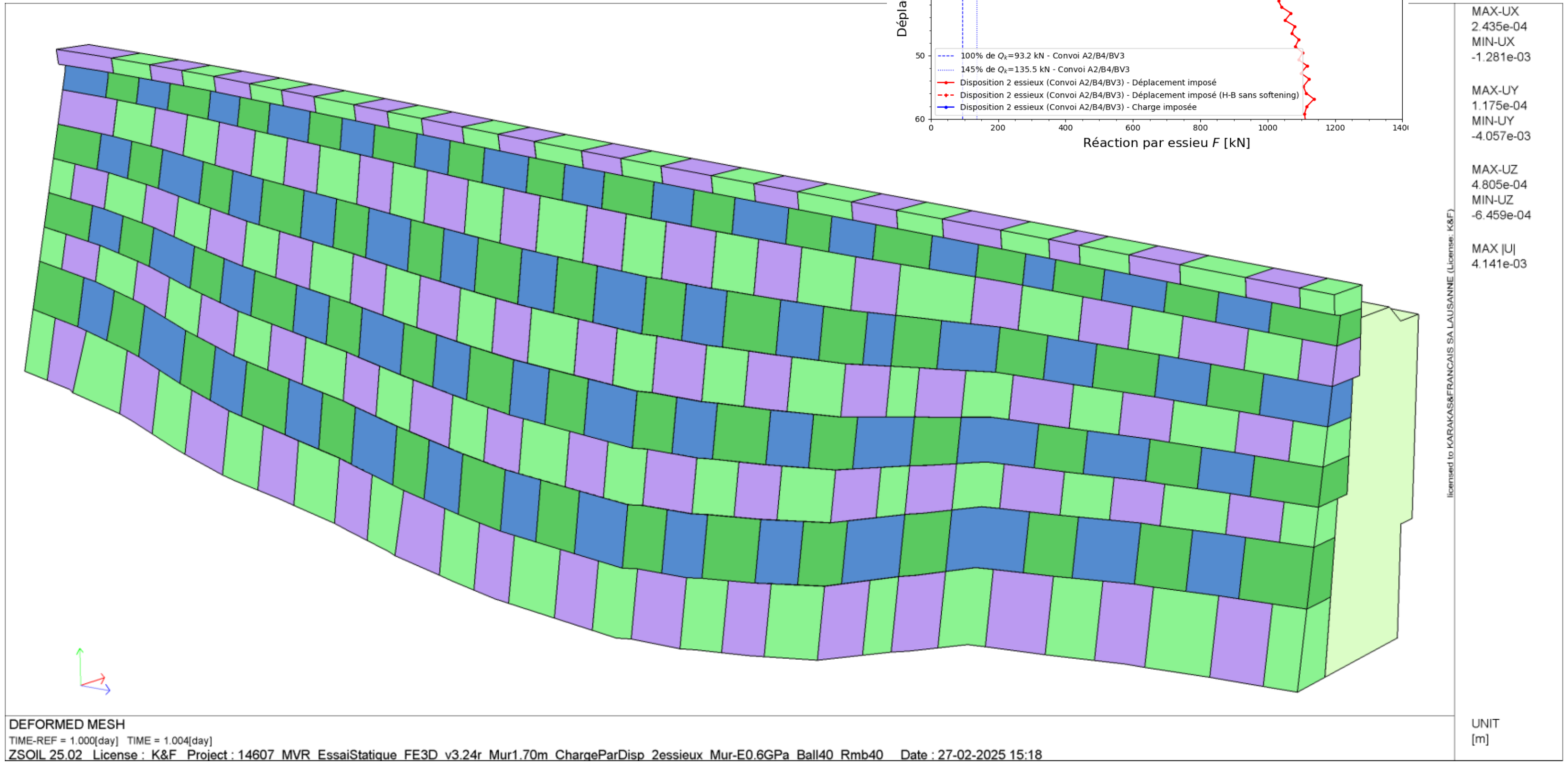
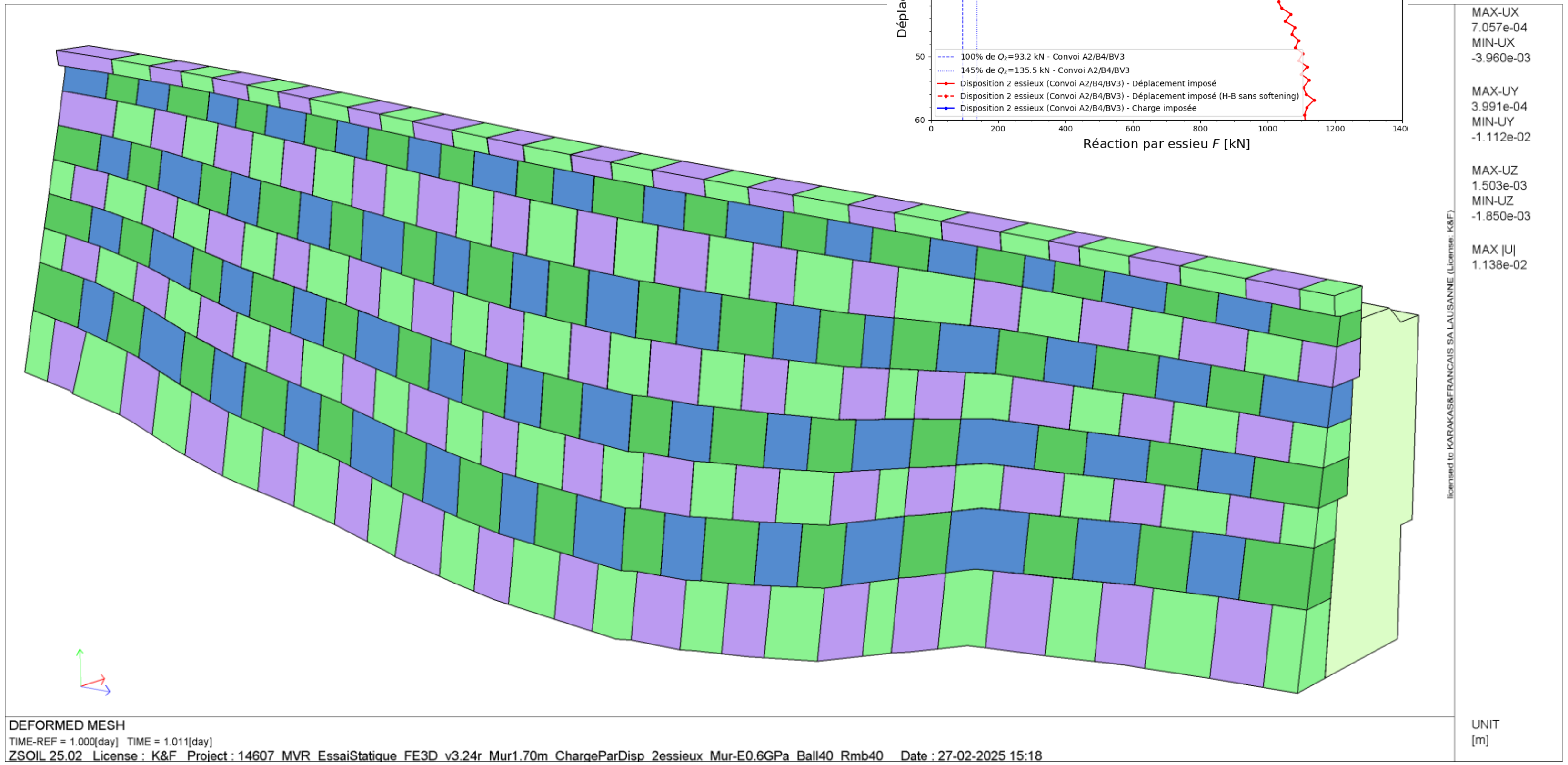
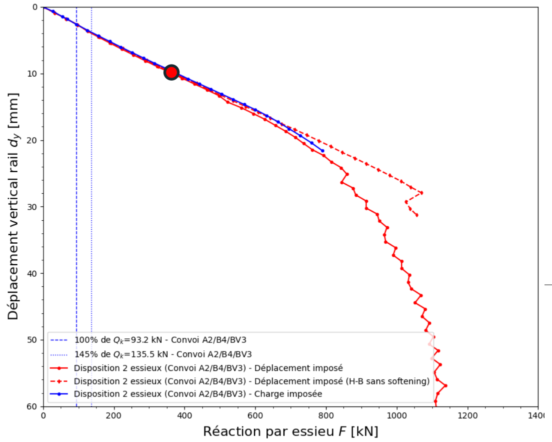




