Numerical Investigation of NATM/SEM Construction Strategies for Ground Deformation Control in Residual Porous Clay: A Case Study from the São Paulo Metro, Brazil

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MIDAS

OUTLINE

- Motivation
- Case Study: Paraiso tunnel of the São Paulo metro, Brazil.
- Constitutive model calibration to represent the residual porous clay
- Three-dimensional FEM model developed to simulate the Paraiso tunnel construction sequence using Midas GTS NX
- Numerical results vs. field data (numerical model validation)
- Numerical investigation:
    - Influence of the unsupported span length and lining stiffness
    - Influence of the partial-excavation sequence using benches
    - Influence of the pre-support umbrella system

- **Results presented here are discussed in detail in the article below:**

- Vitali, O. P. M.; Celestino T. B.; Bobet, A. (2022) *Construction strategies for a NATM tunnel in São Paulo, Brazil, in residual soil. Underground Space. 7(1*): 1-18. https://doi.org/10.1016/j.undsp.2021.04.002

- **Information about the Paraíso Tunnel was obtained from the doctoral dissertation of Professor Alexandre Benneti Parreira:**

- Parreira, A. B. (1991). *Analysis of Shallow Tunnels in Soil – The Paraíso Mined Tunnel of the Paulista Line of the São Paulo Metro*. Doctoral Dissertation, Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Brazil.

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MOTIVATION

- Growing demand for tunnels and underground structures in major urban centers;
- NATM/SEM tunneling methods are widely used, and controlling ground deformations is critical to prevent damage to buildings and existing infrastructure;
- In tropical regions, unsaturated, highly weathered residual clayey soils with high void ratio and collapsible behavior are very common.
- These soils exhibit a complex geotechnical behavior, and the ground deformations induced by tunneling remains largely unexplored.
- The study presented in this webinar aims to enhance our understanding of ground deformations induced by tunneling in residual porous soils.

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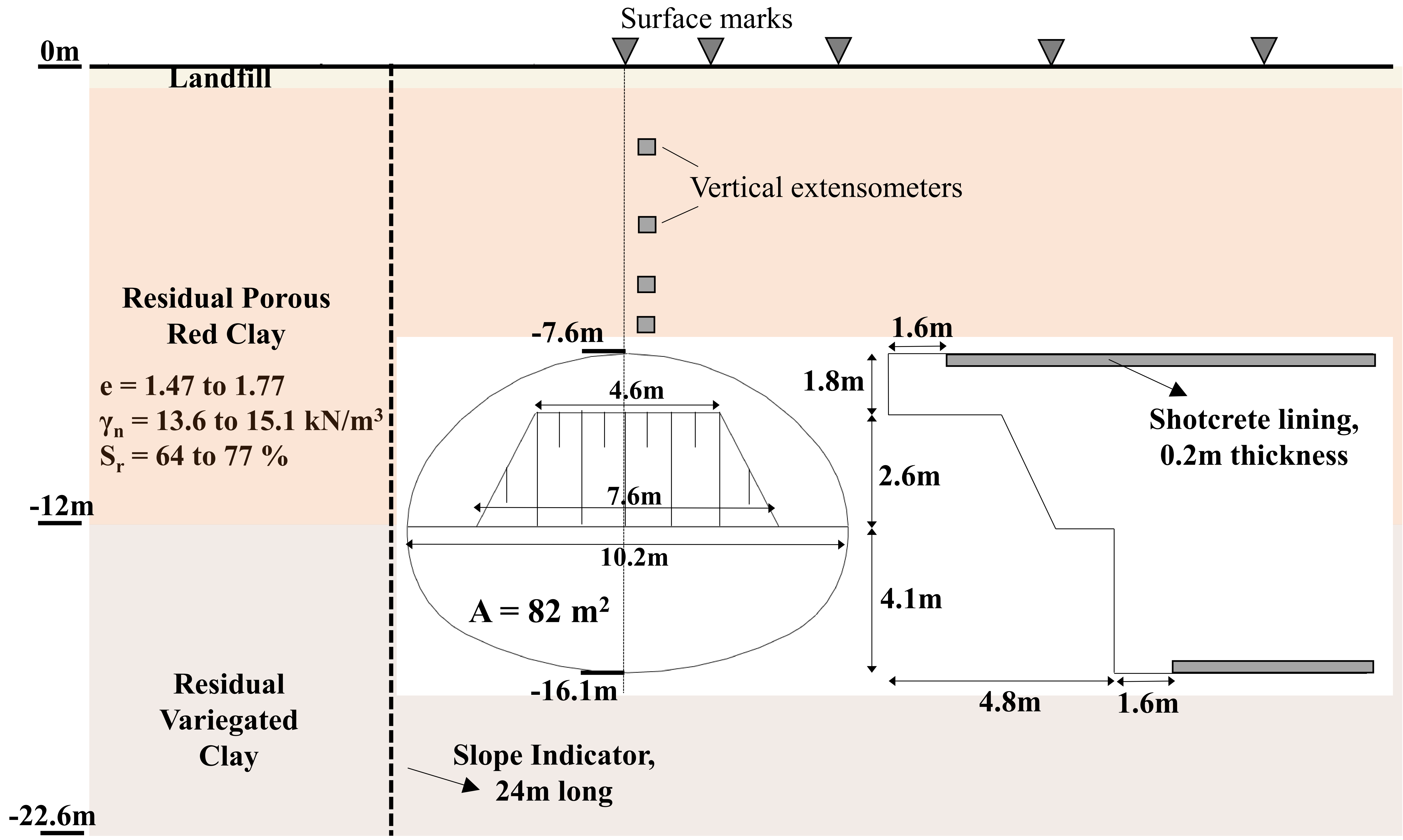
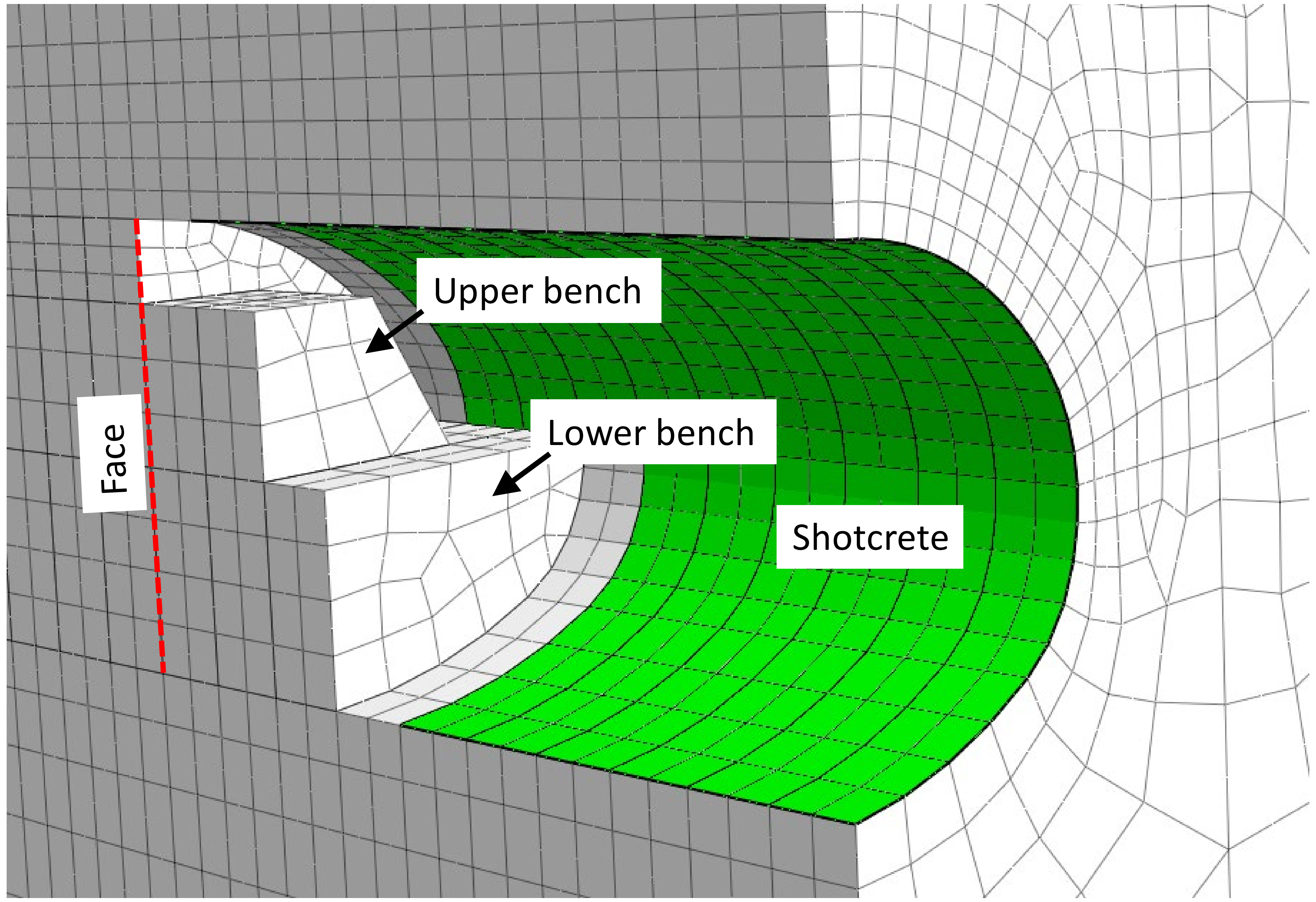
CASE STUDY: PARAISO TUNNEL OF THE SAO PAULO METRO

- Tunnel localized in a densely urbanized area in Sao Paulo, Brazil.
- Traditional Top heading-Bench-Invert excavation sequence





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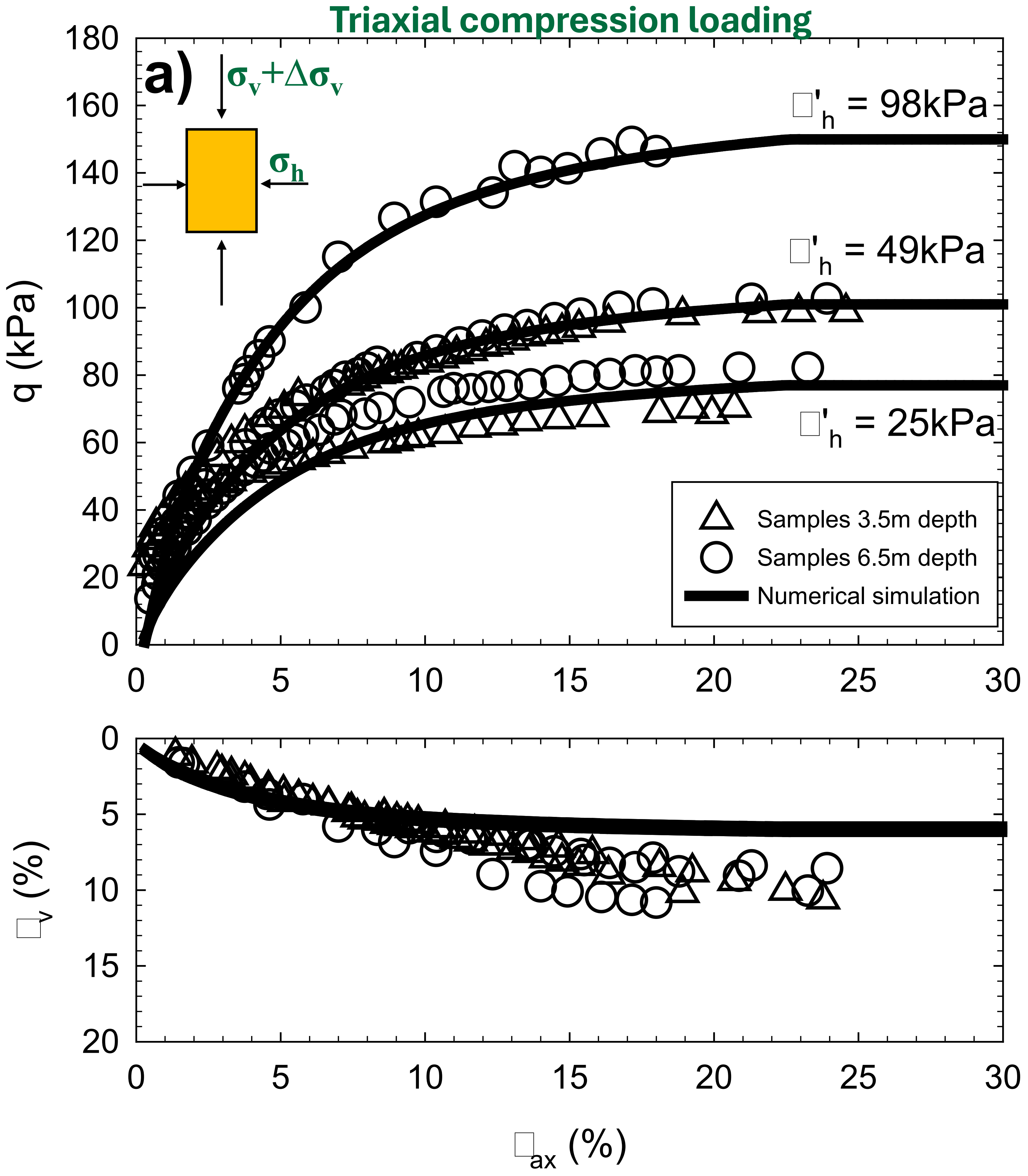
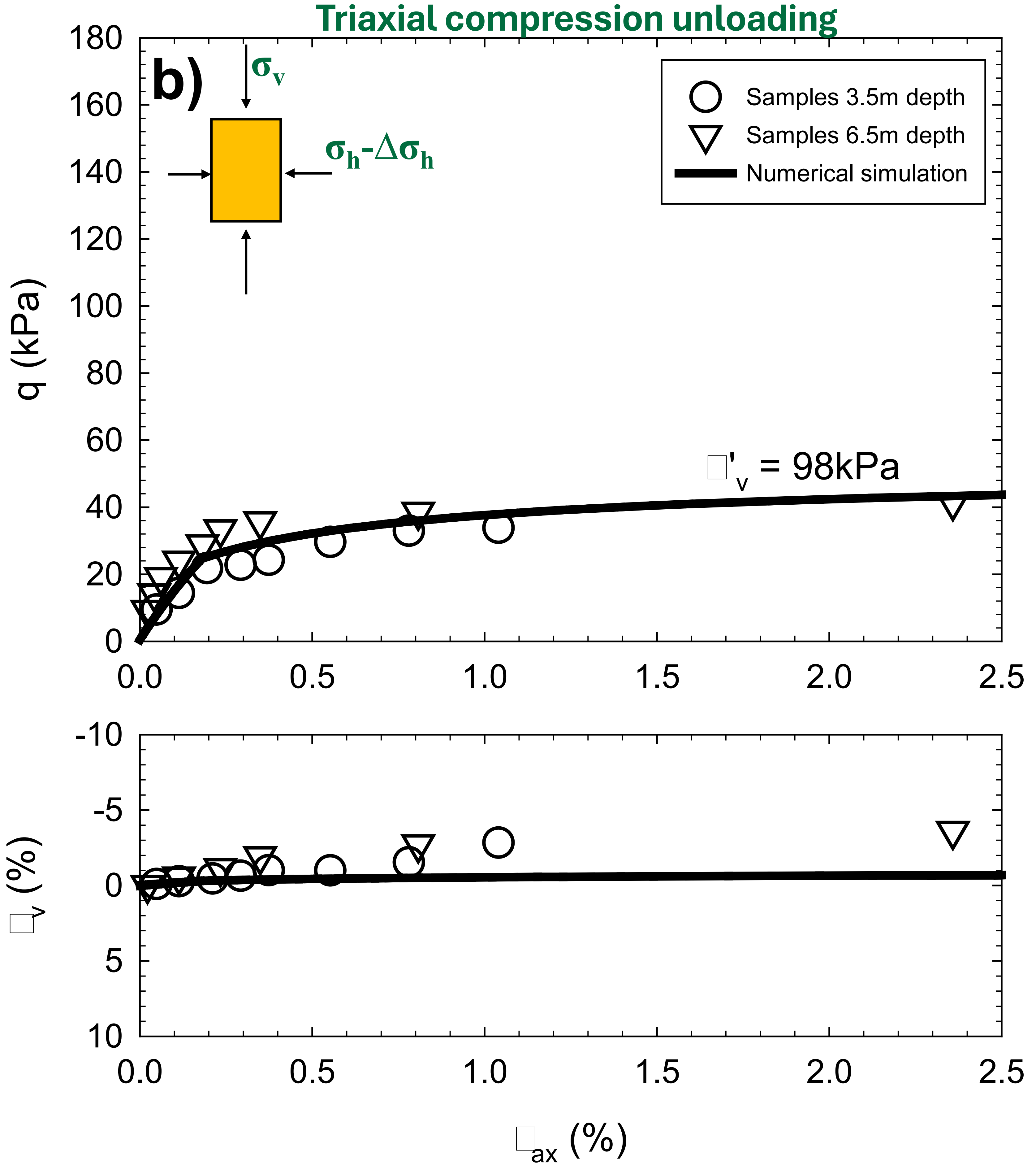
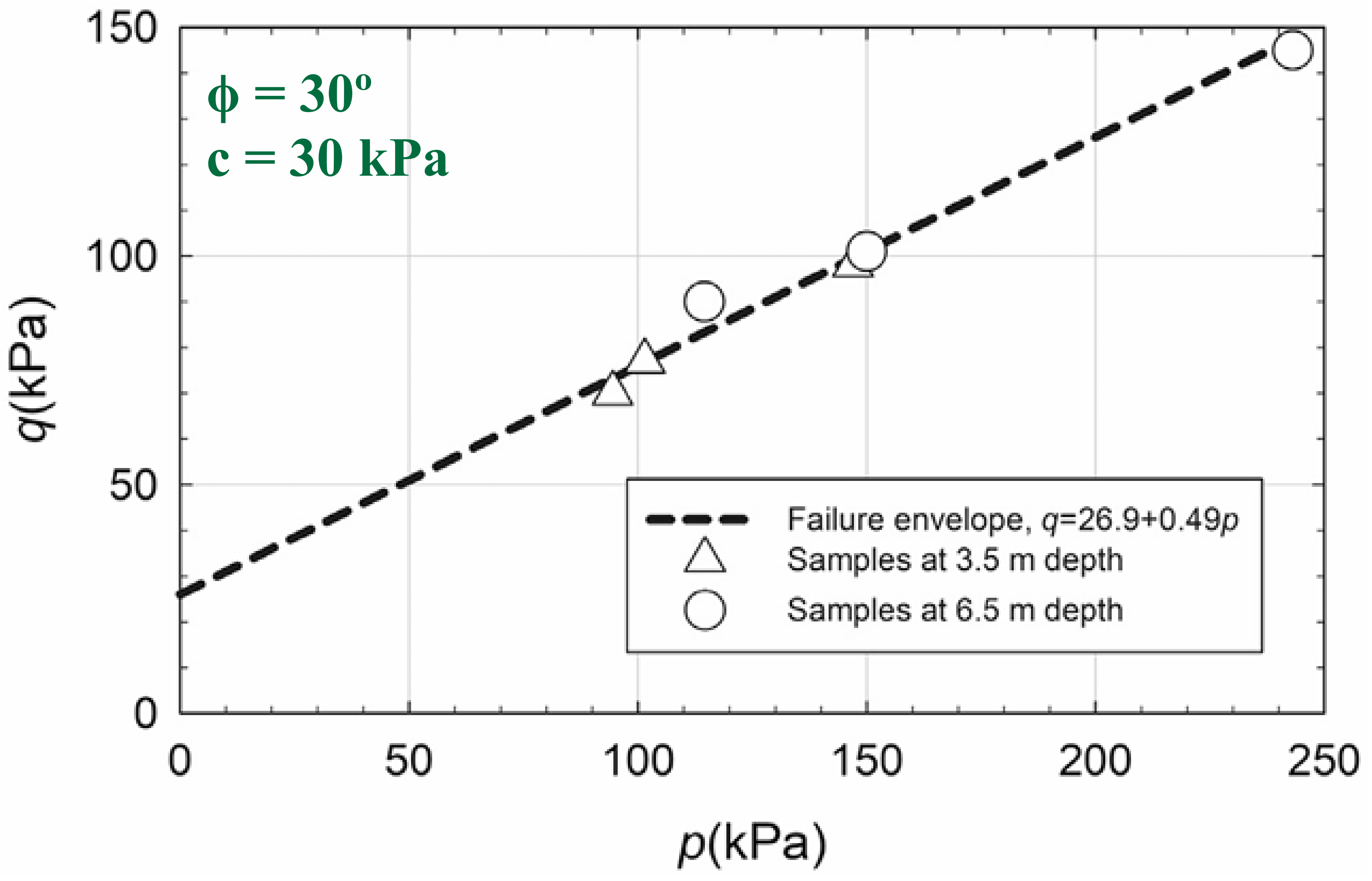
Constitutive model calibration to represent the residual porous clay

- Calibration based on high quality triaxial testing using internal instrumentation.
- Undisturbed block samples of residual porous clay were collected from 3.5 and 6.5 m depth
- *Only triaxial tests conducted at confining stresses less than or equal to the in-situ vertical effective stress were considered to preserve the natural soil structure, as higher confining stresses could have caused its collapse.*







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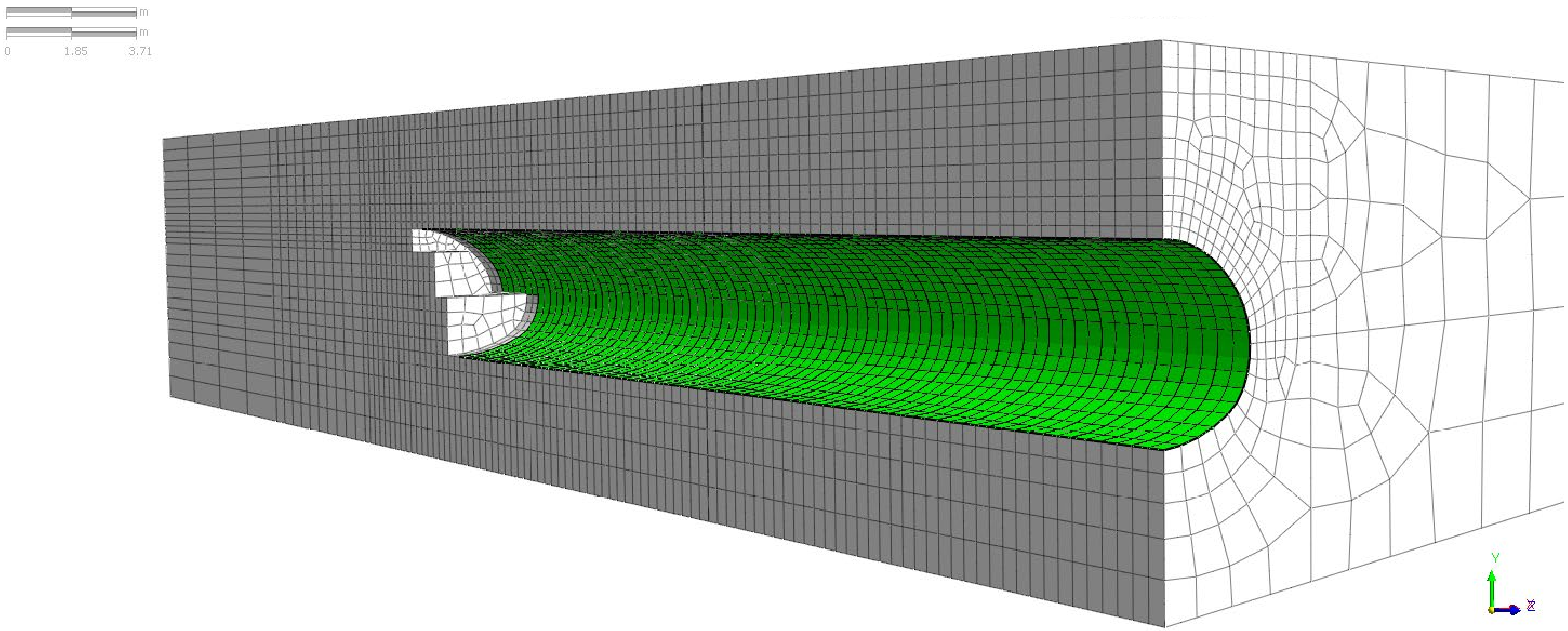
Three-dimensional NATM/SEM FEM model using Midas GTS NX

- Model dimensions, mesh refinement and second-order elements (i.e., quadratic interpolation) were adopted to ensure numerical accuracy.
- *Vitali, O. P. M.; Celestino, Bobet, A., 2018. 3D finite element modelling optimization for deep tunnels with material nonlinearity. Underground Space, 3(2), 125–139. https://doi.org/10.1016/j.undsp.2017.11.002*
- *Vitali, F.P.M., Vitali, O.P.M., Celestino, T.B., Bobet, A., 2024. FEM modeling requirements for accurate highly nonlinear shallow tunnels analysis. Soil and Rocks, 47(1), e2024000923. http://doi.org/10.28927/SR.2024.000923.*

Three-dimensional NATM/SEM FEM model using Midas GTS NX

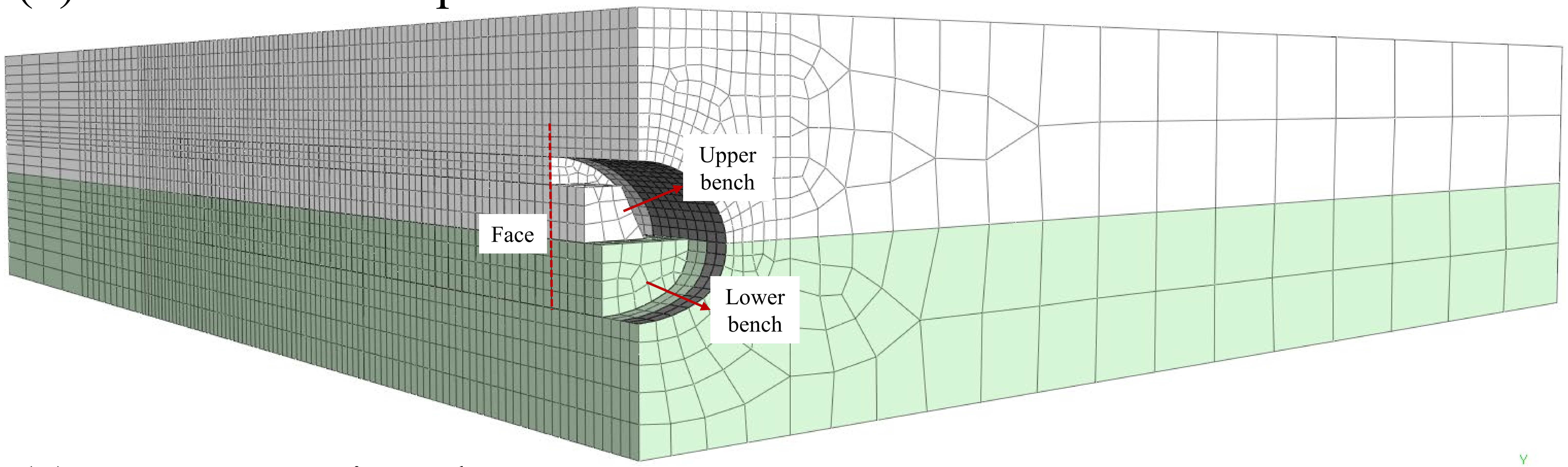
- Construction Sequence simulation:



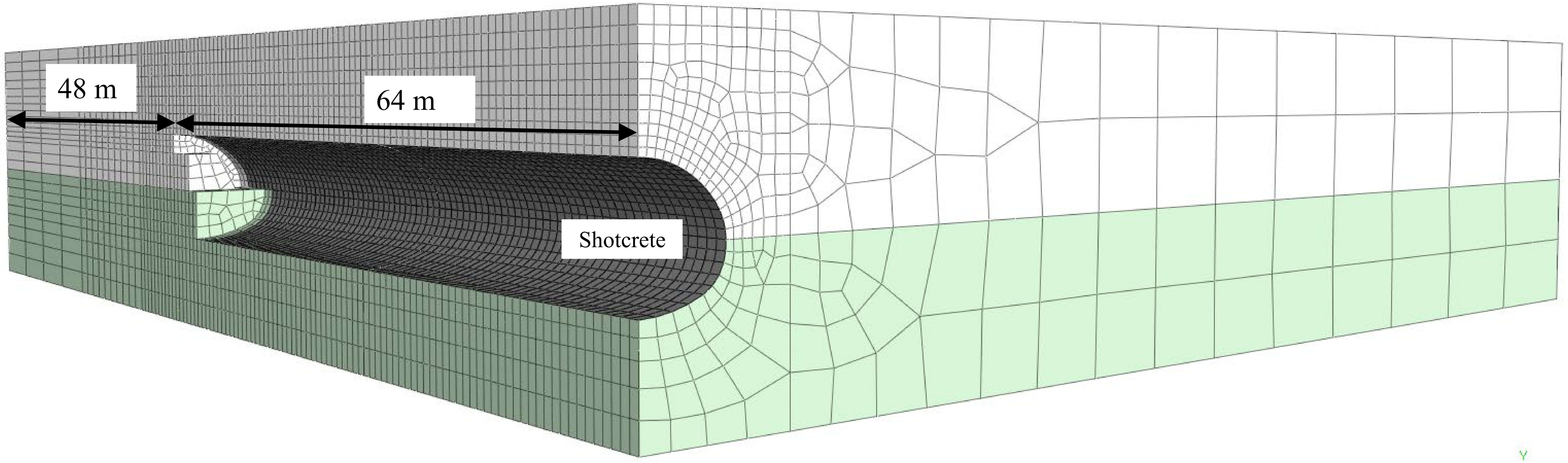
Three-dimensional NATM/SEM FEM model using Midas GTS NX

- Construction Sequence simulation – 37 excavation phases:

(b) First excavation phase



(c) Last excavation phase



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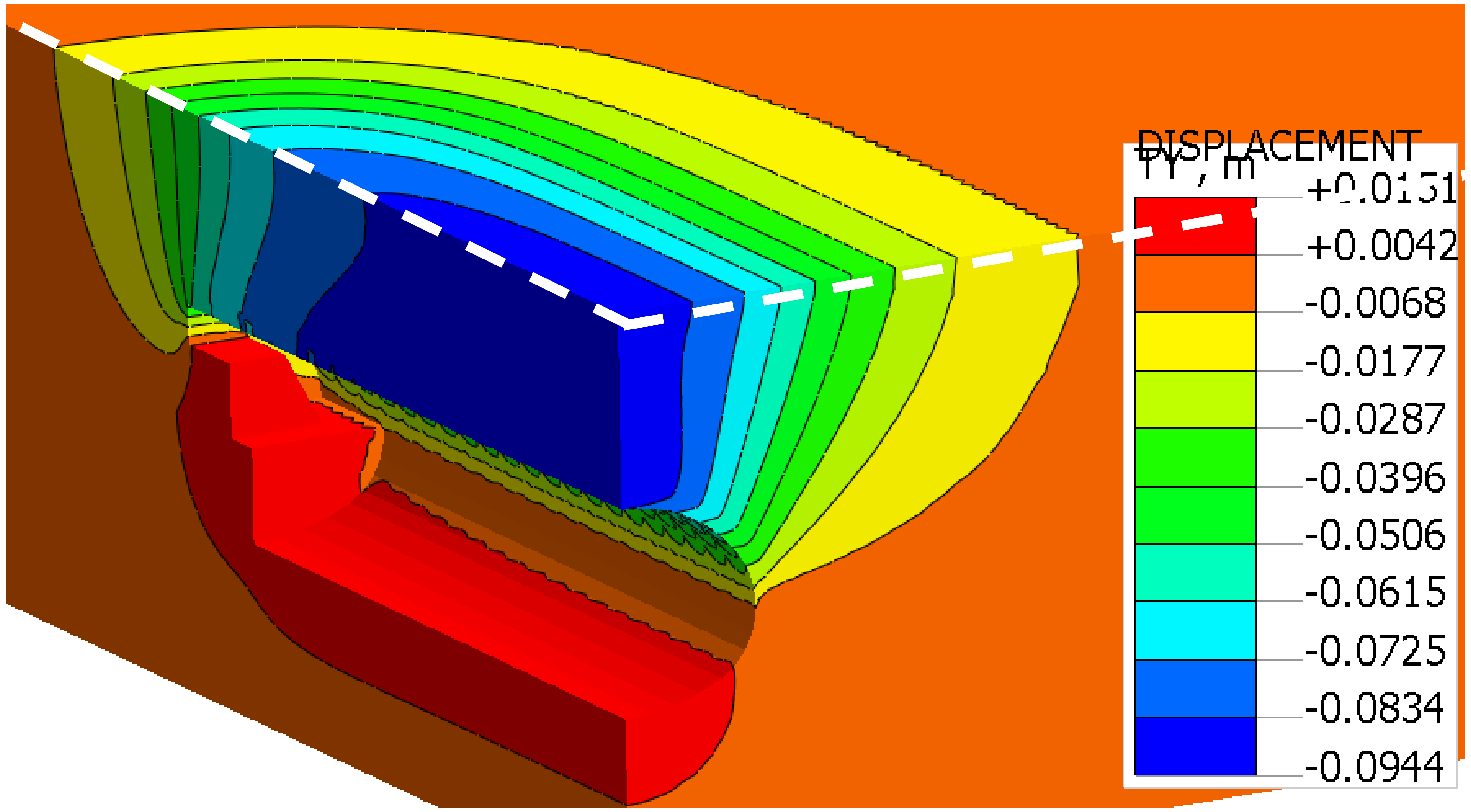
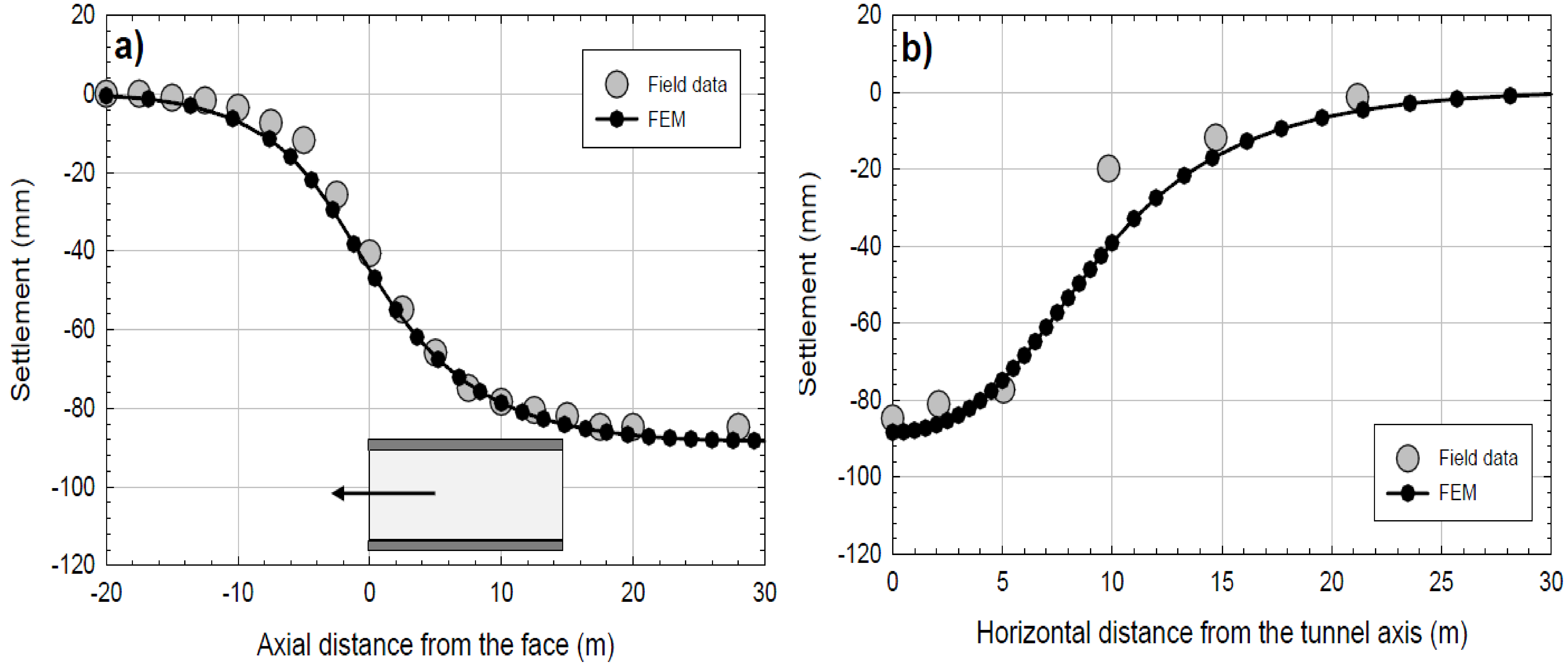
Numerical results vs. field data (numerical model validation)





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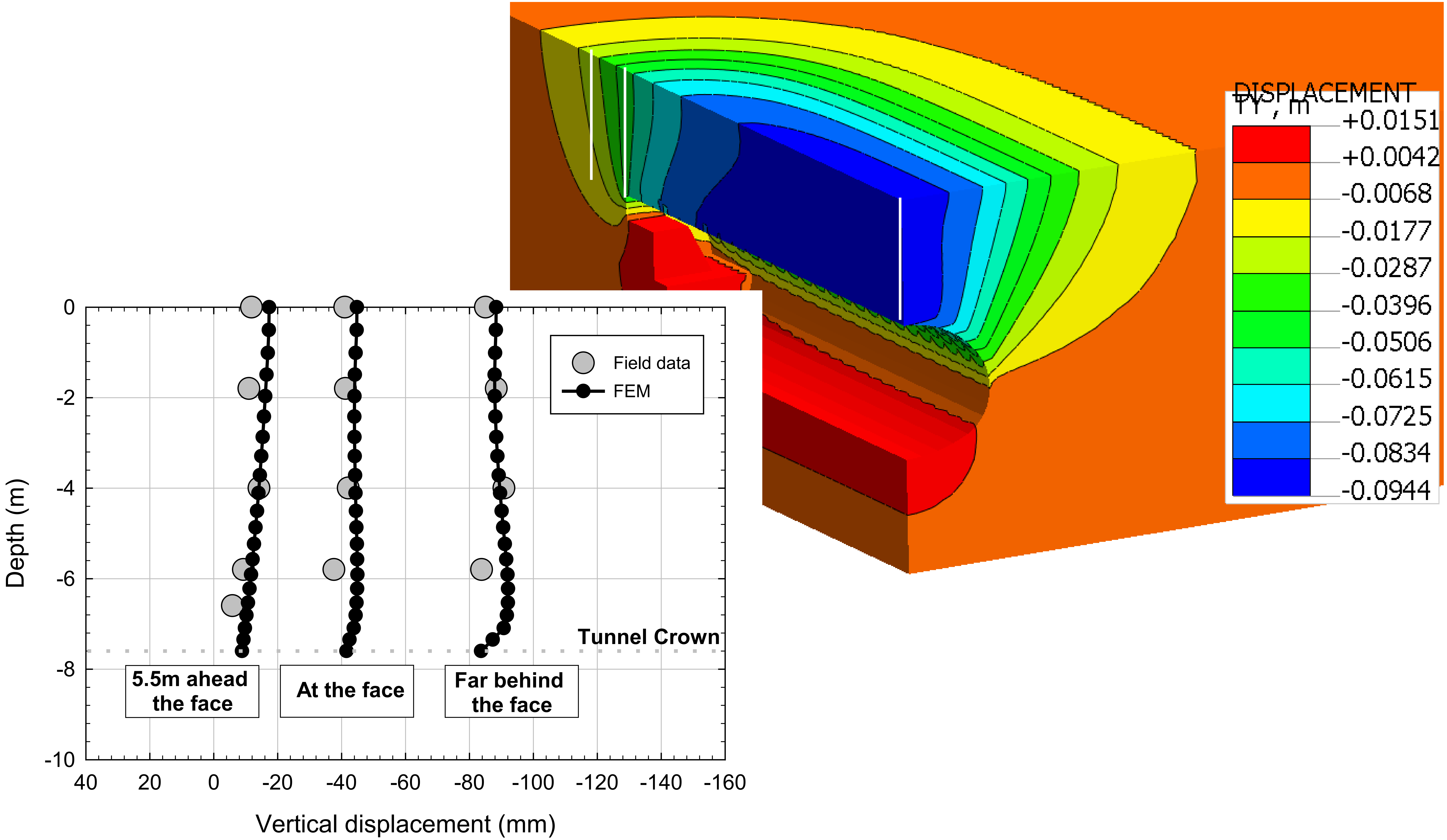

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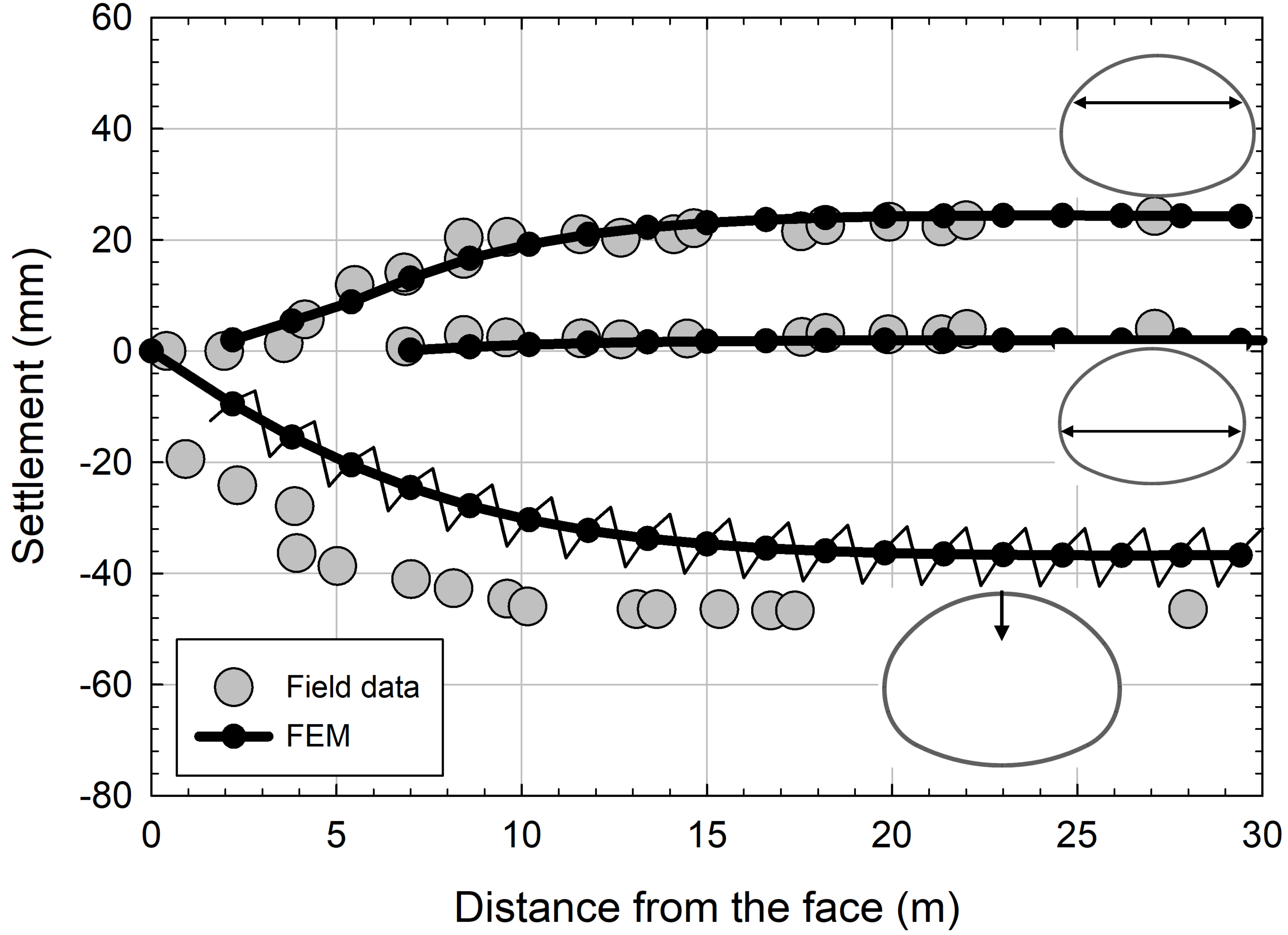