Case study

Assessment of wall-facing kinematics





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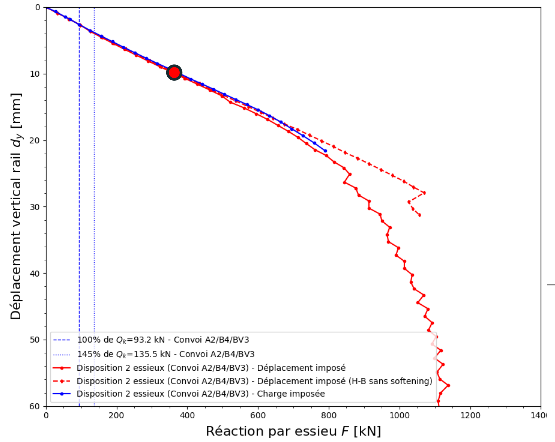
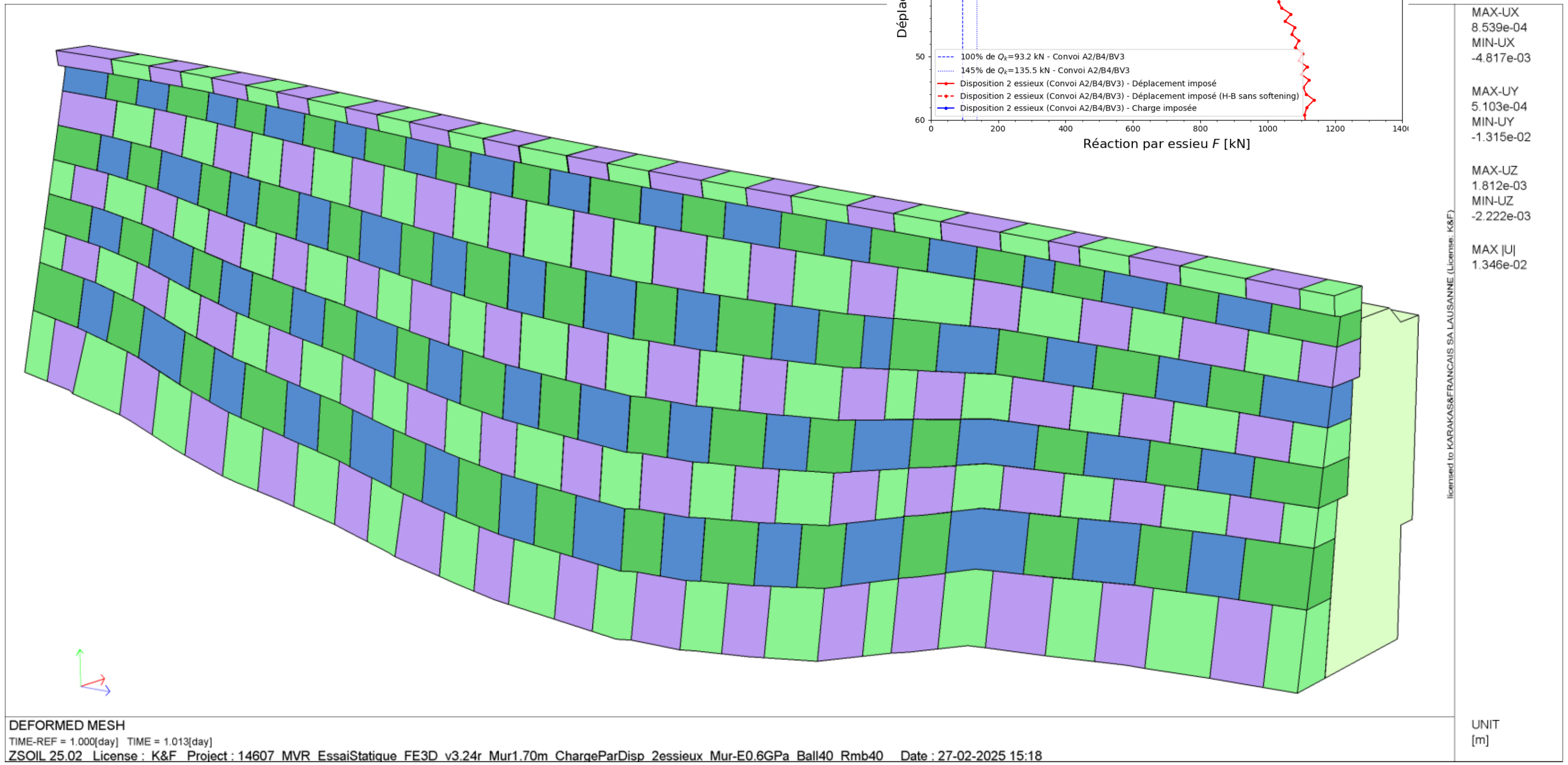
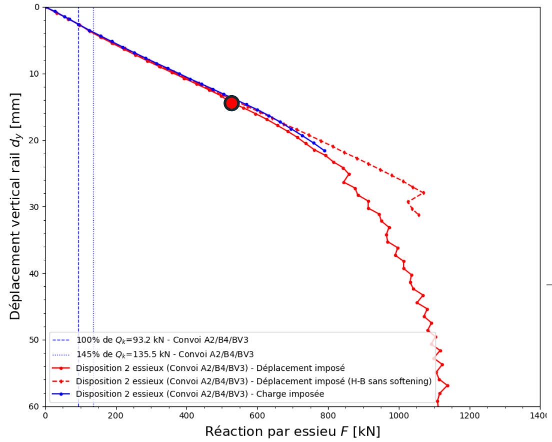
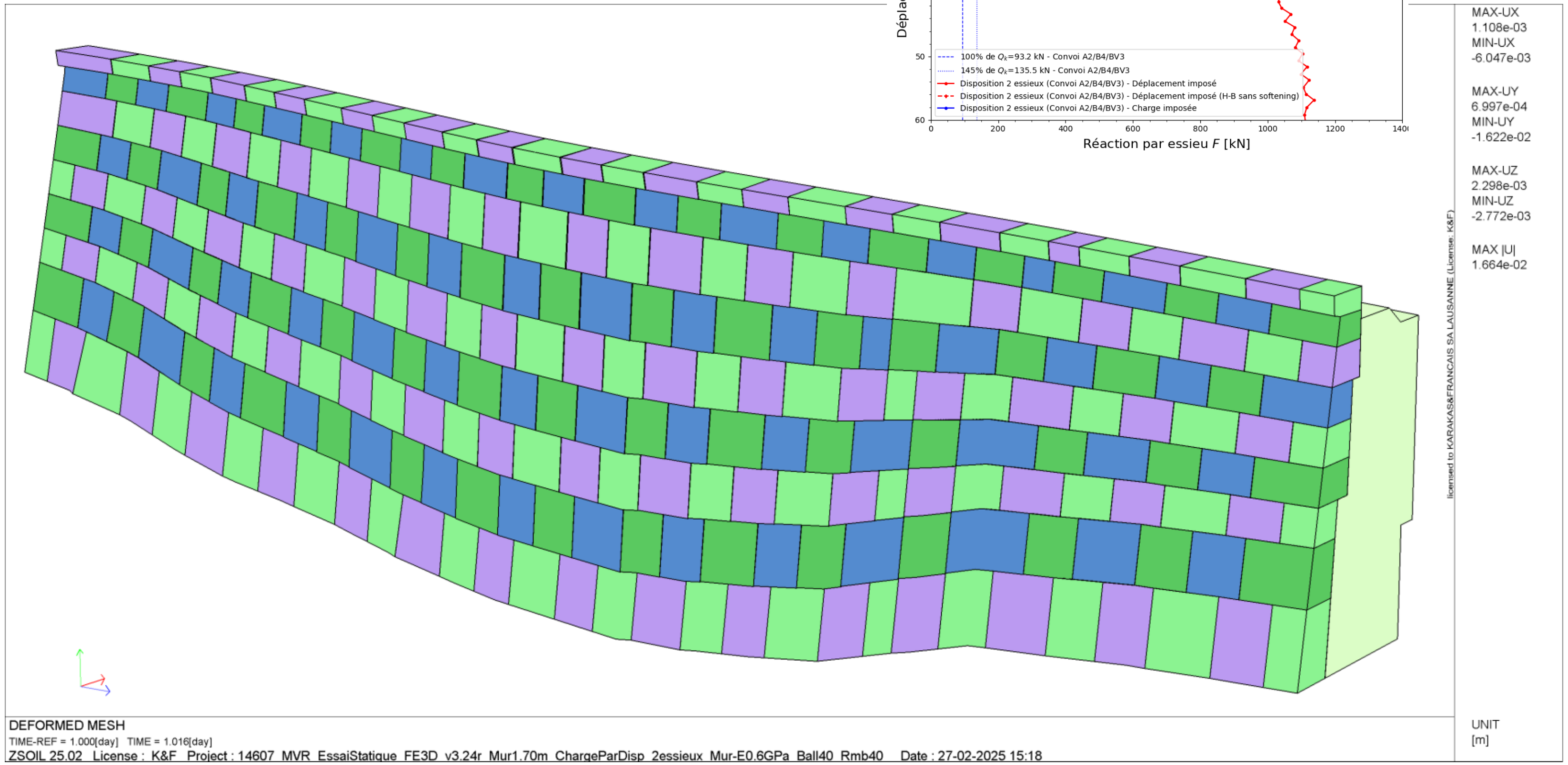