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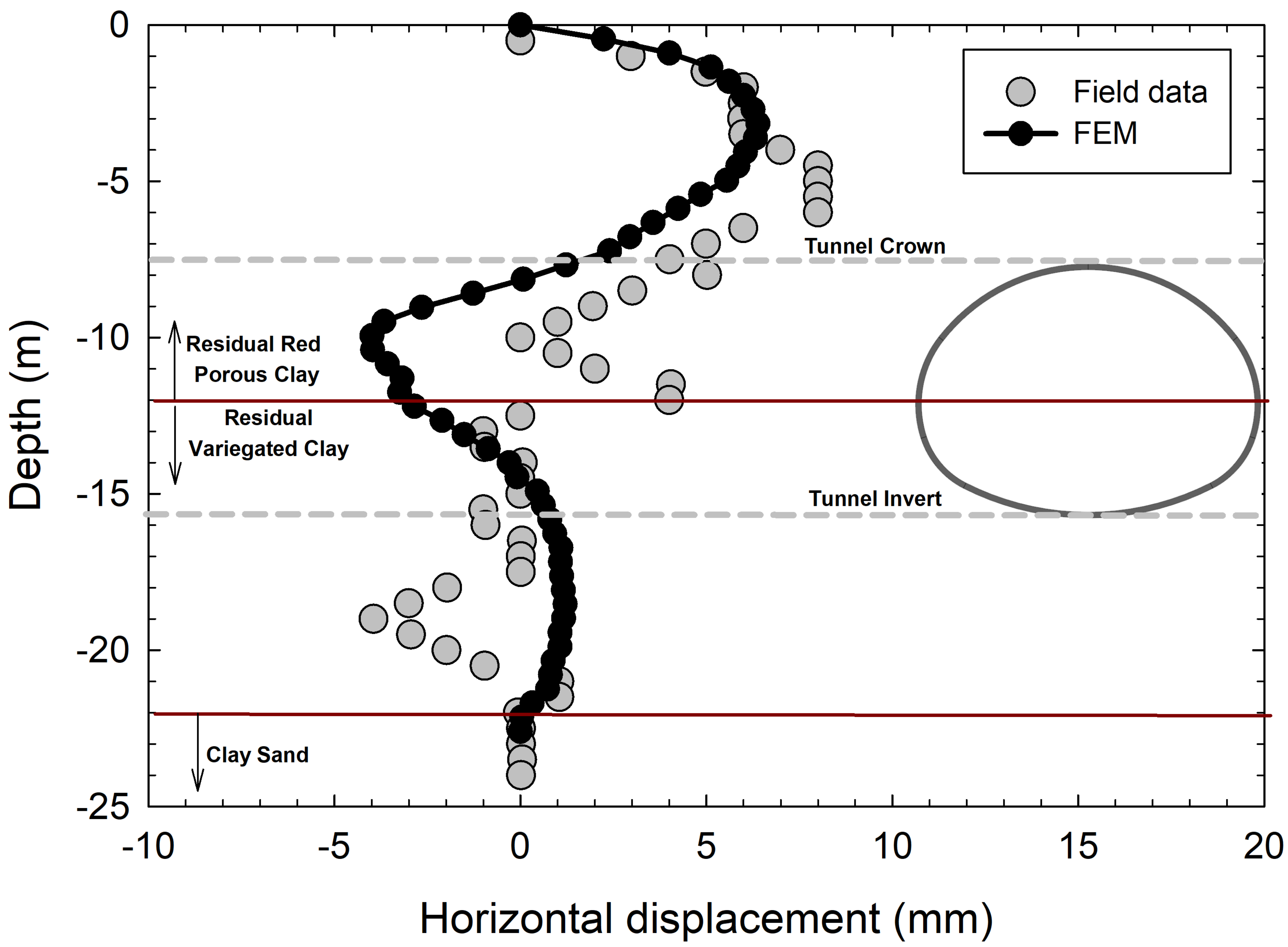
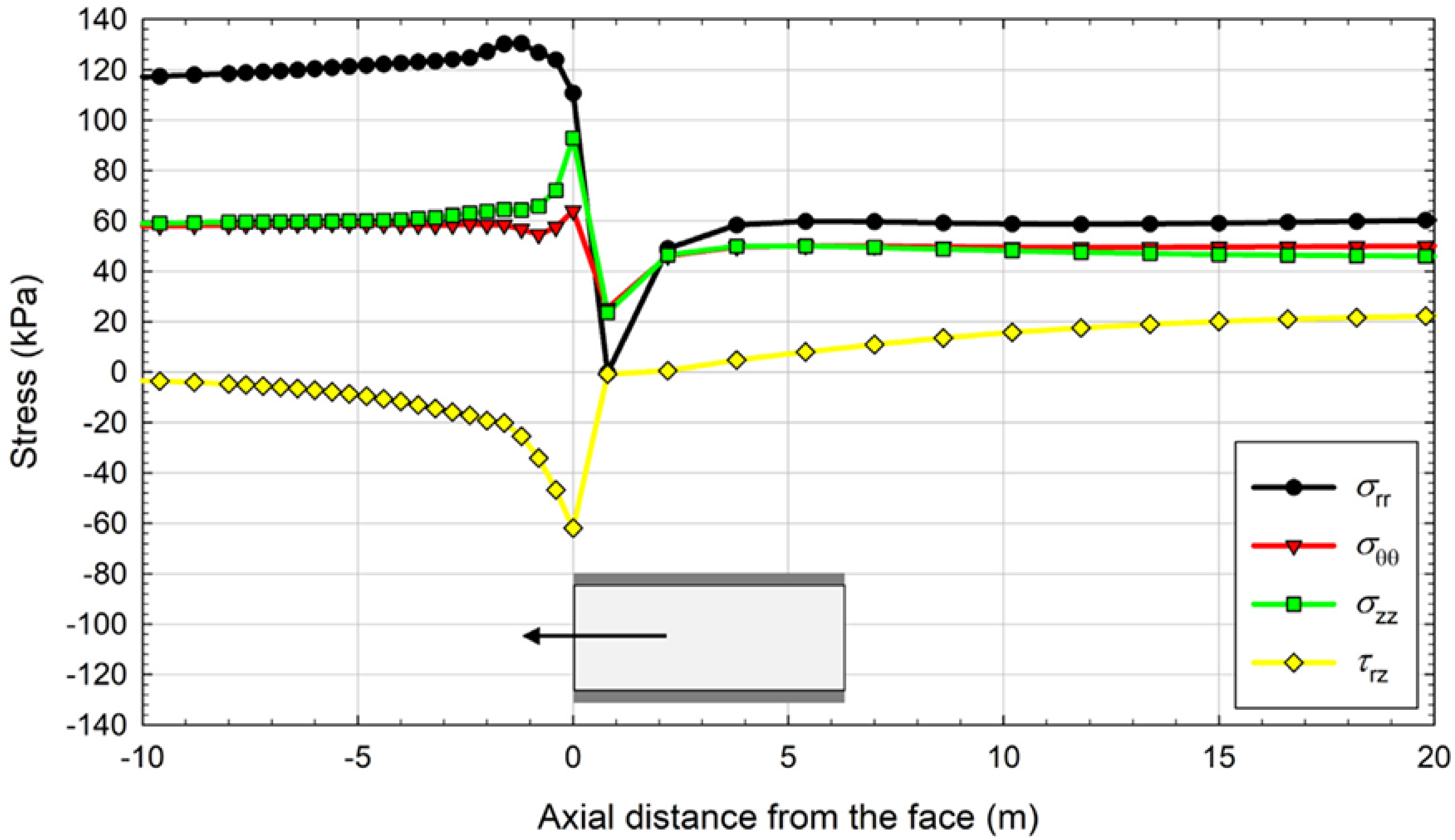


Numerical results vs. field data (numerical model validation)

- Stresses at the tunnel crown: Importance of 3D FEM modeling for NATM/SEM tunnels.



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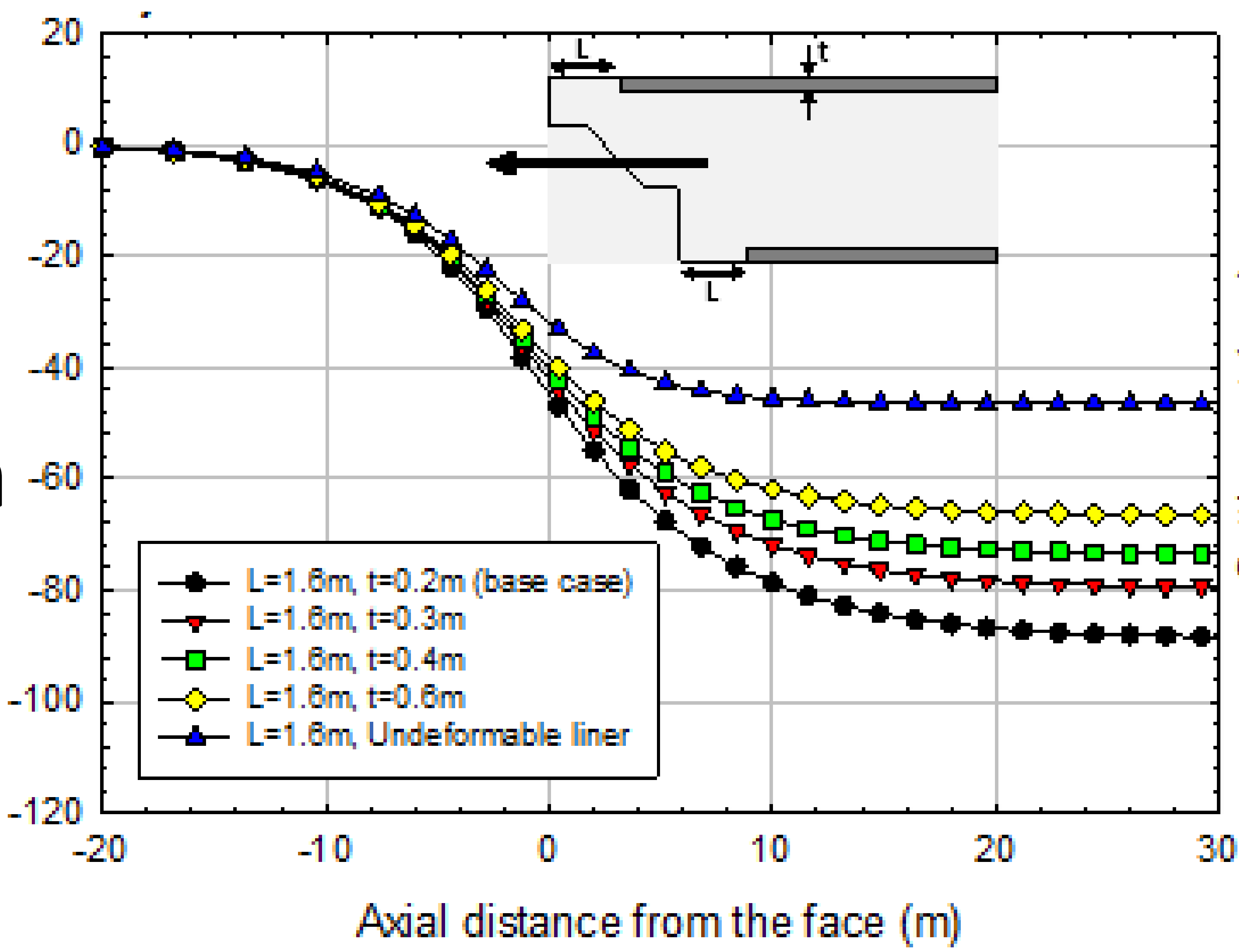
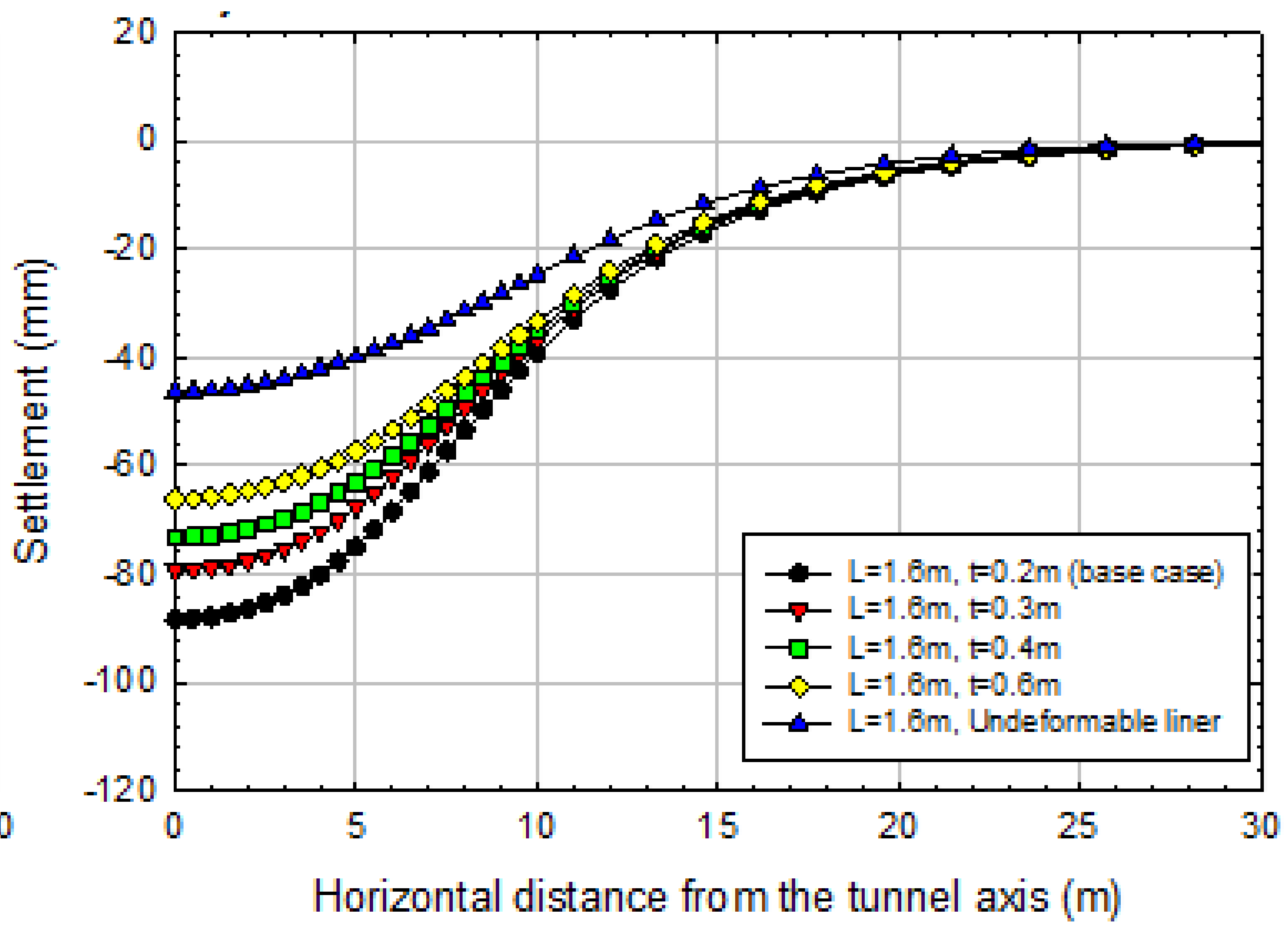
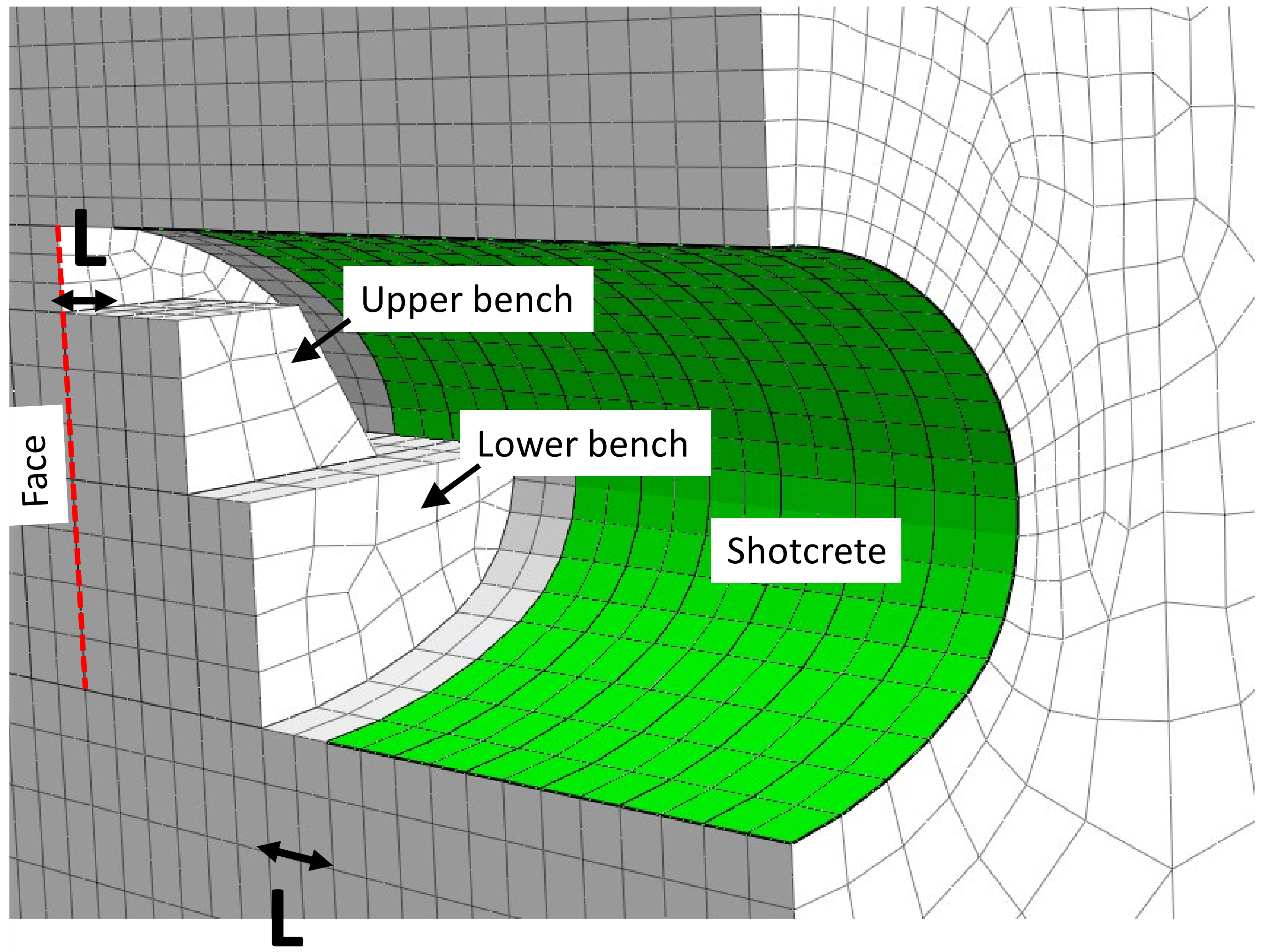
Numerical investigation: Influence of the unsupported span length and lining stiffness

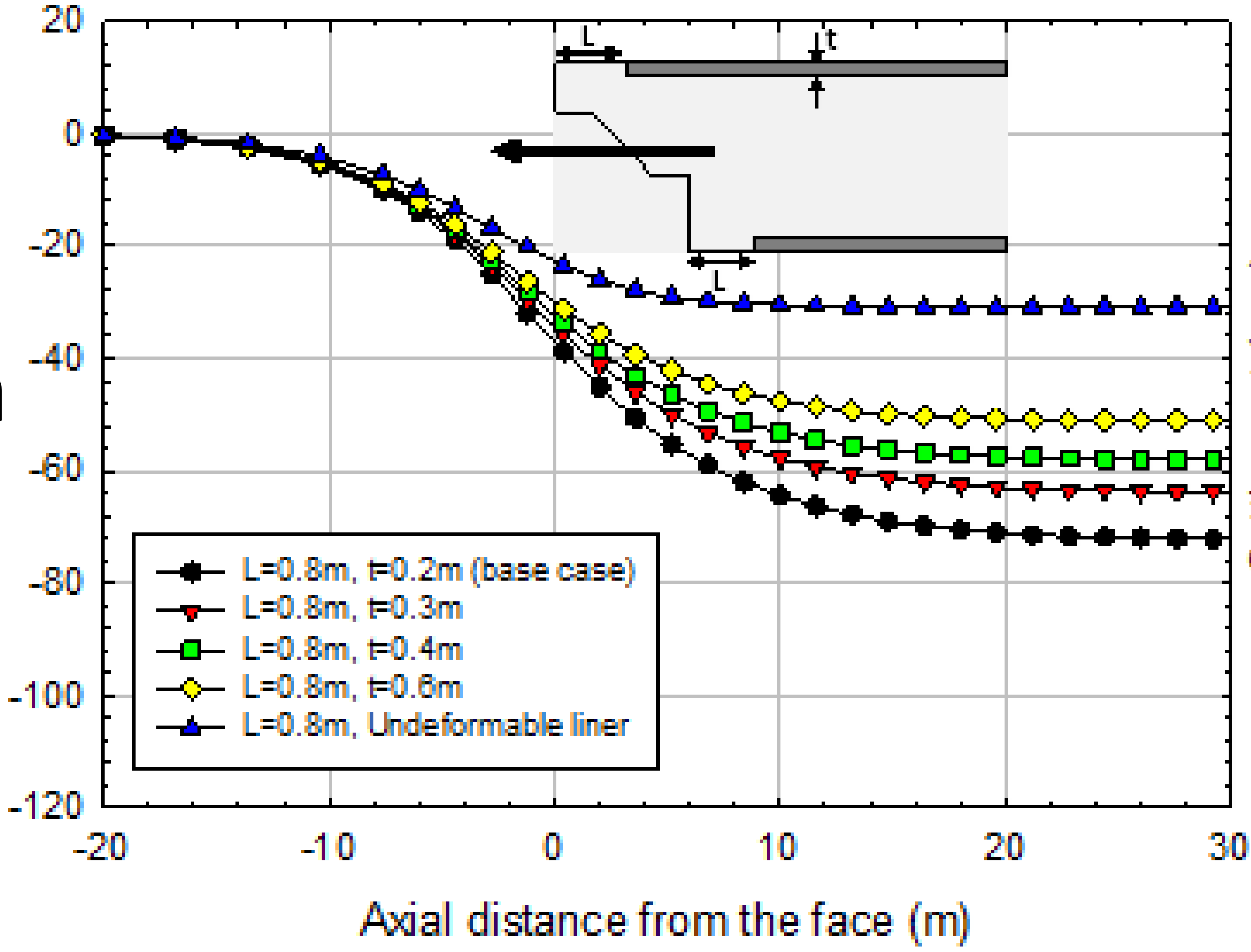
L=1.6m

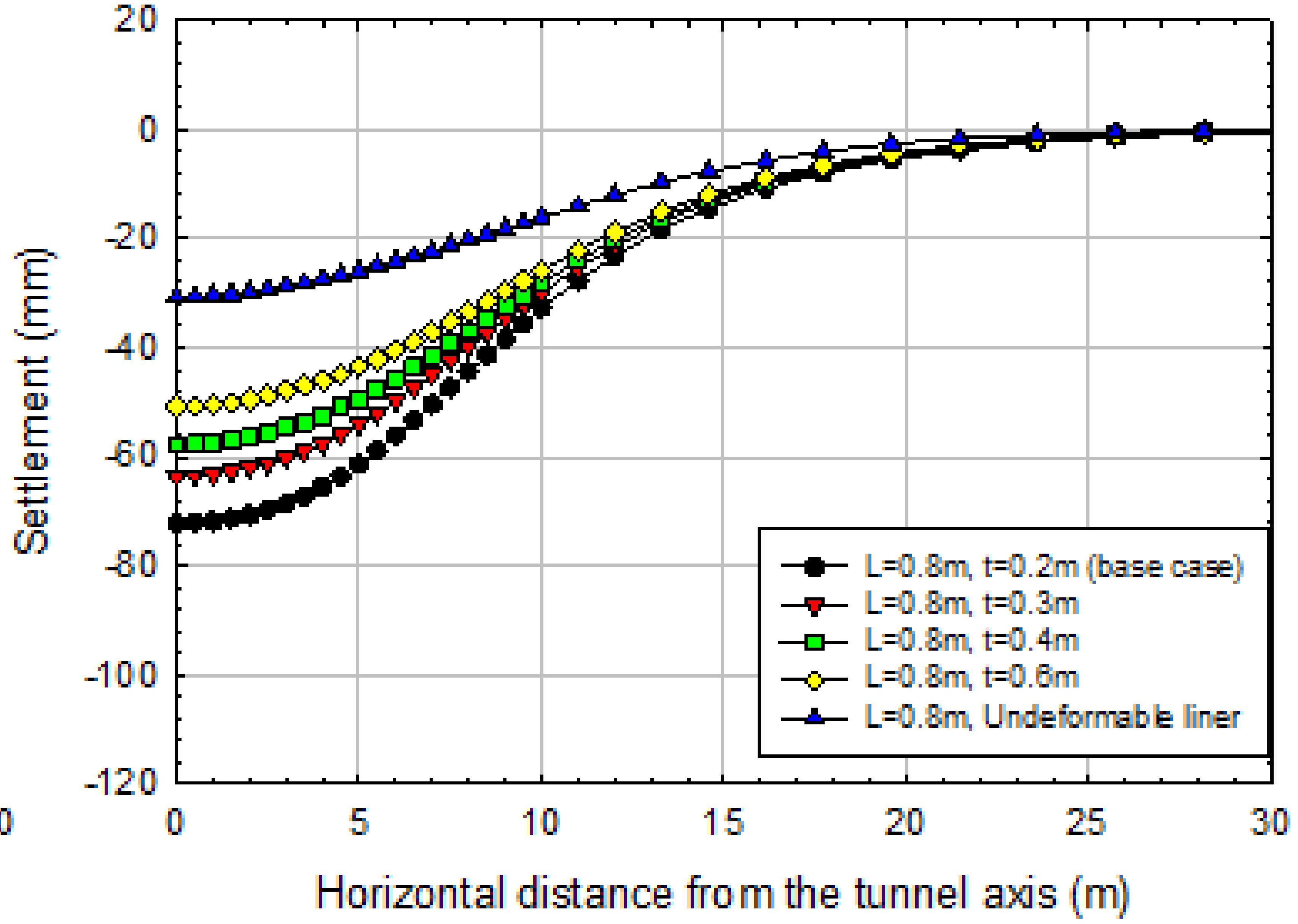




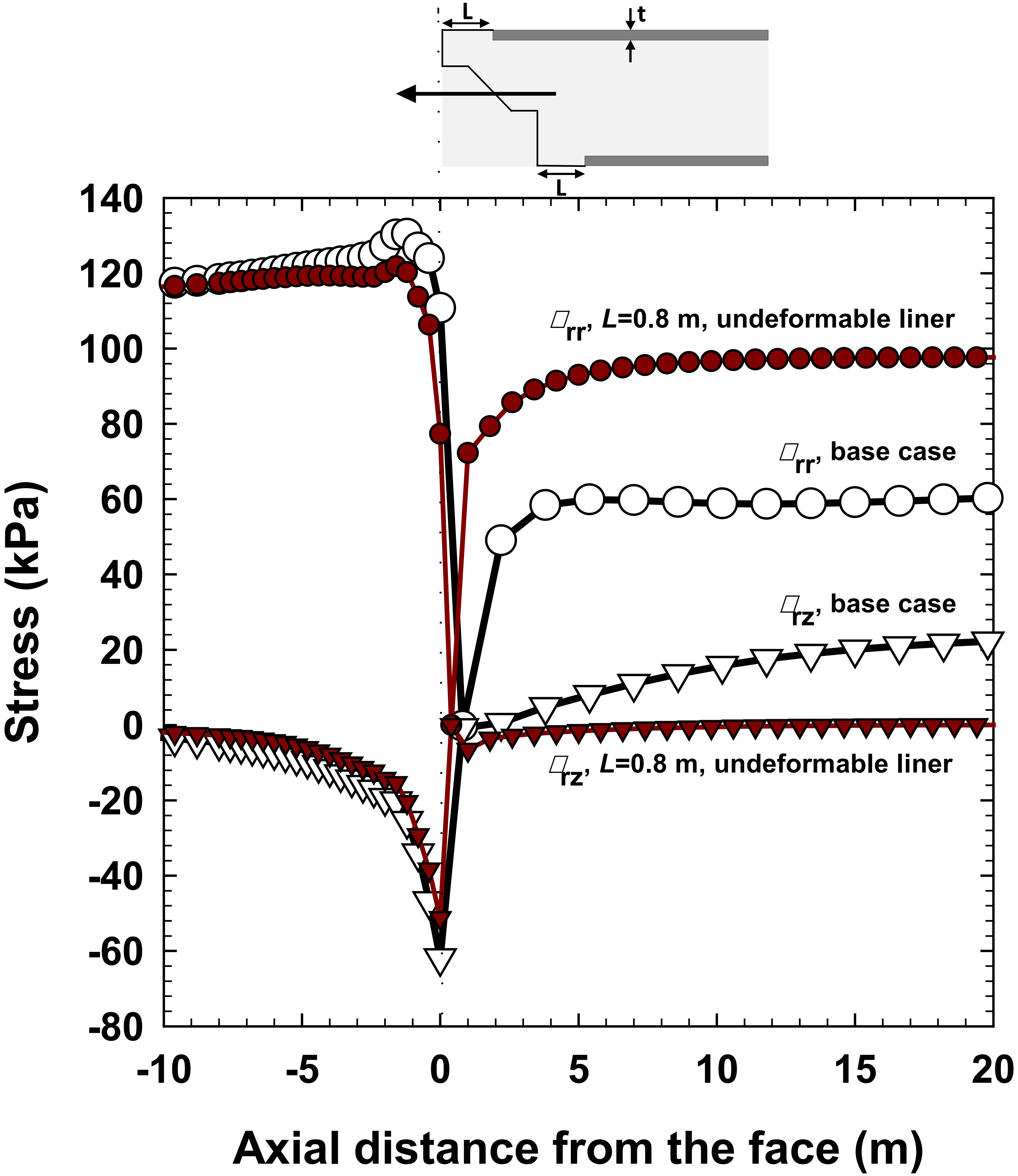


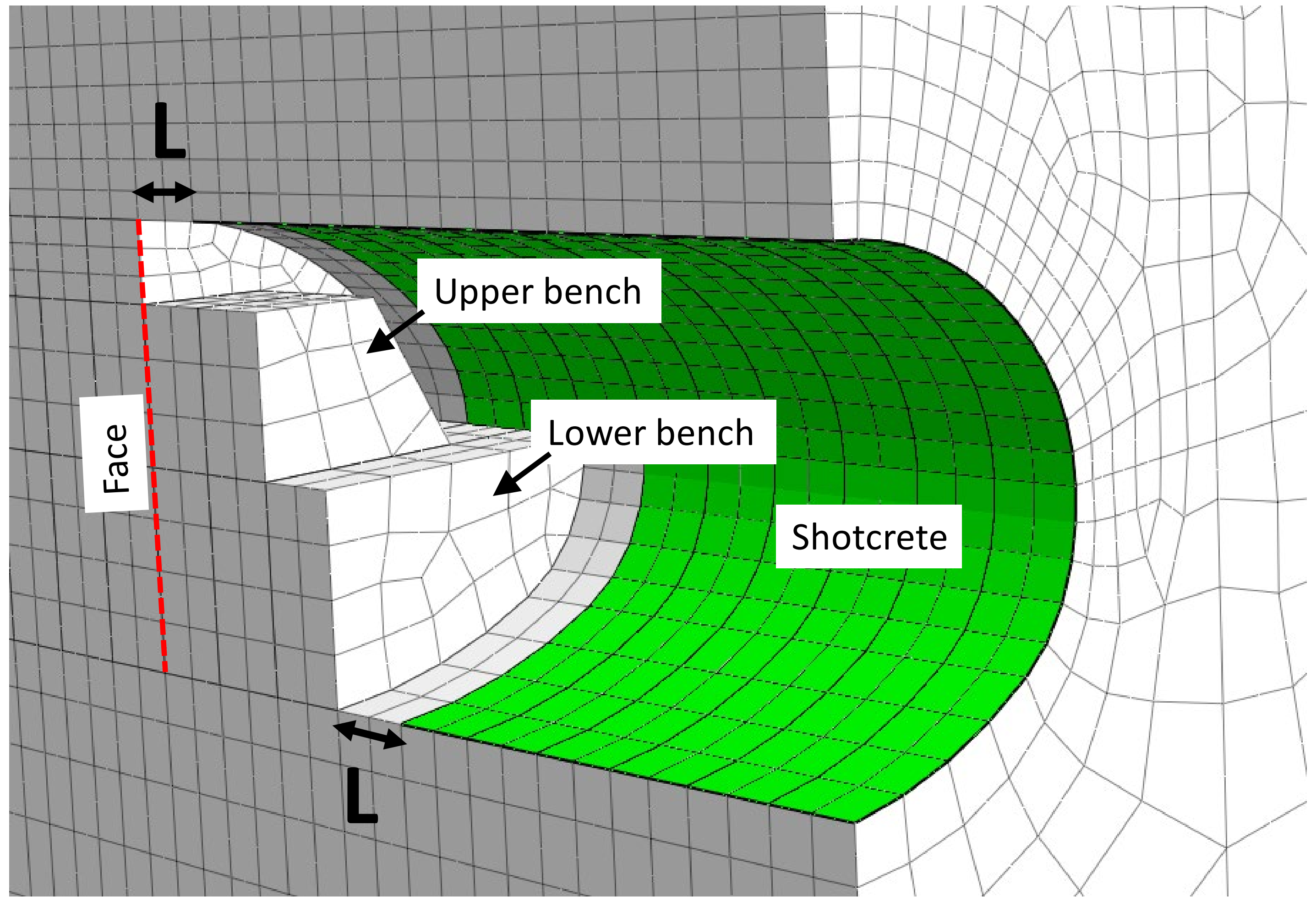
L=0.8m





Numerical investigation: Influence of the unsupported span length and lining stiffness