Case study

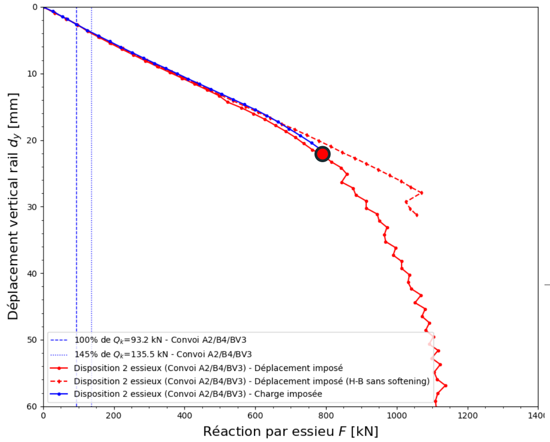
Assessment of wall-facing kinematics

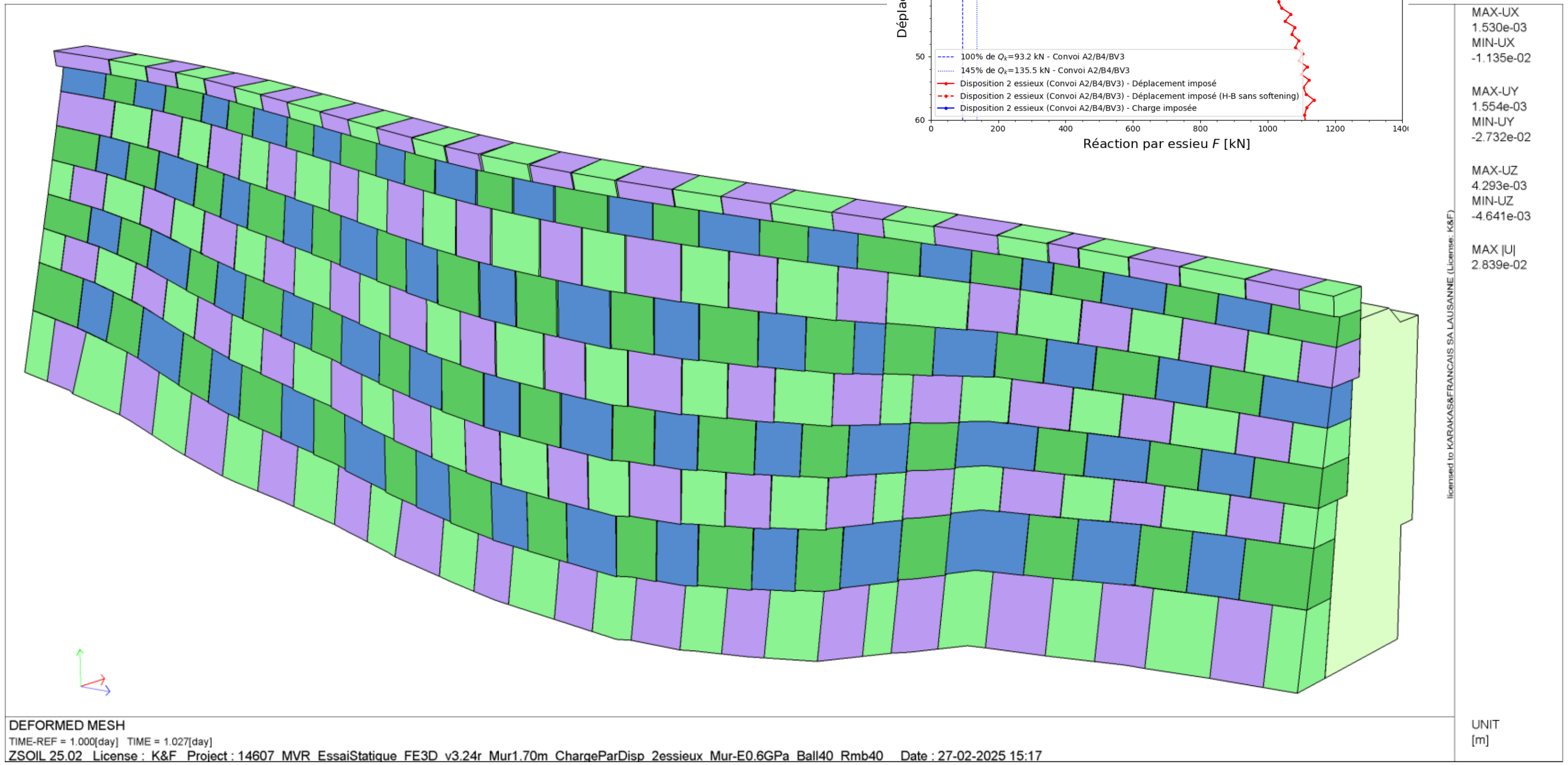




Case study

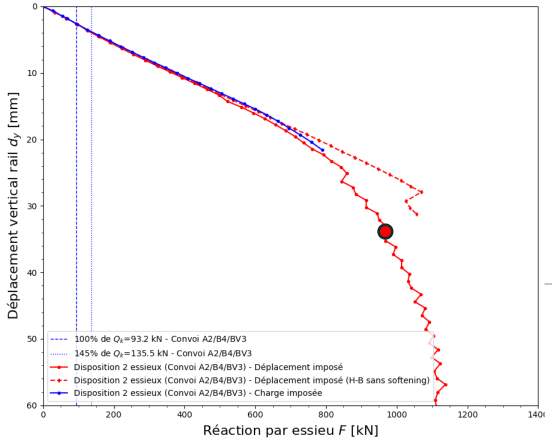
Assessment of wall-facing kinematics

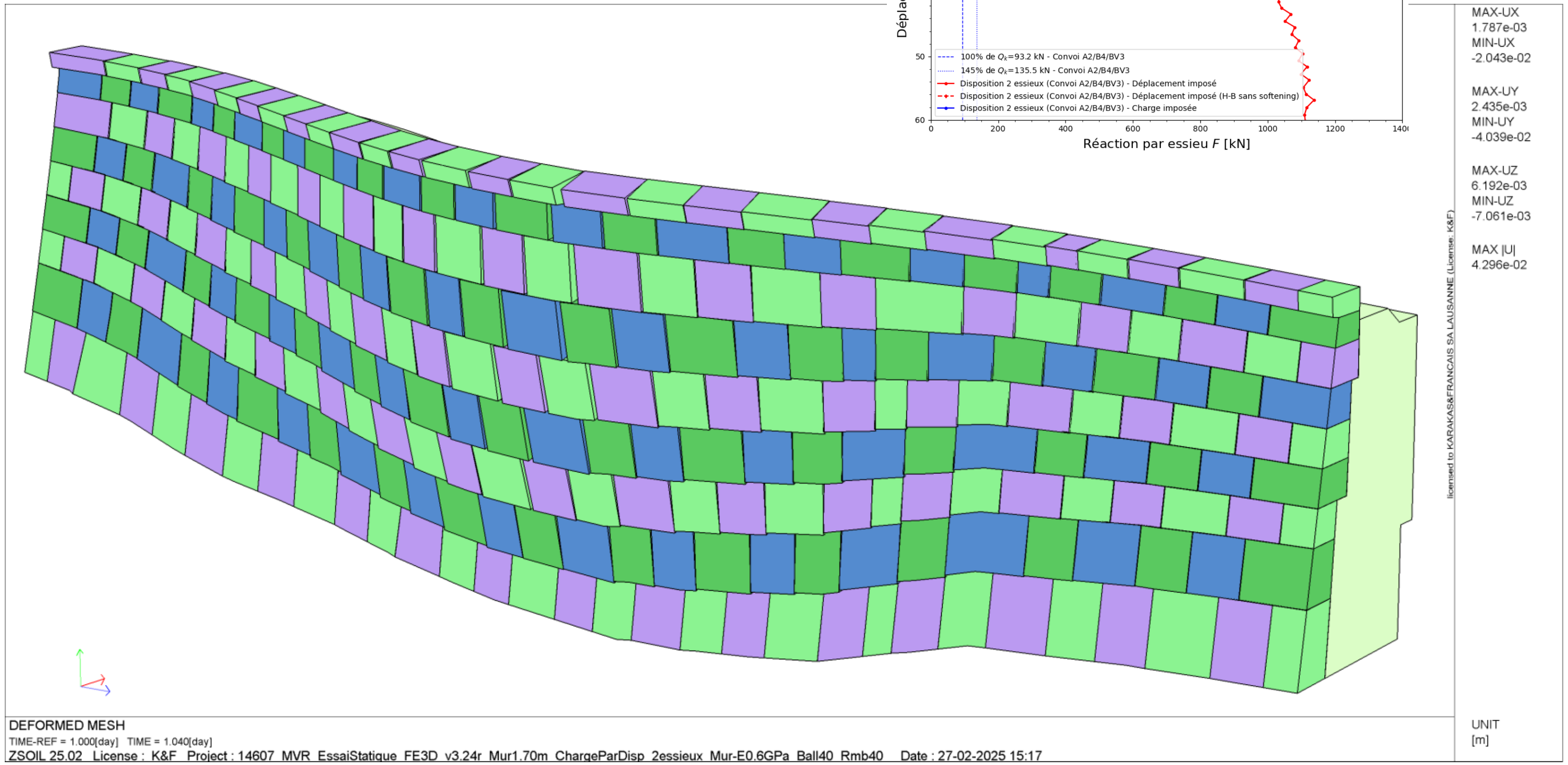




Case study

Assessment of wall-facing kinematics

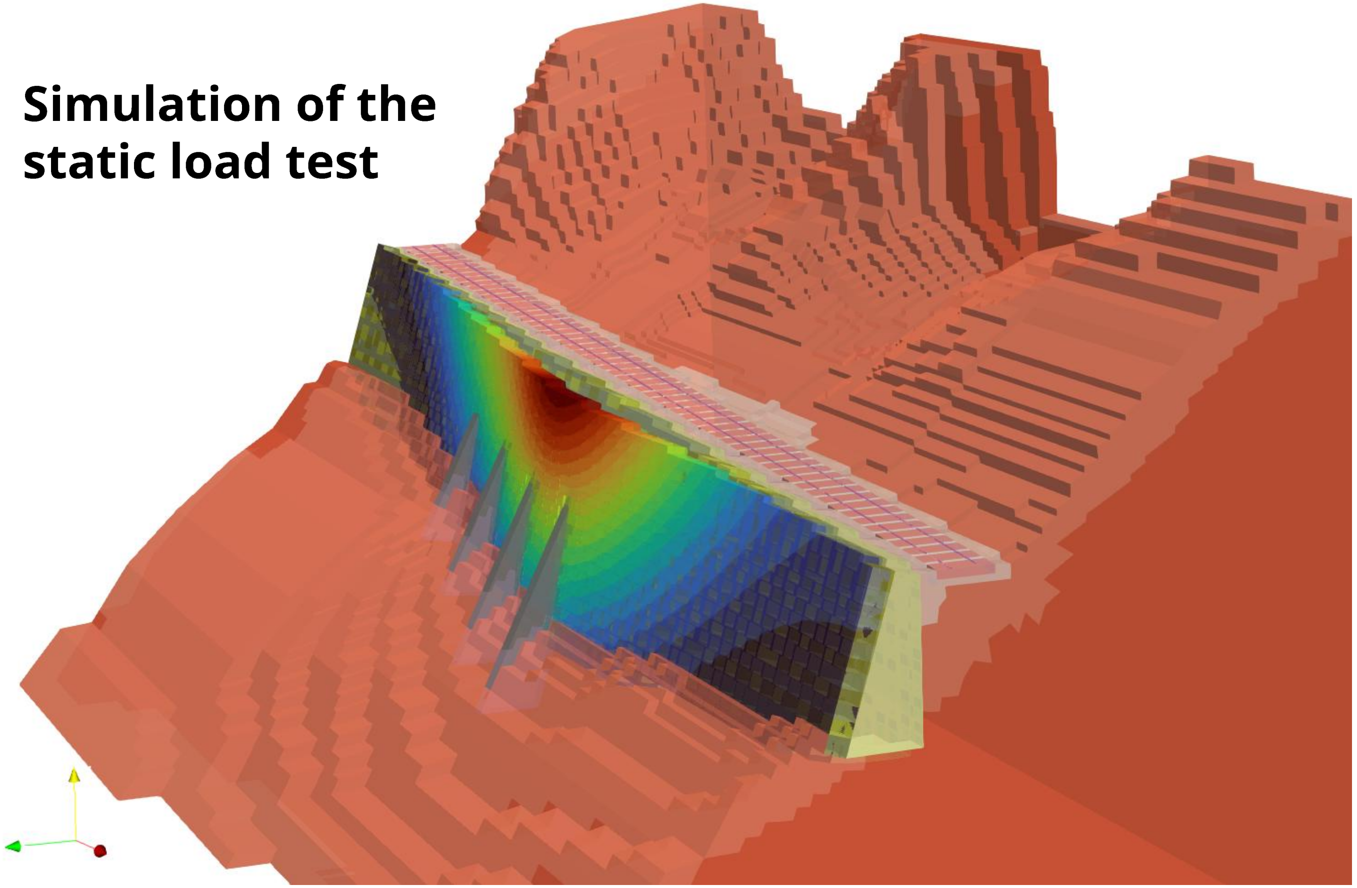




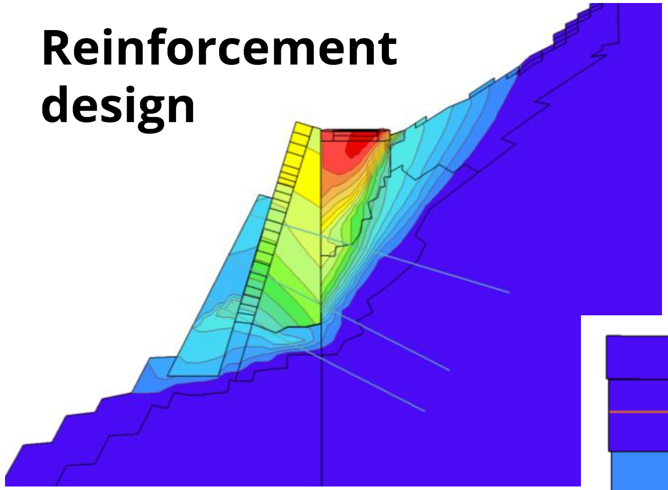
Case study

Application of the methodology to the assessment of other walls

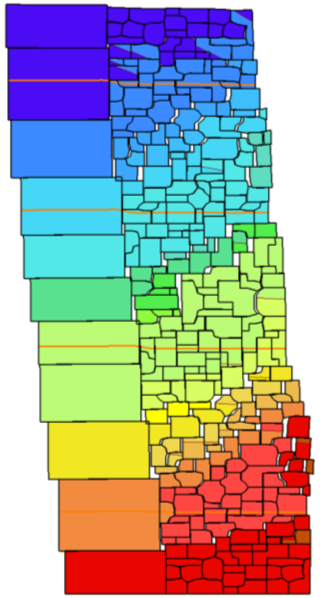
Simulation of the static load test



Reinforcement design