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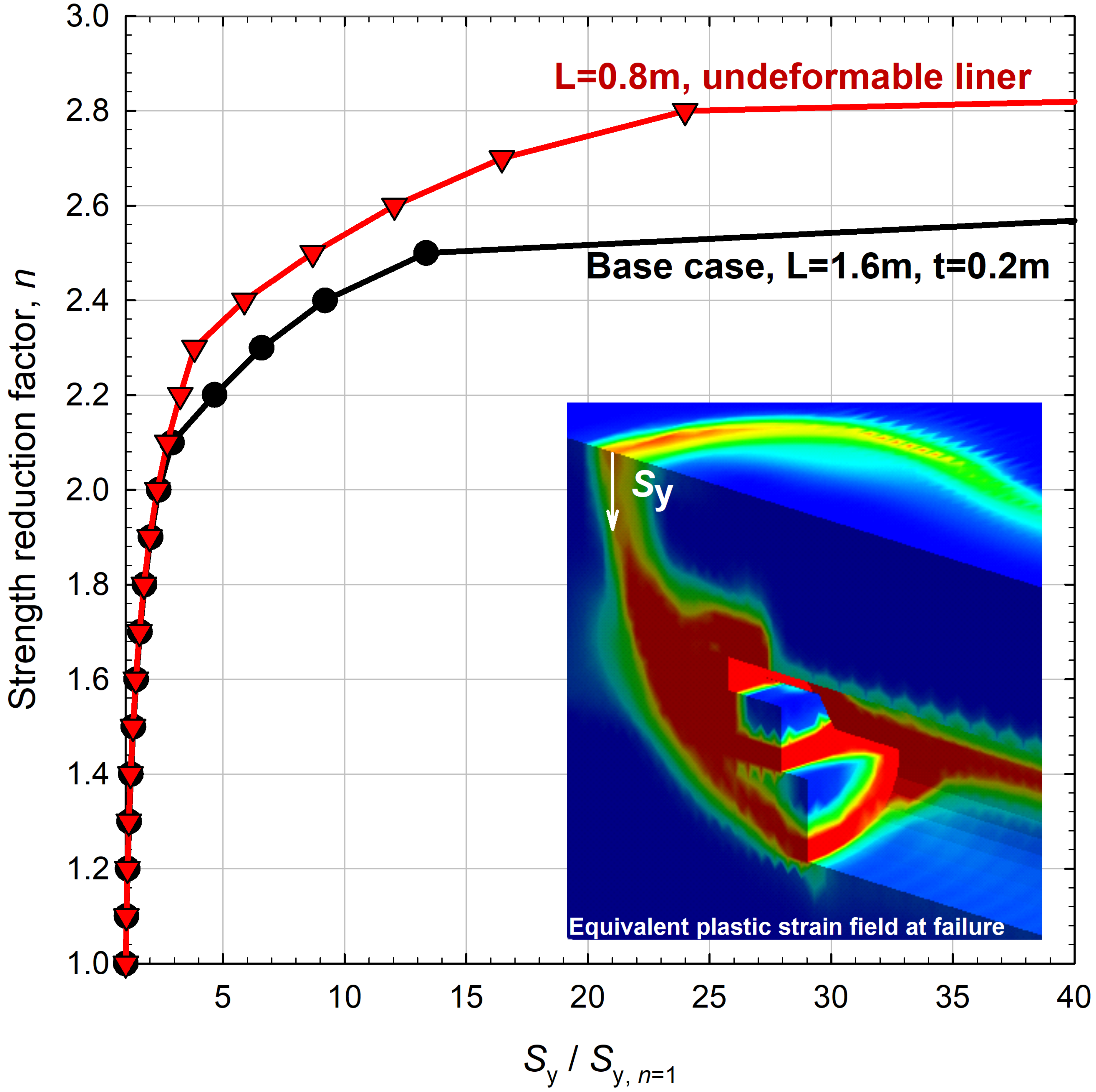

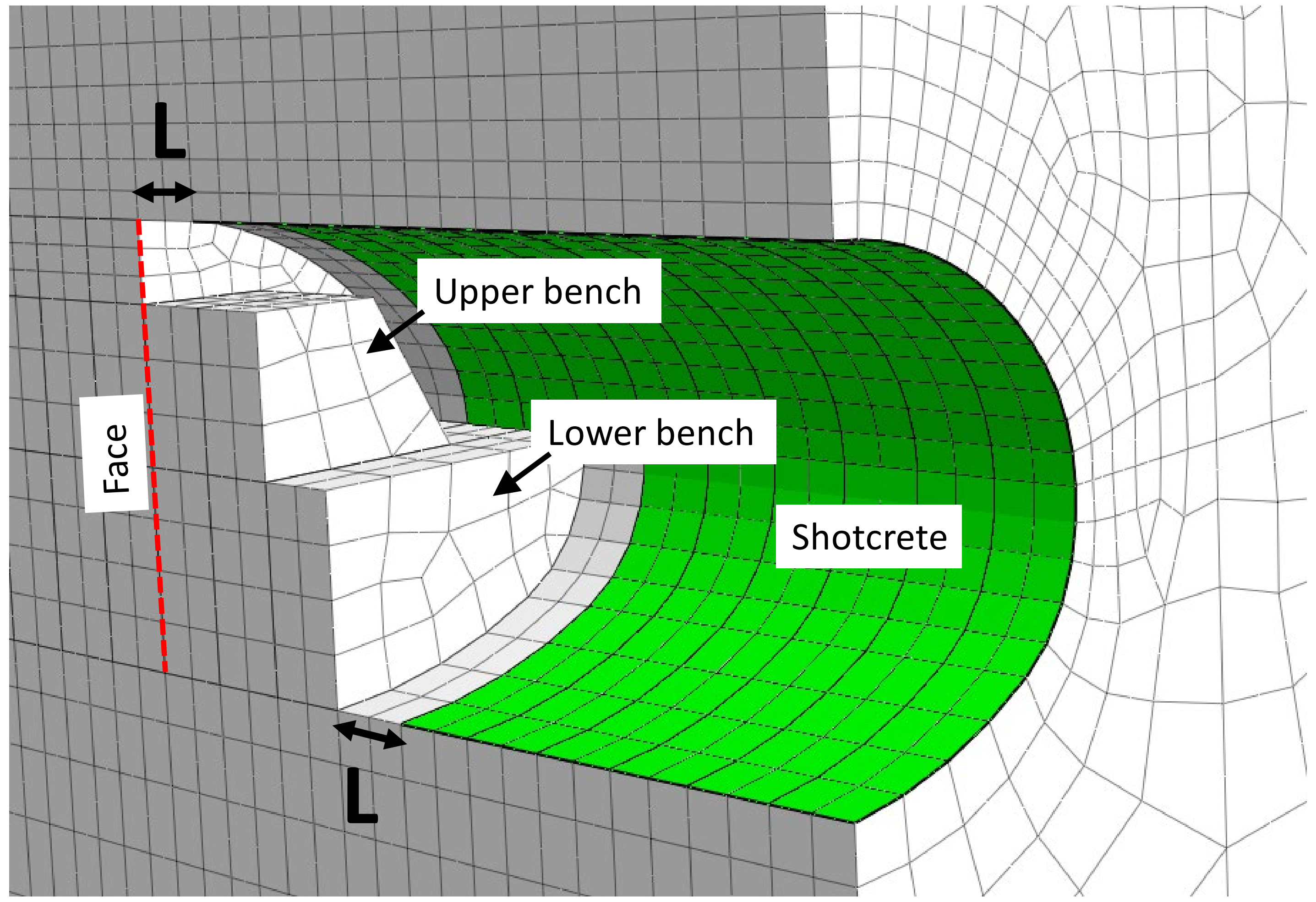

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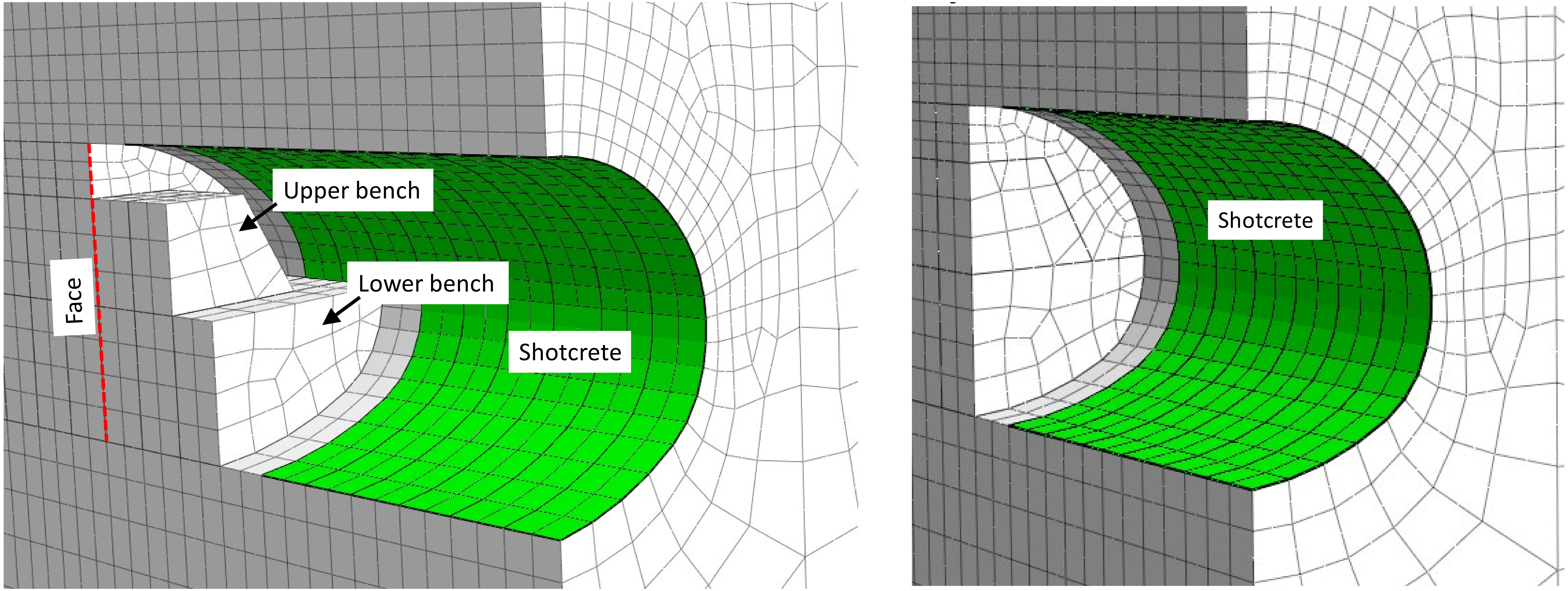
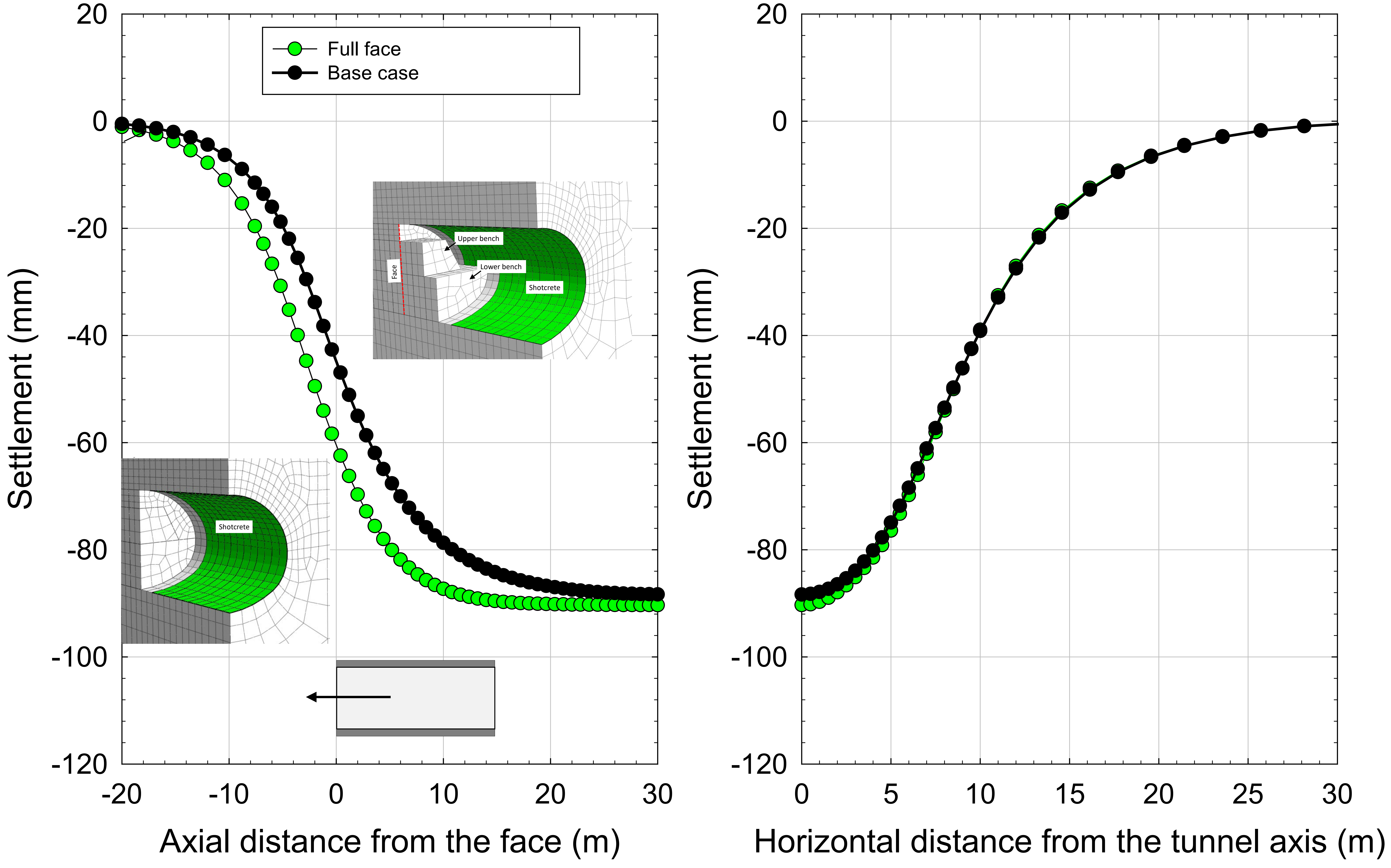
Numerical investigation: Influence of the partial-excavation sequence using benches



Numerical investigation: Influence of the partial-excavation sequence using benches



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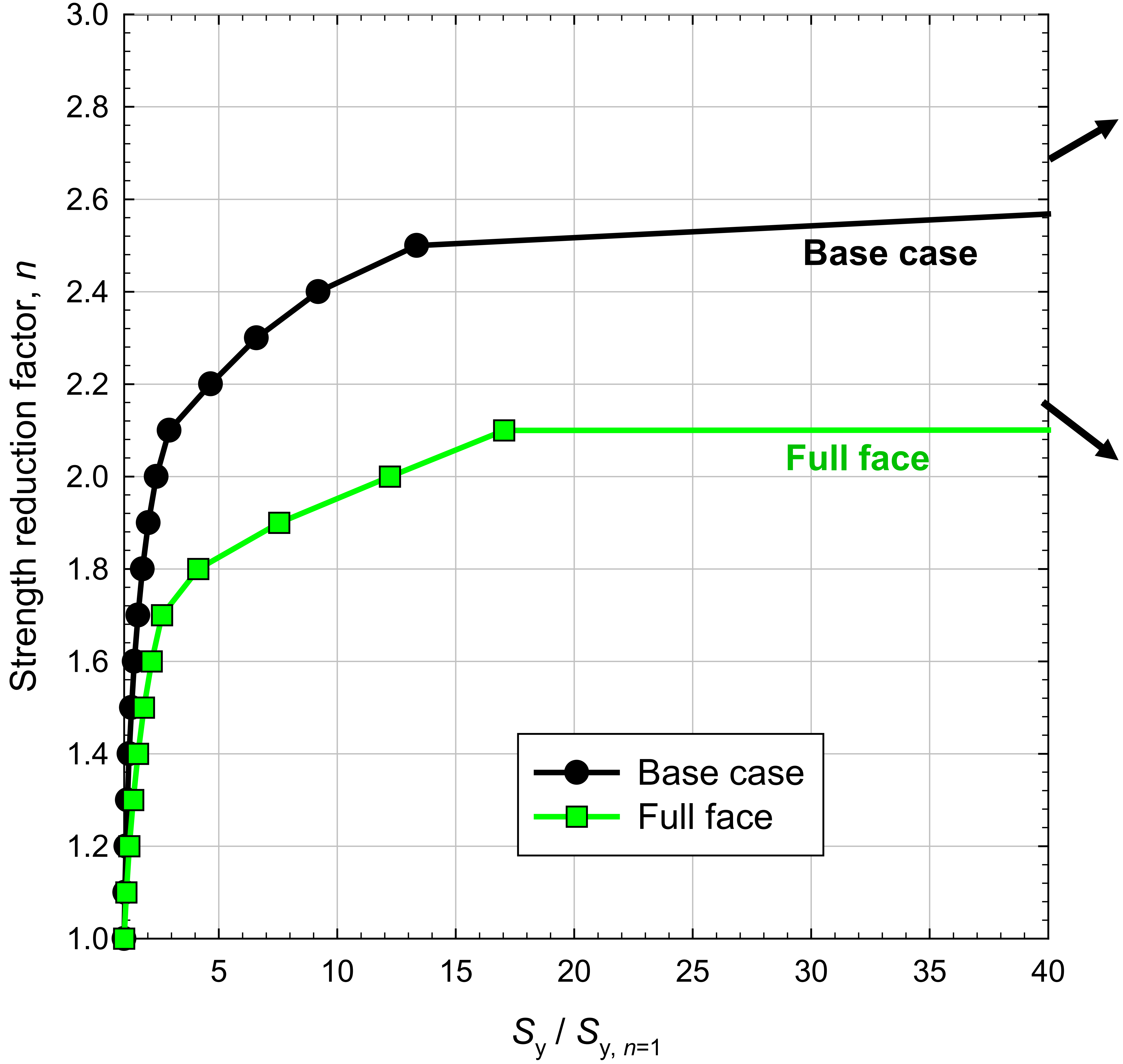