Effectiveness of grouted anchor rods



05 Final remarks

Conclusions

- **Masonry can be modelled at different scales**, from homogenized continuum approaches to detailed discrete representations. The appropriate choice depends on the structural problem, expected failure mechanisms, and required level of detail.
- **ZSoil provides several tools for masonry modelling**, but some limitations remain, particularly in the description of interfaces and contacts, including tensile resistance and the transition from peak to residual strength.
- **Homogenization provides a practical bridge between meso- and macro-scale modelling**, allowing the complex response of masonry to be represented through equivalent continuum properties while keeping the data preparation and computational effort reasonable.

Conclusions

- **Discrete modelling offers a more realistic representation of masonry failure mechanisms**, including joint opening, sliding, cracking, and relative block movements, but requires more detailed geometrical information and material parameters and probably the use of large displacement contact formulation.
- **The case study demonstrates** how field measurements, full-scale testing and mixed macro–meso modelling can be combined to build and calibrate a representative numerical model, enabling the assessment of capacity limit and realistic failure mechanisms.

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Find us

Lausanne

Av. des Boveresses 44
1010 Lausanne
021 / 654 44 88
geotechnique@kfsa.ch

Genève

Ch. des Poteaux 10
1213 Petit-Lancy
022 / 301 52 61
geneve@kfsa.ch

Martigny

Rue de la Poste 3
1920 Martigny
027 / 723 20 11
valais@kfsa.ch

Bulle

Rue de Gruyères 106
1630 Bulle
026 / 912 20 00
bulle@kfsa.ch