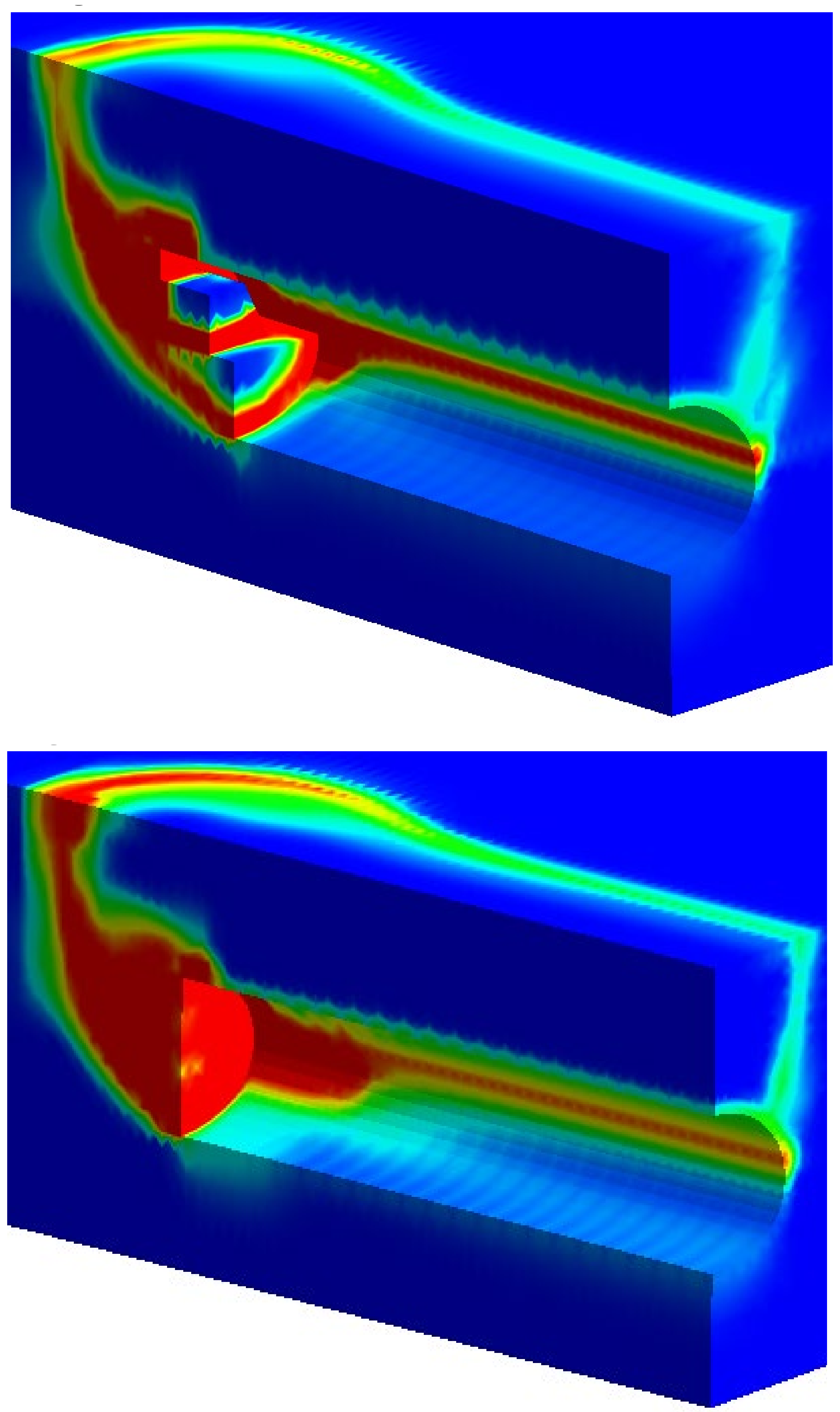

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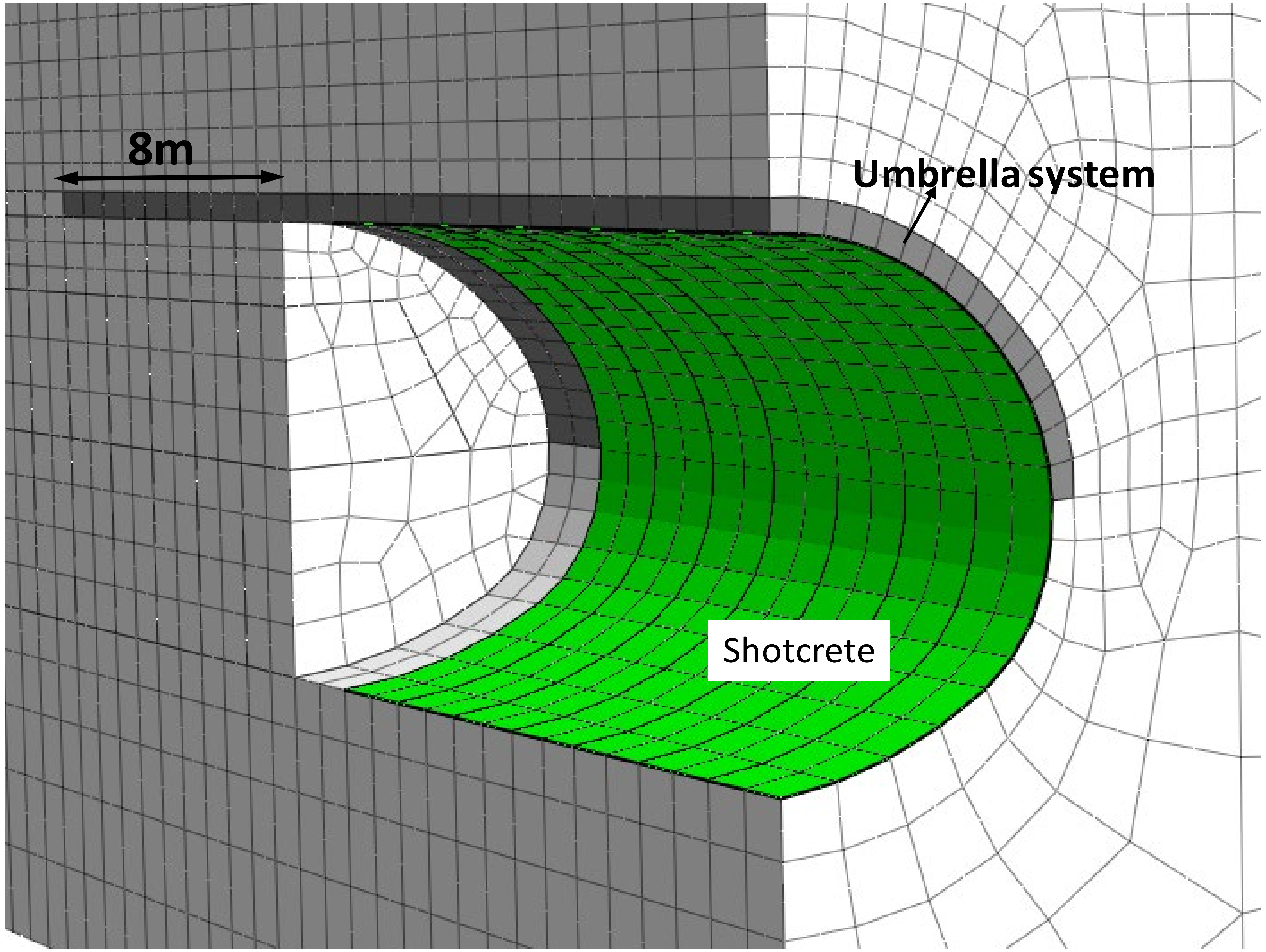
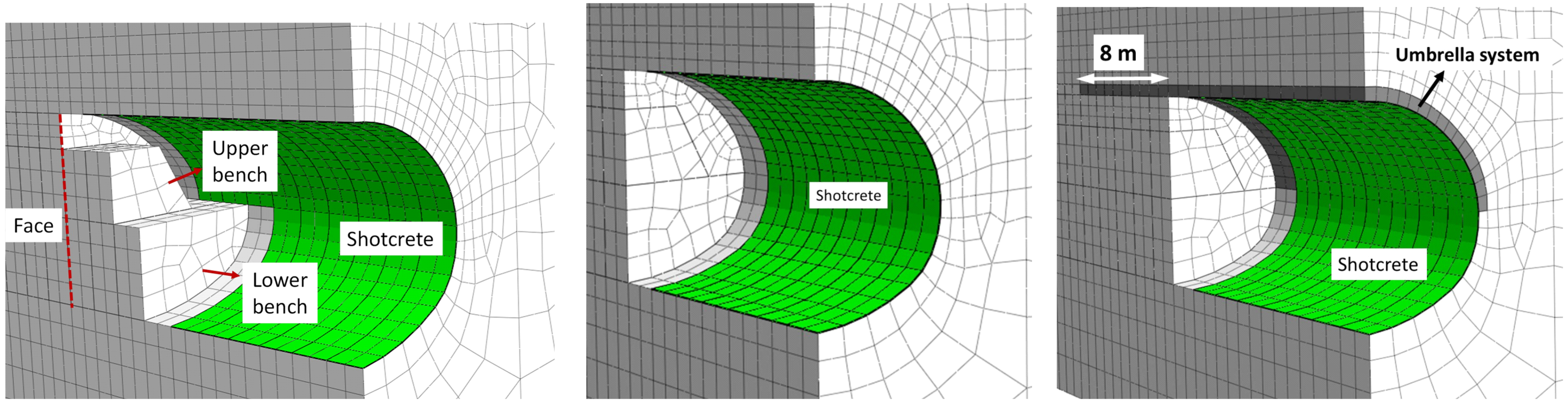
Numerical investigation: Influence of the pre-support umbrella system

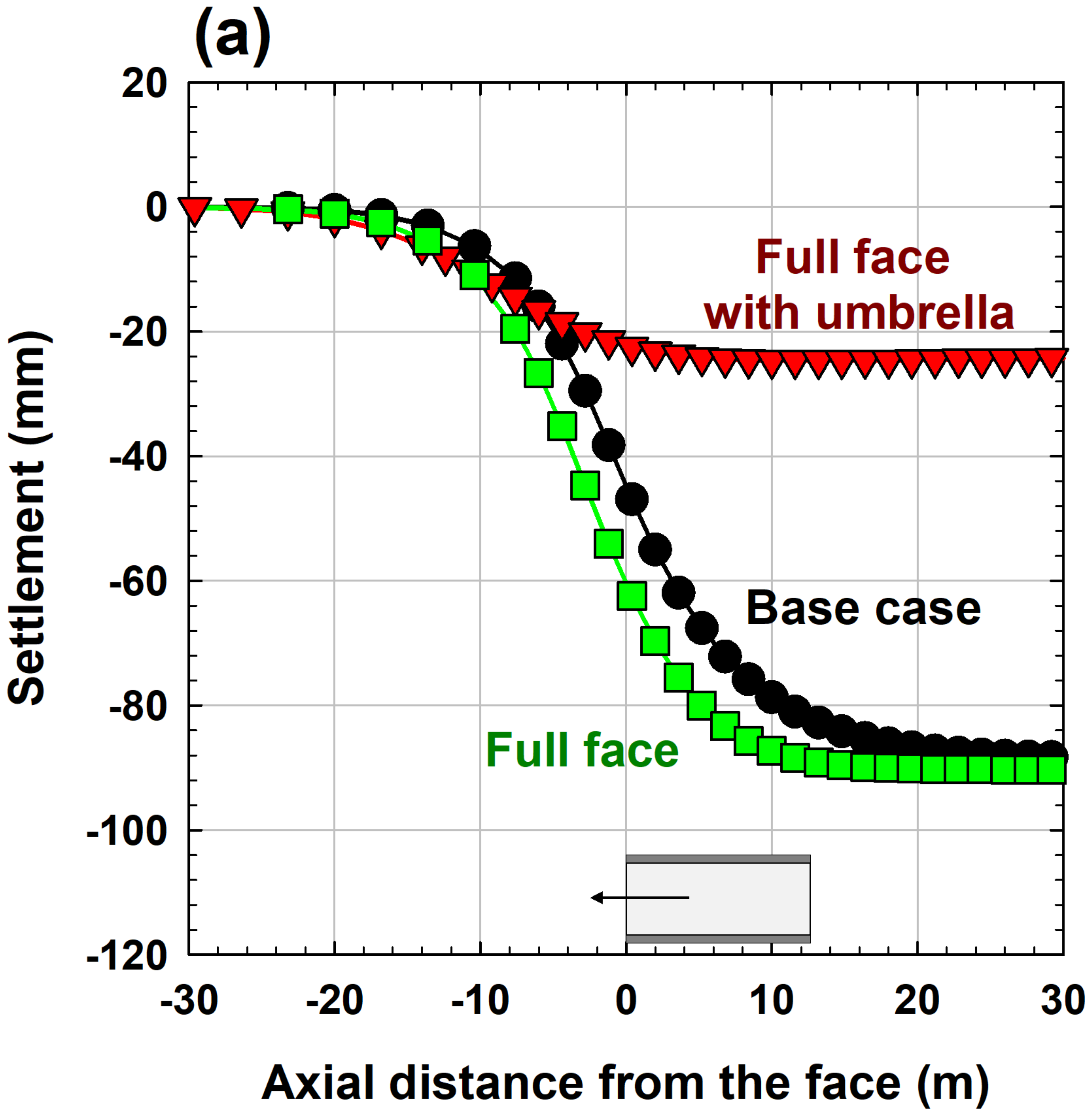
- Pre-support umbrella system properties: E = 1 GPa; v = 0.2, c = 700 kPa.
- These parameters correspond to continuous reinforcement along the tunnel perimeter using grouted steel tubes with an outer diameter of 113 mm and a wall thickness of 6.3 mm.

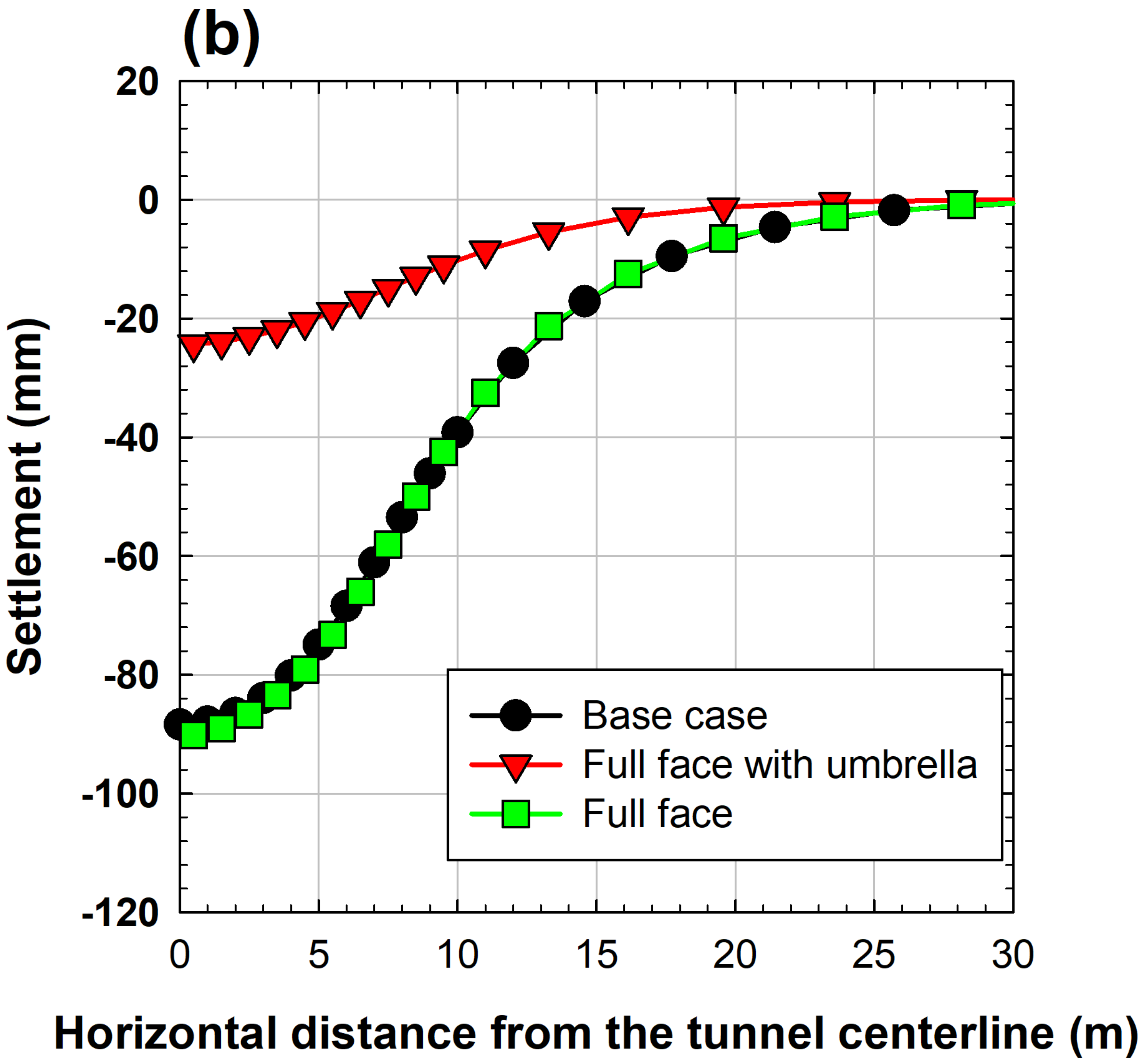


Numerical investigation: Influence of the pre-support umbrella system

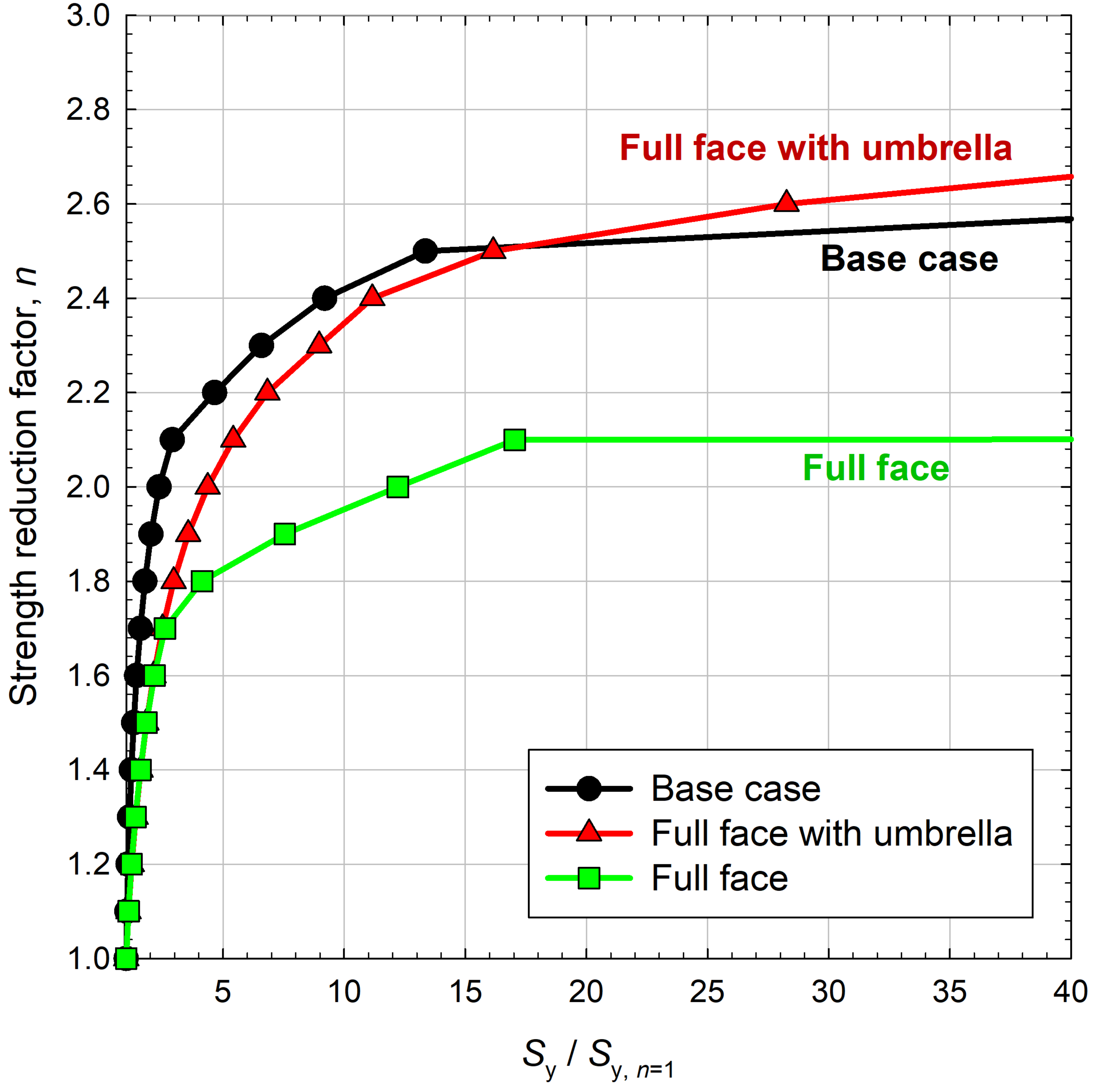
Base case | Full face | Full face with umbrella system

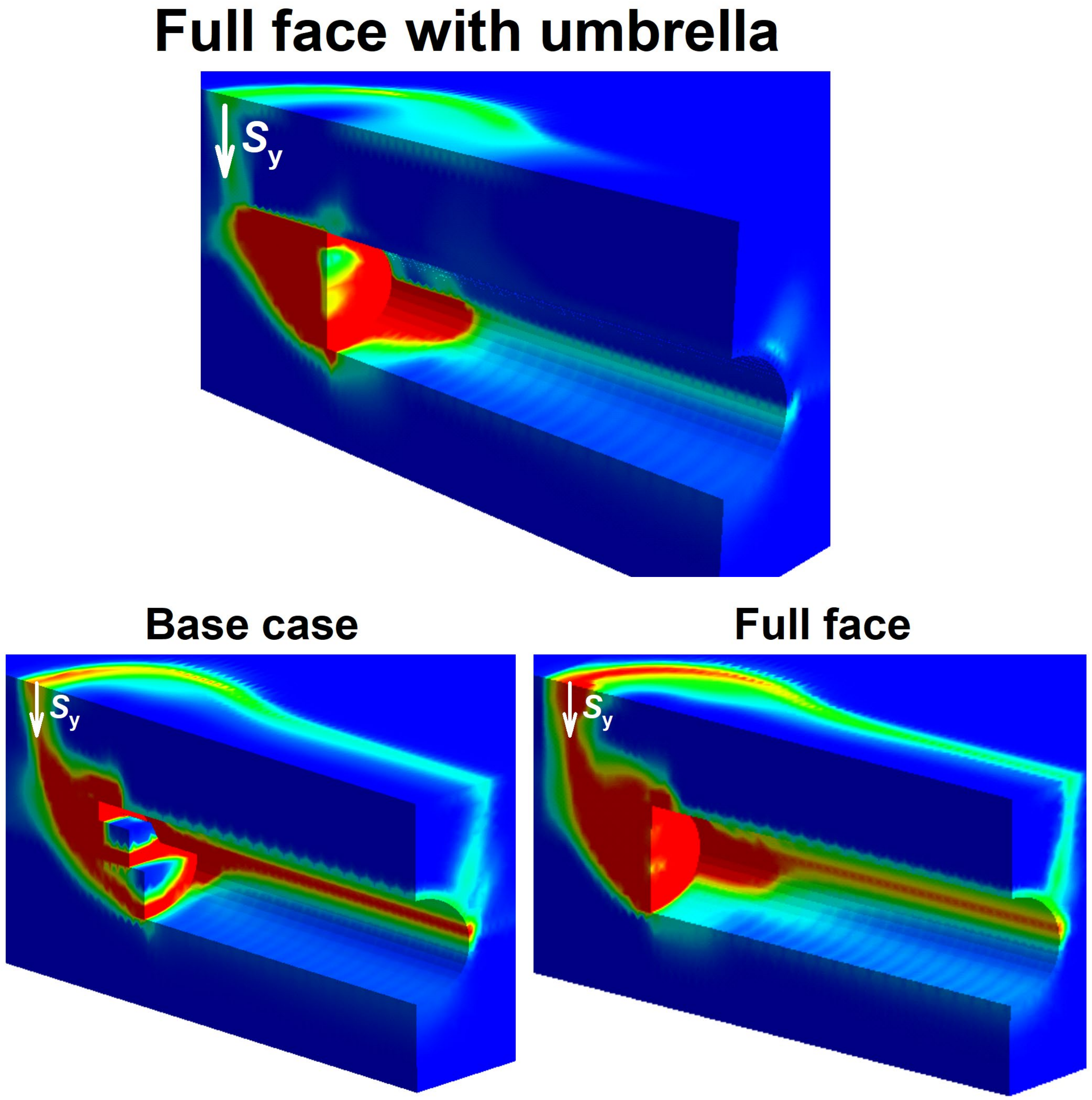






Numerical investigation: Influence of the pre-support umbrella system

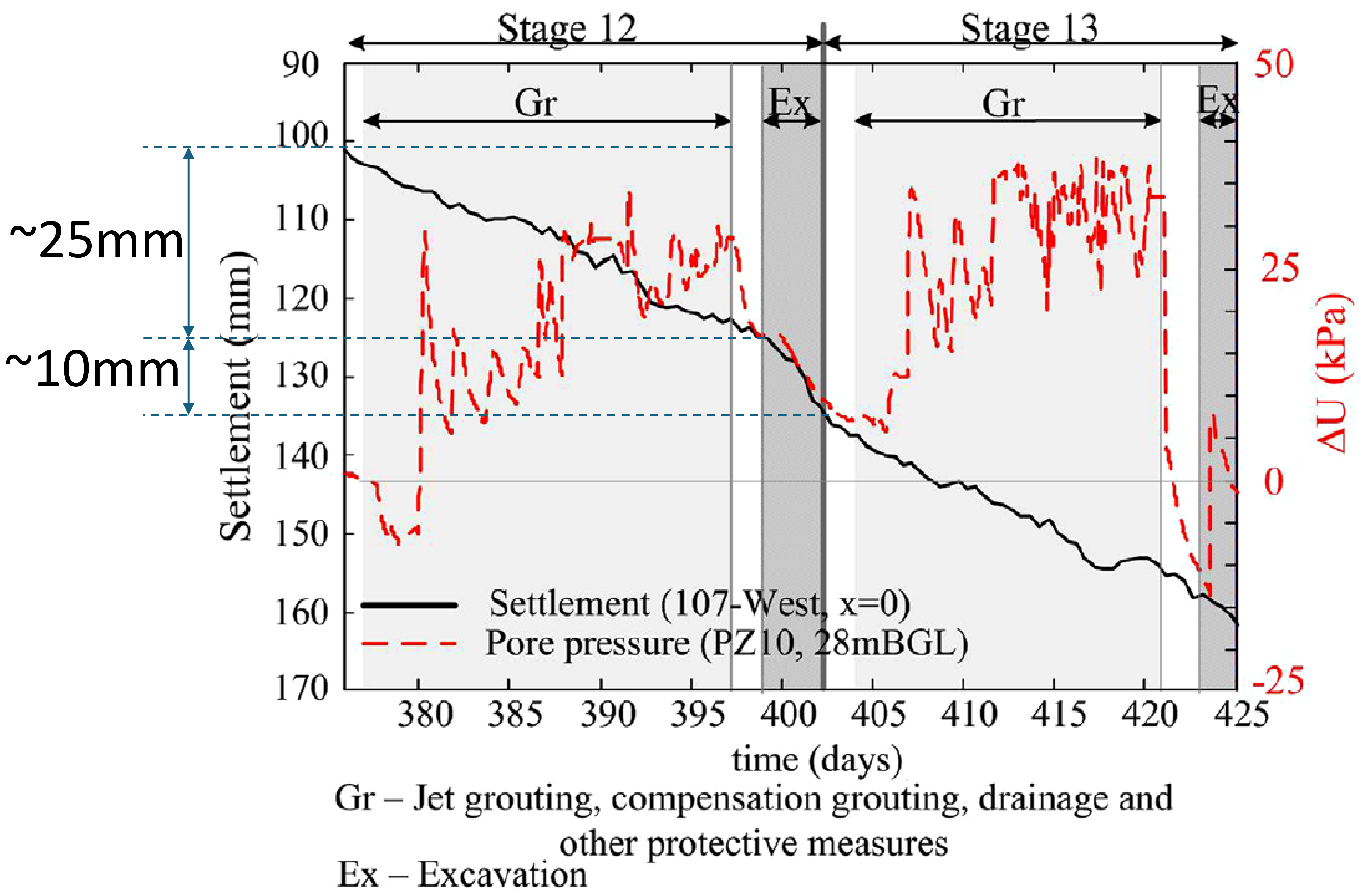




Numerical investigation: Influence of the pre-support umbrella system

"Despite the extensive protective measures adopted during this project, large volume losses have been observed, particularly where horizontal jet grouting was carried out from within the tunnel excavation alone"

Farrell, R., Mair, R., Sciottic, A., & Pigorinic, A. (2014). Building response to tunneling. Soils and Foundation, 54(3), 269–279.



- The numerical simulation did not account for deformations caused by the drilling and cement grout injection operations. The deformations resulting from execution can be significant.

CONCLUSION

- The actual behavior of NATM/SEM tunnels in complex geological conditions can be simulated accurately by adopting advanced constitutive models calibrated with high-quality laboratory tests and by considering the three-dimensional nature of the construction process.
- Reducing the unsupported span length and increasing the stiffness of the primary lining are effective measures to reduce ground deformations and also enhance face stability.
- The benches are highly effective to enhance face stability and reduces ground deformations ahead the tunnel face; however, the benches delay the closure of the lining, which may increase ground deformations behind the face.
- It is desirable to “close” the tunnel’s primary lining as close as possible to the tunnel face.
- Implementing pre-support with jet-grouting columns reinforced with steel pipes can be highly effective in reducing ground deformations, provided that the execution of the treatment does not tself cause significant deformations in the ground.